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How do users adapt to a short-range battery electric vehicle in a two-car household? Results from a trial in Sweden

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ABSTRACT

We supplied 25 two-car households with a short-range battery electric vehicle (BEV) to study their adaptation to a BEV replacing one of their conventional cars. The data includes GPS-measured driving of the households' two original cars for 2–3 months, and for the BEV and the remaining conventional car for 3–4 months. We performed interviews with the households before and after the BEV trial period. We can thus compare the change in measured driving patterns and the users' experienced adaptation in relation to their measured driving adaptation. We find large heterogeneity in measured adaptation, with some users driving the BEV more than the replaced car and some less. Most users state a preference for using the BEV, but this is not always detectable in the GPS data. Similarly, expected issues with the range limitation from the GPS data do not predict satisfaction with the BEV from the qualitative data.

Introduction

Electric vehicles are an important technology to reach the climate targets set by e.g., the Paris Agreement (McCollum et al. 2014; Williams et al. 2012). Therefore, there is an interest in understanding how to best support an introduction and further expansion of battery electric vehicles (BEVs) in the transportation system (Biresselioglu et al. 2018). Part of this is to understand how well BEVs fit households' driving patterns and whether users perceive that the vehicle fulfills their needs. Further, it is important to understand if users would be willing to adapt their driving behavior or other needs to the vehicle's capability, or if the BEV design and performance need to adapt to the users' demands and needs. In this paper, we study the adaptation process to a short-range BEV (~130 km range) exchanged for one of the two existing conventional vehicles among 25 two-car households in Western Sweden during a trial period of 3–4 months. Uniquely, we rely on both GPS data from all the vehicles, both before and during the trial period, as well as interviews, also these before and after the trial period.

Initially, mostly a few short-range BEV models were available from some OEMs. The most recent electrification development has been mainly towards longer-range, somewhat larger and more expensive, BEV models supplied by almost all manufacturers. This has come as a market response to dramatically cheaper batteries, consumer expectations, manufacturers' electrification strategies, and electrification policies, most pronounced in the form of imperative fuel use and CO_2 regulation combined with purchase subsidies. However, for further electrification, there is still a need for knowledge on the possible adoption of short-range BEVs. Apparently, with time more short-range used BEV will enter the market. Economic limitations among some user groups may point towards cheaper BEVs. Addressing the lower end of the car market may be more challenging from an economic point of view (Nykvist et al, 2019). In a recent BEV trial in two-car households in Sweden, it was observed that the average age of the existing cars was high (Karlsson 2020). Thus, exchanging these for (new) BEVs may pose a considerable financial cost and any possibility of using cheaper small-range BEVs will relieve this burden (Miller, 2020). With more electrification, manufacturers will need to consider how to market BEVs for electrification of all vehicles in multicar households, in which the majority of private cars in industrialized countries are found (Whelan 2007). The possibility of accelerating the electrification of the car fleet to meet climate targets may depend on keeping the battery sizes small and thus the battery production capacity expansion down. Further, the total environmental impact, as well as resource burden and costs from the BEV production, will decrease significantly with smaller sizes of the batteries (Chordia et al. 2021; Ballinger et al., 2019; Xu et al. 2020).

Previous literature on BEV trials has focused on specific aspects and has been mainly based on interviews or surveys of the participants. Daramy-Williams et al. (2019) review studies related to user experience both of trials and owners. Bunce et al. (2014) focus on the charging behavior of 139 users who have trialed a BEV for 3 months. Franke et al.

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(2012) use travel diaries and interviews with 40 users who leased a BEV for 6 months. They develop a framework to discuss factors affecting the users' experience of limited range. Bühler et al. (2014) look at the effect of experiencing a BEV on the acceptance of the vehicle. They base their analysis on the same trial as Franke et al. (2012) as well as on around 30 additional users. Jensen et al. (2013) perform a two-wave stated preference experiment to assess the change of preferences and attitudes related to attributes of BEVs such as driving range, top speed, battery life and charging availability. A report of one of the first BEV trials in the US was accomplished by Turrentine et al. (2011). They surveyed about 450 households that tested a converted MINI E and performed interviews with about 50 of these. They studied the learning process of driving and living with a BEV, the response to new attributes of the BEV, and what added value a BEV could have. Another early, but shorter trial in the UK was studied by Graham-Rowe et al. (2012) by interviewing 40 drivers after 7 days of BEV usage. The results highlight some of the barriers of early BEV models, but there was also an expectation that the BEV would improve through technological development.

A few papers in the literature study movements of the vehicles through GPS measurements instead. Jensen and Mabit (2017) focus on the choice between the existing conventional vehicle and an added trial BEV, while Karlsson (2020), using data from the same vehicles as in this paper, studies how well the BEVs exchanged for one of the two conventional cars are utilized.

Other research on BEV adaptation can broadly be divided into two categories. One focuses on driving patterns, mainly on conventional cars, and tries to understand how a BEV, with limited range and high investment costs, would fulfill the driving needs of the user and what the economics of the car choice would entail (Jakobsson et al. 2016; Khan and Kockelman 2012; Plötz et al. 2017; Tamor and Milačić 2015). These studies are by nature quantitative and use data analysis and statistics. The other research category is based on surveys or interviews and may focus on either early adopters of BEVs or potential future BEV owners. This research can either be of quantitative or qualitative nature and may help to understand actual user behavior with regard to electric cars (Axsen and Kurani 2013; Axsen et al. 2018; Egbue and Long 2012; Ryghaug and Toftaker 2014).

The first approach, focusing on driving patterns, can be further categorized for two-car households. One subset of these studies has analyzed driving data for conventional cars with the purpose of either estimating how well a BEV, when having different battery sizes, would be able to replace one of the cars and how economical that would be (Jakobsson et al. 2016; Khan and Kockelman 2012), or to what extent the households can optimize, or maximize, their car usage within a household to fulfill a large part of their driving needs with a BEV as one of the cars (Karlsson, 2017a; Tamor and Milačić 2015). However, these approaches correspond to opposite extremes compared to what actually might happen if a multi-car household adopts a BEV (Karlsson 2020). It is likely that some of the 'problematic' long-distance driving can be easily circumvented by swapping between cars. Still, it is also unlikely that a household will be able or willing to do a complete optimization based on driving patterns only due to several constraints (such as towing, car size, sense of personal ownership of a particular car, etc.). A more user-centered approach is required to understand to what degree, and how, households will adjust their behavior to a BEV,. Based on the identified research gap, we pose a general question: *How do two-car households adapt to a short-range battery electric vehicle?* And four specific research questions:

RQ1. How well do BEV fulfill the driving needs of the households?

RQ2. How do households experience a BEV in their everyday driving?

RQ3. How do households adapt to a BEV and how does it affect their driving patterns?

RQ4. How can the quantitative adaptation be explained using qualitative data?

We answer the questions through a mixed-method approach using quantitative and qualitative data. Firstly, we combine results from (1) simultaneous GPS measurements of both a BEV and a conventional car in two-car households with (2) in-depth, open-ended interviews about the experiences of the car users in the households. Secondly, we combine this GPS data with similar earlier GPS measurements in these households while they still were using two conventional cars. Thus, we can identify how the users' driving patterns changed when they used a BEV in combination with one of their conventional cars. This driving adaptation is then also compared to the users' experienced changes based on the interview data. Thus, we contribute to the literature by providing an in-depth analysis of the adaptation to a short-range BEV in two-car households. To our knowledge this is the first study that combines all these data sources and an analysis of the difference between them.

In section 2 we describe our research design, data, and methods in more detail. In section 3 we present the results of our analysis. We end the paper with limitations and conclusions.

Material and methods

Research design

The posed research questions have quantitative, qualitative, as well as mixed methods aspects. RQ1,"How well do electric cars fulfill the needs of the households?", treated in Sections 3.1–2, relates to the quantitative aspect and takes into account the type of driving the household typically does with their two cars (prior to electrification), and if the given battery range can fulfil this driving. The question is also analyzed through the qualitative data.

RQ2,"How do households experience a BEV in their everyday driving?" mainly relates to the qualitative aspects of the study, and the results are presented in Sections 3.2–3. RQ3, "How do households adapt to a BEV and how does it affect their driving patterns?" is answered mainly by utilizing the quantitative GPS data from both measurement periods and comparing these. These results can be found in Section 3.4. In addition to this, we also identify from the interviews different ways to adapt to a BEV beyond driving patterns. These results are presented in section 3.2.5.

Finally, RQ4,"How can the quantitative adaptations be explained using qualitative data?" treated in Section 3.5, is a fully mixed methods question in the sense that it requires mixing at the results and interpretation layers of the study. In the terminology of Creswell and Clark (2007) we have thus created a concurrent explanatory research design to answer this question.

Experimental set up and data description

Our data set contains two data types on 25 commuting two-car households situated in or around Gothenburg in Western Sweden. The first data type consists of two sets of GPS measurements of both cars from two time periods: before and when the households had one of their vehicles replaced by a BEV. The before data was gathered during 2013–2014 on their two conventional cars. For the second period, we supplied a short-range BEV (Volkswagen e-Golf MY 2015, US EPA range 133 km), along with a 3-kW home charging equipment, to each household. We requested the household participants to choose which one of their regular cars they would set aside and replace with a BEV. We denote the first period, the *pre-trial* period, and the second the *trial* period. The trial period measurements were carried out during 2015–2016. The car in the pre-trial period that the BEV later replaces is named the *replaced* car. The remaining car is denoted the *persistent* car; this terminology is used in both the pre-trial and the trial periods. Measurements in the trial and the pre-trial periods were spread over the year, although the specific periods of the single household may not have been the same. Distributions of the measurement lengths are available in Table 1.

Besides collecting GPS measurements, we performed interviews. One

Table 1
Summary statistics of observation days of the two GPS data sets.

Percentile	Min	25th	Mean	Median	75th	Max
Trial period	37	93	103	99	107	152
Pre-trial period	31	67	72	73	77	148

just before the trial period started and one when it ended. Both interview sessions were semi-structured and contained mainly open-ended questions, however, they had different foci. The first session intended to gather information about the users' expectations of BEVs in general and the trial period in particular. It also gathered information on car purchase history, regular and irregular trips that the household may do, as well as other needs that a car may fulfil for them (towing, goods, tool transport, etc.). The second session focused on the experiences from the trial period, initially letting the participants guide the discussions to whichever topic had made an impression (charging, range limit, size of the BEV, etc.), and later being guided to cover the relevant topics. The first interview session averaged 37 min in length, and the second session averaged 43 min. The semi-structured question sheets are available in the appendix. All but three interviews were carried out by two researchers, and all but one at the household's home (this interview was carried out at a restaurant). The interviews were recorded, and both researchers took notes separately. The interviews were transcribed and manually coded based on themes related to adaptation.

The GPS data in the pre-trial period was originally gathered as part of a project focusing on the potential to maximize electric driving in two-car households, should one car be replaced with a BEV (Karlsson, 2017a). The households that participated in that project were selected randomly from the Swedish vehicle registry with some inclusion criteria. The criteria were that the households contained exactly-two privately owned cars, they were from Gothenburg or one of 13 surrounding municipalities, and the car owner(s) were below 65 years of age. Furthermore, the cars had to be below 200 kW maximum engine power, below a weight of 2000 kg, and be of the model year 2002 or newer. The selection criteria picked out 11 % of the cars in the region owned by around 18 500 households as eligible. 3358 of these households were randomly inquired for participation. With the inquiry, some further restrictions were introduced: that they used at least one car for commuting at least 10 km one way, that there had to be at least two active drivers, and that there was no company car in the household (which is not seen in the registry). The 128 households (around 4 %) that responded positively and fitted the further restrictions were selected to participate in the first study and got logging equipment installed. For 64 of these households, the quality of the gathered GPS data was high enough on both cars, that is, good enough to be able to reconstruct with high certainty the driving in terms of distances, start/stop positions, and points of time for a period of around two months. We have no socio-economic data on the households. Still, from the car registry, we have that the car owners are, in average, 2.0 years younger among the 64 compared to randomly selected 3358 two-car households. However, the car properties do not differ concerning age, weight, rated power, and specific fuel use (Karlsson 2020).

An additional selection was made among these 64 households for inclusion in the trial period for the present study. This selection was based on achieving a broad representation of different households, cars, and driving. One more strict criterion was that the households had changed their driving behavior as little as possible since the pre-trial period. This criterion meant that we excluded households that had moved, had switched jobs, or in any other way dramatically changed their driving needs. This resulted in just above 25 households; and with a positive response of close to 100 %, exactly 25 households were included in the trial. We use only the same 25 households when analyzing the pre-trial period data in the present study, and not all 64.

Of the 25 households selected for this study, all but two live in detached houses. The majority have children and are young, middle-aged. In all households, both cars are used for commuting. This implies that they are not representative of the population. However, given the small sample size, this could not be expected. It was also not our intention to achieve representativeness but rather to capture behaviors within a plausible group of BEV users. All interviews were conducted with both adults in the households, and in two cases, children with driving licenses were present. Though we strongly prioritized households as similar as possible in the two measurement periods, some had changed cars between the two periods. In these cases, it was not obvious which one was the replaced car and which was the persistent car. However, most of the households (prior to the trial) have one primary user of each of the households' cars. We have chosen to designate the sold-off, or retired, cars in the households replaced based on if it had the same primary driver as the car that the BEV replaces (and equivalently for the persistent car).

Our user sample differs from studies that include users who purchased or leased their own BEV. Instead of being taken from early adopters, they were initially randomly selected from non-BEV owners from the vehicle registry. However, they accepted participating in BEV-devoted research in the first place and in a BEV trial in the second. Also, BEV economics (Jakobsson et al. 2016; Karlsson, 2017a), as well as the development in the extensive BEV market in Norway (Figenbaum and Kolbenstvedt 2016), point to an early market in two-car households. Our sample may therefore be more similar to an early majority than previous research on actual BEV usage, which has been dominated by early adopters (Daramy-Williams et al. 2019; Rezvani et al. 2015). This should be kept in mind while interpreting the results, as our (suspected) early majority may differ from early adopters in several ways, such as willingness to adapt.

Finally, it should be noted that our sample of 25 households is small. Therefore, we cannot make direct generalizations as our results may neither be statistically significant over the sample population nor representative for two-car households in general. We will maintain a case-based focus where we more specifically describe how the users in the households adapted to the situation of using a BEV and thereby illuminate different possible adaptation behaviors. We will also attempt to explain why specific quantitative results occur based on the qualitative data.

GPS data pre-processing

GPS data were collected with a frequency of 1 Hz and aggregated into trips with start and end points, start and end times, and driven distances. Furthermore, the on-board diagnostics port (OBD) on the BEVs continuously collected data, including speed and odometer data on all BEVs, and state of charge for 19 of the BEVs. Additional data were available from the home charging stations, though these were not used in this study.

Many types of errors may occur in GPS-gathered data necessitating pre-processing and cleaning. Some of the errors include: devices not turning off after the car is parked in a parking garage, causing a continuously measured driving around the garage and incorrect time-stamps; small data segments may be missing due to lost GPS signal (tunnels, driver accidentally detaching the antenna cable); large data segments may be missing (detached antenna cable without the driver noticing, malfunctioning measurement unit); a longer trip may be divided into shorter trips due to frequent stops in traffic jams or a stalled engine, and so on. A complication to these errors is that most simple indicators may occur naturally. For example, that a car does not start its next trip where the preceding trip ended is not a guaranteed error indicator. The car may simply have been on a ferry, which also occurs regularly in the Gothenburg region.

The data has been corrected for these errors where it has been possible to do so without too much uncertainty of what has happened, e.g., artificial trips have been injected when a car's starting location differs from the previous end location and the missing distances and time

periods are small enough to provide reasonable certainty of how it has been driving. When the uncertainty was too large, data was removed in multiples of entire days for both cars. The reason for removing entire days is to maintain a measure of how long the measurement period has been, including non-driving days. We, therefore, maintain comparable driving days between the cars in the household and the same fractions of weekdays, weekends, and vacation periods. Additionally, some data have been removed because the driving patterns during the time of measurement were highly atypical for the household and, therefore could not be used to compare the trial period with the pre-trial period (e.g., long periods of sick leave).

Among the 25 households in the study, five had too large data losses to be effectively used in the analysis. We, therefore, use only 20 households in the quantitative analysis. These are numbered as households 1–20 when displayed individually in the results section. Of these, households 6–15 had partial winter driving in the trial period, with especially-one cold week, while the others were driven over spring, summer, and fall in the trial period.

Results

Quantitatively expected fulfillment of driving needs

In the literature, a common way to address RQ1, i.e., how well a BEV could fulfill the driving, is to count how many days a conventional car is driven above the range limitation, thus assuming only overnight charging (Jakobsson et al. 2016; Khan and Kockelman 2012; Pearre et al. 2011; Plötz et al. 2017). This measure is referred to as Days Requiring Adaptation (DRA). The number of DRAs in the pre-trial period for the replaced and the persistent car are available in Table 2.

These observed number of DRAs are fewer than expected for a typical car in Sweden. E.g. Jakobsson et al. (2016) find that for a sample of 429 cars, representative of Swedish driving, a range of 130 km yields close to 20 % of the cars in each category of Table 2. For a sample of 20 cars, this would equal four cars in each category, or eight if summing the replaced and persistent cars together. A part of the explanation for the fewer DRAs are the lack of one-car households, as these tend to have above average number of DRAs, and that the replaced cars are slightly older than the ones in Jakobsson et al (2016). The difference could also be an artefact of a small and non-representative sample.

As shown in Table 2, the households have to a larger degree, replaced cars with fewer DRAs. Specifically, the choice of car to replace coincided in 14 of the 20 households with the lowest-DRA car, of which 13 also had the lowest annual driving distance. However, car factors such as size (small), towing option (no), and fuel (gasoline), tended to coincide more with chosen replaced car than with various car movement patterns and charging indicators, such as DRA and workplace charging option (Karlsson 2020).

Qualitative results related to driving need fulfillment

The interview data allows us to assess the experienced adaptation within the households, i.e., the answers of RQ2 that are closely related to how the BEV fulfills the driving needs. Thus, the qualitative part of the answer to RQ1 and RQ3.

Experience of DRA

As described in the previous section, DRA have commonly been used in quantitative analysis as a measure on BEV driving need fulfillment. Therefore, it is important to understand how often DRAs occur in practice and how households deal with them. Some DRA can be expected to be easily mitigated by swapping cars between trips, choosing other times to travel, or charging the BEV. In contrast, others may result in households having to abstain from specific trips.

Table 2
Number of replaced and persistent cars that have specified number of DRA per month in the pre-trial period, assuming a BEV with a range of 130 km.

DRA per month	0	0 – 1	1–2	2–4	>4
Replaced cars	8 (40 %)	5 (25 %)	5 (25 %)	2 (10 %)	0
Persistent cars	3 (15 %)	5 (25 %)	6 (30 %)	5 (25 %)	1 (5 %)

In our sample, we only found one household stating that having a range-limited car was a contributing factor to refraining from making one trip they otherwise might have done. But they also pointed out that there were other reasons for not making the trip. This incident might thus constitute a non-mitigated DRA in practice. In all other cases, the households have managed to solve their driving needs with various strategies, meaning that the existing DRAs have been a minimal to a non-existent problem in practice.

The strategies adopted to handle DRA were larger re-planning of their trips and travel, including switching cars away from home (one stated instance), borrowing a car from someone else (three households mentioned a few cases), or renting a car while on vacation (one instance). Another way to assess the possibility of DRA is to ask the respondents how often they drove their two cars long distances at the same time. We posed this question in the pre-trial interviews to 11 households, and out of these, 8 responded that it never happened, while 3 were unsure if it had ever happened or might have happened once or twice. This might not happen very often because many of the households have children and thus the parents avoid simultaneous longer trips.

How problematic was the limited range?

On the direct question of how large a problem the range limitation had been, a majority of 15 households stated that the problem had been minor. Three that the problem normally was minor but could be major during the winter when the range was reduced even more. Two that it was large enough to hesitate before a purchase but worked well in practice. Two that the uncertainty in range was too big of a problem. And three that the range limitation was a medium-big to a big problem when using the car. Thus, the range limitation seems to (on average) not be a major problem, and the direct calculation of DRA in GPS data analysis alone may overstate the problems of using a BEV in a multi-car household. The multi-car aspect is important to keep in mind since most households point out that it is not a problem because they have another car for the longer trips.

While the limited range in practice has not been a major problem, almost all households thought the limited range was one of the most negative aspects of the BEV and would want to have a longer range. For some households it was a question of having more margins, i.e., to feel comfortable taking some extra trips or if something unexpected happened. One household brought up the example of not being able to drive another kid home after sports training because they were not sure they could make it home afterward. Others wanted a longer range to use the BEV more since they enjoyed driving it and it had lower costs. They thus wanted to shift even longer trips to the BEV, e.g., driving to the summer house without stopping to charge. Another example was families with many daily activities between which they didn't always come home or have breaks that allowed them to charge enough.

We found three factors that influence the perception of how problematic the limited range is. One factor is the effect of cold weather. A regression analysis from the battery State of Charge (SOC) data and driving patterns of the BEVs used in this study indicate that the combined effect of studded winter tires and a temperature decrease from + 20 Celsius to −20 Celsius could result in a halving of the range (Karlsson, 2017b). The households that tested the vehicle during the winter found the range more problematic since the cold weather and the studded winter tires reduced the available range. Another is learning to understand how much range was actually left. Some households felt much more secure and combined reading both the state of charge of the battery gauge and the display showing the remaining range, as well as an understanding of what affects the available range, such as driving style

and weather. Thus, the insecurity of not knowing what exact range was left was more problematic for some households than the actual limit. The third factor was related to the previous one but was more specific about how much range the drivers feel comfortable having left when they came home. Some interviewees expressed that having 30–40 km when coming home as being "not that much range left", while others had driven until there was less than 10 km of range left. This was also related to their behavior with fueling a conventional vehicle. One interviewee pointed out that they refueled their normal vehicle when the tank was half empty.

Planning car use

One way of assuring that all the driving needs can be met is planning the trips in the household. This applies to both the planning of everyday trips and long trips. In our interviews, we found several different behaviors regarding planning. All the households used both cars for commuting, but the households had a choice of assigning the cars between drivers. For some, the obvious choice was the person with the longest commute. They further made choices about which car to use for evening or weekend trips. The majority of the households (18 of 25) stated that they used the BEV for more trips than the car it replaced. This varied from choosing the BEV for extra evening trips ad hoc when these trips were to be initiated, to doing a full daily planning of the car use at the breakfast table to maximize the BEV use. The most common strategy (16 of the 18 households) can be seen as an 'extension' strategy (Karlsson, 2017a), i.e., besides the driving of the replaced conventional car, they also added trips to the BEV from the persistent car, if it was possible to do so. Two households exhibited a very flexible car use, i.e., they shifted vehicles between the drivers to try to maximize the BEV usage. One of these households made full days planning regularly, and the other one frequently drove the BEV until it was close to out of charge.

Among the 7 households claiming they did not drive the BEV more than the car it had replaced, strategies were more diverse. Two households systematically picked the BEV for the shortest trips. A few households have a one-car driveway (where one of their cars blocked the other from exiting), and out of these, one household never attempted to move the outermost car, thus employing a fully random car selection. The others with a one-car driveway chose randomly and planned to some degree. A further three households performed no mixing of the car usage in-between the drivers; that is, the same person always drove the BEV.

There were differences among the households in how they perceived the need for planning. Three households discussed the planning in more negative terms and found it cumbersome and time-consuming. One interviewee points out that, for instance, he had to spend half an hour in the evening looking up charging stations. Seven others acknowledged a need to plan but found it minor or at least less than expected. One even expressed that they were surprised that it was so simple. Three households reflected on the connection between the limited range and the need to plan, i.e., a longer range would reduce the need to plan. The remaining ten households didn't mention planning in the interview.

Charging

One strategy to deal with the range limitation is to charge the car at other places than at home and work during days with a lot of driving. Within our sample, 11 households claimed they never charged away from home and work, 10 households charged a few times away from home and work, and the remaining three charged several times away from home and work (no clear answer in one household). This hints that charging at public stations is a viable strategy for a sizable part of the sample, while the remainder used these only given easy access and a strong need. This is confirmed by the battery data showing that three out of the 19 SOC-logged vehicles only charged at home, and of the remaining 16, only six charged outside the home due to trips longer than the range ($\geq$120 km). However, this was not common behavior. It happened only between one and five times during the whole trial period.

The setup of the trial may have limited the charging behavior, especially for fast charging. Since the households knew that they only had the BEV for a short period, there was no real incentive to start accounts or register for fast charging, especially since they had another vehicle that they could use instead. Some households pointed out that they didn't need to charge because they used the BEV only for everyday driving and not for longer trips. Thus, they did not feel that it was worth the effort to learn and find information about charging.

Several households found public charging and fast charging unreliable. They couldn't trust that the charging stations would be working, non-occupied, or compatible with their BEV. This was primarily a concern when they discussed planning possible long trips with the BEV. The perceived unreliability of the charging infrastructure was one of the major deterrents for the households to undertake longer trips with the BEV.

Other ways to adapt

In section 3.4, we look at how the driving patterns are adapted to the BEV. From our interviews, we found that the households adapted to a BEV in other ways as well. The most common was a change in driving styles. This could be driving at lower speeds, especially on highways or more long-distance trips, or even avoiding highways not to have to drive above 90 km/h. Some households also discovered how they could benefit more from the regenerative breaking. In general, it can be said that the households with a more positive attitude toward BEVs better understood what affected the amount of range that was left and how they could get more range out of the vehicle from their driving style. One household took it as a challenge to try to get as much range as possible out of the BEV. One strategy to get more range was to turn off the heating in the car either during the whole trip or during parts of the trip. One household always had gloves in the car and put in sheepskins to sit on to keep warm.

Interview results related to the experience of using a BEV

In this section we answer more general aspects of the experience of using a BEV (RQ2). Most households (20) stated that the overall experience of using a BEV was positive or strongly positive. Of the remaining households, four had mixed feelings, and one didn't make any clear statement. None of the households reported an overall negative experience. The households in general, appreciated the driving experience, that it was quiet, cheap, and environmentally better to drive. They had the feeling that it was a modern car.

When asked about the negative aspects, range limitation was stated by 12 households as the most significant negative factor, while three households stated that no particular negative aspect was present. Many households mentioned the uncertainty in the cars internal range estimate (which typically started on an estimated 190 km, but in practice only averaged 120 km in total driving according to several respondents). Two household ranked this uncertainty as the major negative aspect. This uncertainty in how far the car actually could travel contributed to an overall uncertainty feeling concerning the BEV's reliability. Similarly, the availability and reliability of charging away from home were also seen as insecure. Ten households used the BEV during the winter, and of these, three stated the winter cold and its impact on the range as a negative factor. Other negative aspects included problems with the home charging station, required charging time, and lack of towing capability.

From the interviews, we find a few aspects that seem to affect the experience of the BEV. One is the perception of the need to plan their driving. Common among the households with more mixed feelings about the BEV was that they perceived the need for planning as more negative and cumbersome. This was also related to an attitude toward charging and range. The more enthusiastic households found charging at home at night very smooth and that it was a relief not to have to go to the

gas station. The more hesitant households described the need to charge as something always in the back of their mind. Another factor was understanding how much range actually was left and what affected the actual range, such as driving style and weather. The most positive households found that they had learned how to get as much range as possible out of the BEV and thus also felt more confident in using it more and for longer trips. Cold weather, on the other hand, had a negative effect on the perception. Even the households with a positive overall experience expressed a concern that the available range decreased by over 30 % in some cases.

A further indication of how appreciated the BEV was in the households is the potential for future BEV ownership or leasing. The largest group was cautiously positive: four could consider a plug-in hybrid electric vehicle (PHEV) instead; another four would consider a BEV if the price was lower; seven considered leasing a BEV. The primary motivation for leasing was to avoid the risk of battery deterioration. Six households responded that they would not be willing to purchase or lease a BEV; most cited range limitations, followed by the high investment cost and lack of charging infrastructure as the reasons not to purchase a BEV. For many of the households the BEV was seen as the second car (even if they used it more), which typically, for them, was a cheaper car (such as the car they replaced). Thus, the purchase price would have to drop quite a lot for it to be attractive for them. The participants of one household were split, with one in favor and the other against purchasing a BEV. Three households were very positive: one household had already started leasing a Nissan Leaf at the end of the trial period, one had started queuing for a Tesla Model 3, and one was considering leasing a BEV within the coming year. Thus, the results hint at an overall positive view of the BEV, in line with the general statements. Though there are still some barriers remaining for most households to enable a purchase or lease, and for some households, a short-range BEV is not a good enough option.

The adaptation of driving patterns to the BEV

To judge how much and in what way households have changed their driving patterns, i.e., answer RQ3, we calculate the distribution of daily driving distances for the electric car and the replaced car, respectively, in the twenty households. These results are displayed as normalized histograms in Fig. 1, where the average distribution over all the households is shown in the top left panel, while the other figures contain three interesting individual results. For the overall average, we can see a tendency for the BEV to be more utilized for daily driving distances within a range of around 30 km to 90 km compared to the replaced car, which is less concentrated in this driving span. Thus, relative to the replaced car, the electric car reduces the amount of long-distance (90–140 km) and short distance daily driving (0–30 km). The interviews reflect these results where we see both a reluctance to take long-distance trips and an intent to use the BEV for trips below the range. Karlsson (2020) also showed that there was a significant difference in the share of driving below the BEV range (120 km) in-between the replaced cars before the BEV trial, depending on if they were first or second car. (Total annual driving distance determined if the car was a first or second car.) However, the same difference could not be seen in the BEVs during the trial period. He concluded that the BEV use was not determined by which car it replaced, i.e., a first or second car. Household 11 keeps the same driving distances for the BEV as for the replaced car. This is also a case of a typical commuter car. In households 14 and 13, the electric car has to a large extent an increased and decreased driving compared to the replaced cars, respectively. Among all the households, two mainly maintain the same daily driving distances when adopting a BEV, 13 can be said to increase the driving on the electric car (either a little or a lot), two decrease the driving on the electric compared to the replaced, even though the driven distances on the replaced car were below the range limitation, while the last three households cannot be clearly put in any of the categories. Most

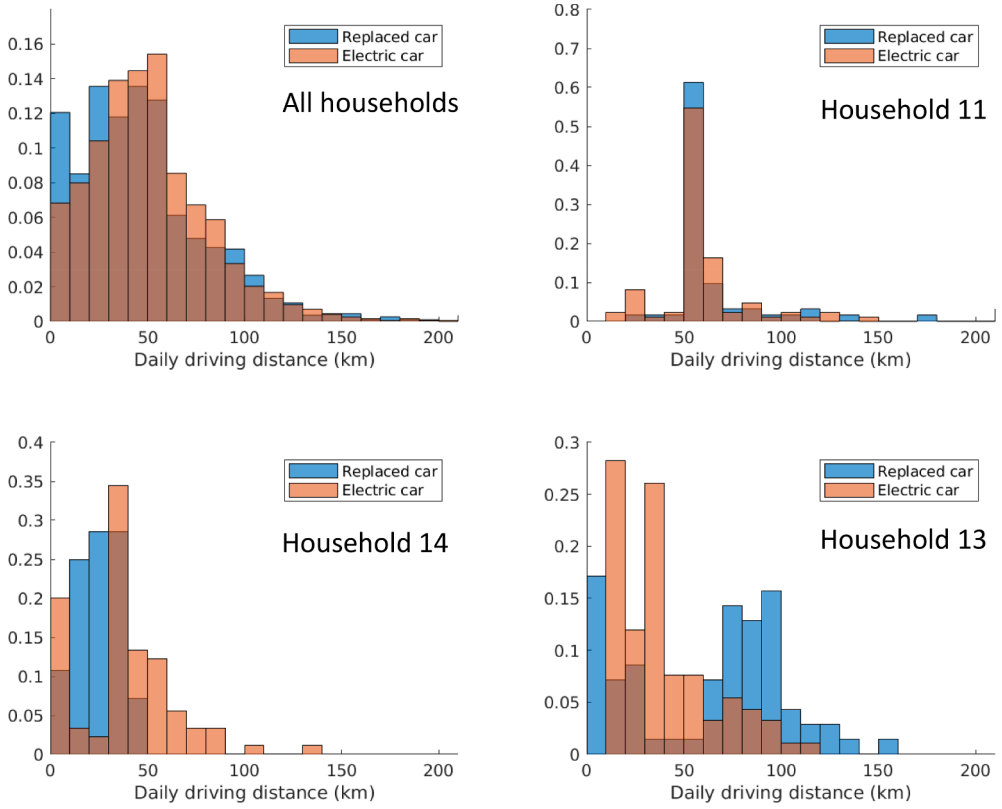

Fig. 1. Distribution of daily driving distances for the BEV (light brown) and the replaced car (blue) for average over all households and three example households. (Dark brown represents overlapping data between the two car types.).

households do not have an as clear-cut pattern as the example households displayed in the figure but have behaviors in-between the mentioned cases. Thus, there is heterogeneity in adaptation patterns.

When comparing the electric car to the concurrently used persistent car instead, the pattern is fairly similar, see Fig. 2. On average, the electric car drives more in the range 30–90 km and individual households exhibit a large heterogeneity. The example household 3 uses the electric car for longer daily trips, while the opposite holds for household 9. Household 2 shows a similar behavior as household 9, but the daily driving distances are very close to the range limitation of the BEV.

Besides differences in daily driving distances, there may be differences when the cars are used. From the interview results, we know that some households state that they don't fully optimize the use of the BEV but that they prefer to use the BEV for extra trips in the evening and on weekends. In Fig. 3, we can see that, on average, in the households, the electric car is starting trips relatively more often later in the day compared to both the replaced car and the persistent car in both measurement periods. In Table 3, we also observe a revealed preference for using the electric car on weekends compared to both the replaced and the persistent car. While both trips and distances were somewhat evenly distributed between the replaced car and the persistent car in the pre-trial period, this has changed into a stronger preference for the electric car in the trial period. Specifically, the number of trips of the electric car increased by 27 % compared to the replaced car, while at the same time, the persistent car reduced its number of weekend trips by 28 %. When measuring distances, the effect is less pronounced, with a 14 % increase for the electric car compared to the replaced and a 29 % decrease for the persistent car.

A natural question is if this stated preference for the electric car, and the measured preference at least during evenings and weekends, have a

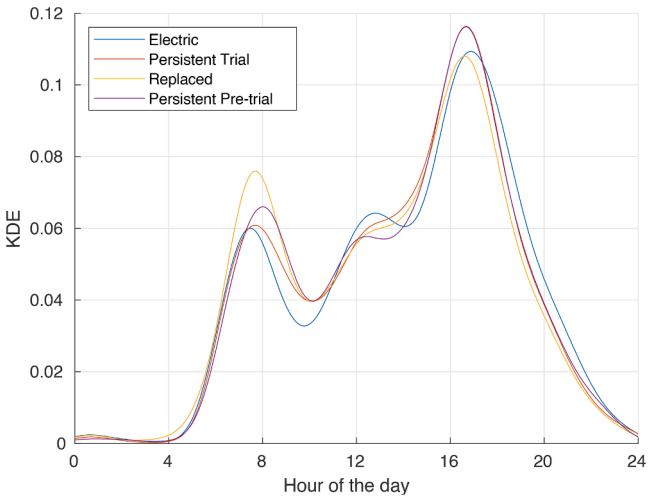

Fig. 3. Distribution (Kernel density estimate (KDE)) of start times for trips over the day for average over all households for both cars in trial and pre-trial period, respectively.

pronounced effect on the share of total household distance driven by the electric car compared to the replaced car. By extrapolating the driven distances in the two measurement periods to annual driving distances, these shares can be calculated. These shares, as well as the fractional increase between them, are shown in Table 4. In just over half of the cases, the fractional change in driving due to the adoption of a BEV is small, with seven households having a change below 5 % and an additional five between 5 and 10 % change. In these two groups, three

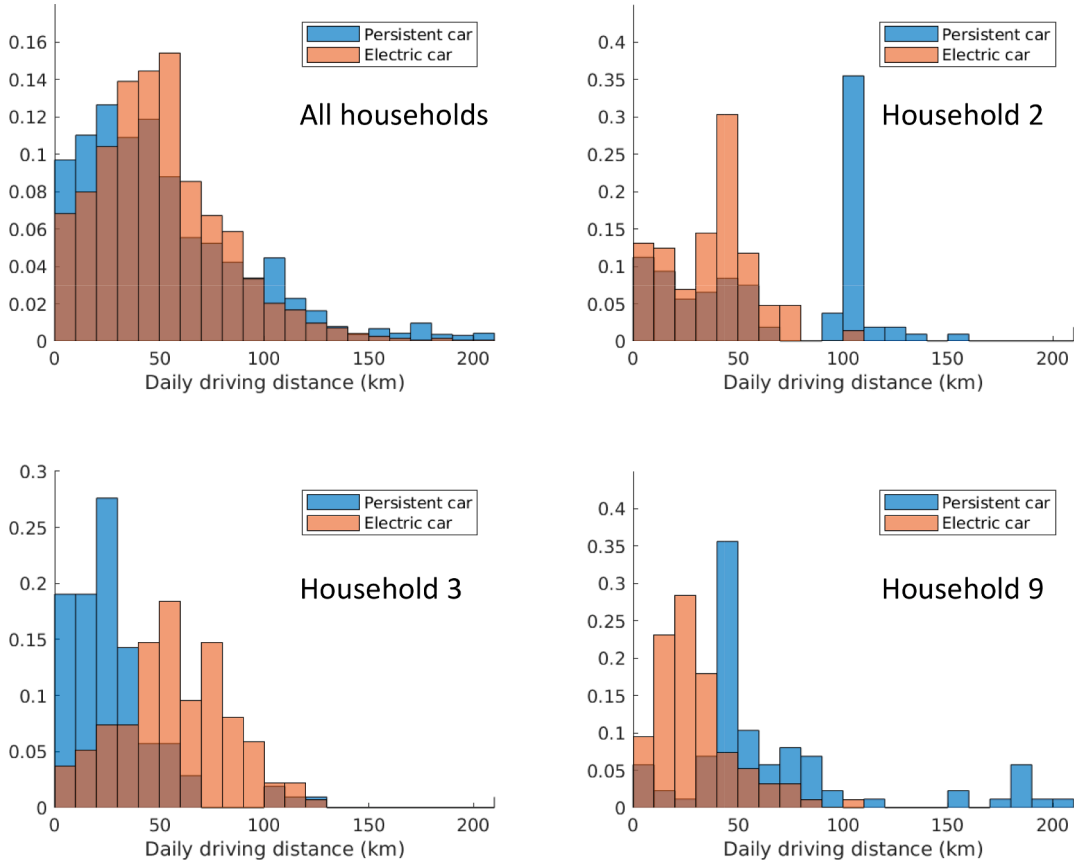

Fig. 2. Distribution of daily driving distances for the BEV (light brown) and the concurrently used conventional car (blue) for average over all households and three example households which are chosen to display the clearest examples of some driving behaviors. (Dark brown represents overlapping data between the two car types.).

Table 3
Share of total number of trips and total distance driven on weekends in each measurement period for the electric or replaced car and persistent.

	Period	Electric/ Replaced	Persistent	Both
Share of all trips on weekends	Trial	13.6 %	8.0 %	21.6 %
	Pre-trial	10.7 %	11.1 %	21.8 %
Share of total distance driven on weekends	Trial	12.6 %	7.2 %	21.8 %
	Pre-trial	11.1 %	10.1 %	21.2 %

Table 4
The share of total household driving distance for the electric car in the trial period and for the replaced car in the pre-trial period, respectively. The last column shows the fractional increase of household driving for the electric car compared to the replaced car. A fractional increase > 5 % is marked in blue and a decrease > 5 % is marked in red.

Household number	Electric car share	Replaced car share	Fractional increase
1	34 %	33 %	3 %
2	40 %	30 %	33 %
3	67 %	50 %	34 %
4	45 %	57 %	−22 %
5	41 %	73 %	−44 %
6	65 %	63 %	2 %
7	44 %	42 %	6 %
8	35 %	34 %	4 %
9	31 %	29 %	9 %
10	43 %	47 %	−7 %
11	59 %	52 %	12 %
12	58 %	63 %	− 8 %
13	58 %	59 %	−2 %
14	52 %	20 %	159 %
15	49 %	48 %	2 %
16	59 %	54 %	9 %
17	46 %	40 %	17 %
18	56 %	40 %	42 %
19	32 %	32 %	0 %
20	35 %	35 %	0 %

households lowered the share of driving of the electric car compared to the replaced. Of the remaining households, two have a substantial decrease in driving on the electric car compared to the replaced car, with 22 % and 44 % reduction respectively; and 5 have a considerable increase of 12 % to 42 %. Finally, there is a substantial outlier with an increase of 159 %.

Another difference in the driving patterns might lie in the type and number of destinations visited with the BEV and the internal combustion engine vehicle (ICEV). This is out of the scope of the current paper but has been analyzed for the same data in Jakobsson (2019). He finds no observable difference in total destinations or the number of unique destinations between the two car types. However, the unique destinations of the ICEV are, on average, farther away.

Explaining the quantitative results using the qualitative data

As described in the previous sections, there is large heterogeneity in both experienced adaptation and GPS measured adaptation. Still, we find some common themes. Almost all the households limit the daily driving distance for the BEV below the range, as shown in Figs. 2 and 3. This is also consistent with the interview data, where most households are reluctant to take the BEV for longer trips. Many households also find that there is not always enough range to do extra trips and errands during all days or "spontaneous detours". This can also partly be explained by some households' resistance to charging away from home (see Section 3.2.4).

Based on Table 4 we divide the households into three major groups: those that have decreased their fractional driving share with the BEV compared to the replaced car (marked in red), those that have remained more or less unchanged (±5 %) and those that have increased the driving share (marked in blue). We compare with the distribution of daily driving distance and how according to the interviews they have experienced their driving.

Four households (number 4,5, 10, and 12) have a decrease in fractional driving distance. There is no indication that this decrease is connected to a more negative view of the BEV, rather the opposite since households 5, 10, and 12 all had very positive views. Household 4 had a more mixed view. They thought it was really good for short trips but experienced range anxiety for longer trips due to both the insecurity about how much range was actually left and the lack of well-functioning charging infrastructure. This could also be observed in the distribution of daily driving distances that were substantially below the range limitation for the BEV. Still, they would consider a BEV with a doubling of the range and more charging stations in place.

In comparison, household 5, which had an even larger reduction in the BEV driving share compared to the replaced car (Table 4), was strongly positive to the BEV. They claimed that they primarily chose the BEV for their trips and that the young adults in the household preferred the BEV as well. A closer investigation of this household's daily driving distances reveals that they had unchanged daily driving distances on the electric car compared to the replaced car, with a slight increase in driving on the electric car for longer distances below the range limitation. A major reason for the overall reduction in electric car driving is that the replaced car had been used for a fair amount of long-distance driving, from 300 to 450 km, while the BEV had not performed similar trips.

Household 10 planned the driving with the BEV based on who would drive the longest, but "not too long", as they stated. They didn't experience the range limit as problematic since it had worked well for their daily driving. Still, they have not dared to take the BEV on trips longer than 100 km. Household 12 stated that they chose the BEV when possible while still expressing insecurity about the range.

The seven households with more or less unchanged driving share (+/- 5 %) were number 1,6, 8, 13, 15, 19, and 20. All, except household 1, perceived that they had used the BEV similarly to the replaced car. Household 1 instead felt that they used to BEV more than the replaced car. This household did not experience the range as problematic but stated that they had to think more about their routing and wouldn't take spontaneous trips along the way. Another common theme of these households was that they explicitly stated that they did not use the BEV for long trips. In the case of household 19 this was no change compared to the replaced car. This household also did not experience the limited range as a problem.

We found different strategies for planning trips in this group. In household number 20 they shifted during the trial period so that the driver with the longest commute used the BEV but not on days when they had extra errands. Household 8 felt quite insecure about how much range was actually left and thus chose the BEV for trips and routes where it was obvious how far they needed to drive. They were one of the more skeptical households. Household 15 shifted their two cars between the drivers "completely due to" whoever would leave their dog at the dog day-care, since the dog always travelled in the persistent car. They had an overall positive view of the BEV but pointed out that it worked mainly as a commuting car and expressed a certain nervousness about pursuing trips longer than 80 km, thus a bit below the actual range limit. Household 19 never changed drivers between the replaced car and the BEV. Household 13 were disappointed about the limited range and that they could not use the car more and for extra trips. Still, they believed that there was an equal split between the persistent car and the BEV.

Among those with a moderate increase in driving share (households 7, 9, 11, and 16), we found two that didn't perceive they used the BEV more (households 7 and 9). Household 7 had a one-way drive lane and would choose vehicle based on the one that was furthest out and had

neither tried to deliberately use the BEV more or less compared to the replaced car. They found it to be a good city car while experiencing the range as limiting for longer trips. Similarly, household 9 really enjoyed the BEV for shorter trips but would avoid longer trips and shared the cars between the two drivers in the household like with the replaced car.

Both households 11 and 16 were very positive about the BEV and perceived that they used it more than the replaced car. Still, for household 11, the distribution of daily driving distances was fairly unchanged between the BEV and the replaced car. Household 16 had a strong aggregation using the BEV in the distance span of 40–80 km, while the replaced car's driving was more dispersed. They repeatedly said that they preferred the BEV for all trips and adopted different behaviors to be able to drive the BEV longer distances. They realized that driving style influenced the range and thus would sometimes deliberately choose the route avoiding speeds above 90 km/h. They also used charging stations away from home and frequently charged at work.

Household 17 had a slightly larger increase, and they also perceived that they had driven the BEV more than the replaced car. They mainly tried to use the BEV for the extra shorter trips but had taken the persistent car for longer trips, e.g., skiing trips. The distribution of cars between the drivers was the same as with the persistent car.

The remaining four households (2,3,14, and 18) all had a reasonably large increase in the share of driving on the BEV. Differences in overall driving patterns can explain the increases for households 14 and 18. For household 18, there was no strong difference in the distribution of daily driving distances compared to the replaced car. Instead, reduction in household total driving between the pre-trial period and the trial period explains the increase in driving with the BEV. The household started using the BEV during the winter and then experienced the range as quite limiting. However, as the weather got milder and they learned to handle the limited range, their impression of the BEV grew more positive. Overall, they believed they used the BEV more when possible if the driving distances were below the range. The notable increase of 159 % from household 14 was due to a combination of a strongly stated preference for the BEV, and a substantial decrease in driving need on the persistent car in the trial period. This household's trial period was over winter, and their persistent car was to a large degree used over summer for reaching distant sports activity locations.

Household 2 had a longer vacation period which decreased the overall driving. They perceived that they used the cars similarly, and it was almost always the same driver that used the BEV. They did not find it worthwhile planning longer trips with the BEV. Household 3, on the other hand, was one of the most enthusiastic households and had learned how to handle the limited range and how to "get the most out of it". Usually, the drivers had their own car, but during the trial they had shifted more between them.

In summary, there are both consistencies between measured changes and experienced changes, and apparent inconsistencies between these two, such as households stating that they prefer to use the BEV, but that such a preference is not directly visible in the measured data. Two conclusions are: interviews may be unreliable predictors of actual car usage choices, and quantitatively measured driving data and their predictions on how well BEVs fulfill driving needs may not accurately picture how households experience using a BEV. Furthermore, there is a large heterogeneity in how households choose between cars for trips, thus assuming either no BEV usage optimization, or a full usage optimization when studying GPS driving data, will yield results inconsistent with actual behavior.

Limitations and future work

The major limitation of this analysis is the sparse data set, containing only 25 households, of which 20 households in the quantitative and mixed methods analysis. Thus, these results should be considered illustrative of possible behaviors during a BEV trial period and cannot be generalized. The results, however, remain relevant given that they illustrate a seldom measured usage group, that is, drivers of BEVs that are not early adopters.

It's not easy to gauge the impact of the user type in the study. One could expect them to be less willing to adapt than early adopters; contributory to this, is the artificial situation where they have been offered a BEV for a few months, rather than spending time and money on gaining information and purchasing their own BEV. In such a situation, the same households may have acted differently, perhaps increasing the BEV's use more relative to the conventional car to offset the high investment cost. On the other hand, the marginal costs of using the BEV were lower as there were no depreciation costs for the user connected to the BEV driving. Given these caveats, many households have preferred to use the BEV, either for environmental or economic reasons.

The two data types used in the analysis have their separate strengths and weaknesses. The interviews are better at revealing motivations for the users' decisions. However, they are limited by the cognitive capacity of the users, that may not fully be aware of their trip planning decision process. Their preferences for car use may also vary across time, while the interviews were conducted at the end of the 3-month trial period. Another aspect that may affect the interview data is the interview situation where two researchers are posing questions and recording the conversation. This was occasionally evident, as new information, such as opinions of the BEV, could be spontaneously given after the formal interview ended and the recording was turned off. Compared to the interviews, the GPS data have the strength of providing the direct usage of the cars, and the possibility to compare the usage of a BEV to a conventional car. However, this strength is limited by the length of the measurement period. No household was measured for an entire year, which would be required to have information of both vacation driving and winter driving for a particular household.

Another limitation of this study is that the users were not allowed to pick a BEV that would best suit them. BEV development has been fast, with new models and battery sizes appearing. For instance, if individual users could have chosen a large enough BEV to fit their dog comfortably, or if the users had had access to a BEV with a 300 km range during the trial period, the results may have been different. However, it should be clearly emphasized that all the households were able to fulfill or adapt their driving needs with the current BEV without abstaining from desired trips. As the households consider the high investment cost for a BEV a significant barrier, there may be a future market for low-range BEVs if this also entails a lower investment cost and a lower environmental burden. Furthermore, as both users in each household were commuting, and many of them had already picked the BEV for the longer commuting trip, it seems as if a larger battery size would not serve to increase the households electrically driven distance dramatically.

The fact that the BEV is driven more often on weekends and evenings than the conventional cars hints that it is used for slightly different purposes than the conventional cars, as also illustrated by the interview data. However, since the quantitative data in this study is of a high quality, it would be possible to research exact destinations for the different car types, thus inferring if the cars are used for different purposes. This is a potential avenue for future research that can add to our understanding of BEV adoption and household adaptation, and driving patterns of BEV usage.

Summary and conclusions

With a novel research design, we have analyzed the adaptation and BEV usage in 25 two-car households that did not take the initiative to obtain a BEV. We can draw conclusions based on two comparisons. One compares measured GPS data from when the households had two conventional cars to a trial period when they had one conventional car and one electric car. The other by comparing measured driving on the cars with experiences and experienced adaptation from interviews in connection with said trial period. In summary, we show:

- Almost all households have a positive or strongly positive experience of the trial period.
- There is heterogeneity in stated adaptation to the BEV, with some homogeneity: 18 households state an increase in BEV usage. There is a larger heterogeneity in measured adaptation to the BEV, with 5 out of 20 households reducing the share of household distance driven on the electric car compared to the replaced car, and 9 households increasing the share driven electrically by less than 10 %. Thus, there is no universal increase in electric driving in the households.
- Besides driving patterns, some households adapt to the BEV by changing their driving style, lowering their speeds, taking alternative routes, and not using the compartment heating as much.
- On average, the BEV tends to take up more driving in the 30–90 km daily distance range compared to the replaced car. For other distances, the BEV reduces its driving compared to the replaced car.
- Statements from the qualitative data were not always consistent with how driven distances changed in the households when adopting a BEV.
- Similarly, GPS measurement of driving patterns and any necessary derived adaptation were bad at hinting at how well the households appreciated a BEV and the experienced fulfillment of their driving needs. Expectations, the perception of the need for planning, and understanding of what affected the actual range were better indicators.
- The battery range, stated as 120 km most often, was sufficient to enable the households to fulfil all their driving needs with some adaptations. However, the majority request a range of at least 200 km if used within a two-car household. A longer range was wanted to use the BEV more, reduce insecurities and the effect of, e.g., cold weather and highway driving.

Overall, the study points out that in two-car households, a short-range BEV can be enough to fulfill the driving needs of the households and often leads to positive, or strongly positive, experiences of a BEV. However, many request a somewhat larger range for convenience. The current market development of BEV is toward larger and larger battery ranges and with that an increased weight and environmental impact from the production of the BEV. However, our results show that at least in multi-car households with access to home charging, a shorter-range BEV can fulfil a large share of the driving and thus should not be excluded in future model developments. Shorter ranges might also make it easier to enter the market segments of smaller cars, where reaching economic parity is more challenging (Nykvist et al. 2019). From a market development perspective, this implies that vehicle manufacturers should not abandon the idea of developing short-range BEVs. However, for these to be attractive, home charging and possibly even workplace charging must be easily available. This implies that regulations and incentives for charging close to home, even for those living in apartment buildings should be stressed from a policy perspective. From a research perspective, our results show that both qualitative methods and quantitative methods per se have their drawbacks in assessing the adoption of BEVs thus future studies should, to a larger extent, try to adopt a mixed-method approach when evaluating new technologies and fully understand daily usage and acceptance.

CRediT authorship contribution statement

Niklas Jakobsson: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Frances Sprei:** Conceptualization, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Sten Karlsson:** Conceptualization, Funding acquisition, Investigation, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix A. Pre-trial interview questions

- Could you please describe your household situation:
  - How many are you, and how old is each person?
  - How many have a driving license?
  - Where do you work?
  - Where do the children go to school?
- Why did you choose to participate in this study?
- Please describe what kind of cars you currently own and why you chose them.
  - Age:
  - For each car:
- Why did you choose this particular car?
- What do you mainly use this car for?
- Who drives which car? If possible indicate in percentage the split between you.
- Please describe how you plan your car trips, which car do you pick for which kind of trip?
- What kind of longer trips do you do?
- Car history:
- Which cars have you previously owned?
- Why did you choose these cars?
- Did you like these cars?
- Which was the favorite one?
- Which car have you chosen to de-register for the trial period? [Translation note: De-register as in stop paying taxes as it is not in use. Marks the ‘replaced’ car].
- Could you tell us what you know about electric cars?
- Do you know anything about subsidies and or other support that electric cars are eligible for?
- Can you charge at work? If yes, do you need to pay for it?
- Have you ever considered buying an electric car? Why?
- Have you ever driven an electric car?
- What kind of expectations do you have? Any specific thoughts?
- Is there anything you are worried about?
- How do you think that you will deal with the limited the range of the electric car?
- What range would you wish for in an electric car?
- Do you need towing capacity?
- Did everything work out with installing the home charger?
- Do you have any questions for us?

Information point: At the ending interview we will ask you about your experiences from the trial period, so if there are any specific impressions you get during this time, then please write them down or remember them until then. We will also ask about charging, which cars you used for which trips, if you did any long trips and so on.

Appendix B. Post-trial interview questions

General questions.

- Now at the end of the trial period, what is your general impression of having used an electric car for a few months?

- Anything specific that made an impression on you, either positive or negative?
- How did your experience compare to your expectations?
- How long time did it take to get used to using an electric car? How long time before you felt comfortable knowing how everything worked?
- How has charging worked?
  - At home
  - Away from home

Car use.

- Did anything specific happen during the trial period that significantly altered your driving? [Note, this question was clearly described to refer to unusual events, such as long-term sick leave].
- Can you describe how you have used the cars, which car did you choose for different types of trips, and did you plan your car use?
- How have you distributed the car use among each other? (please indicate percentage if possible)
- Is this distribution different compared to when you had two conventional cars?
- *If they changed their car use in-between each other:* Did this work out well, or did you find it problematic?
- How have you chosen which car to use for which kind of trip?
- How much have you used each of the two cars? (please indicate percentage if possible)
- Could you talk a bit about long trips
  - Have you used the electric car for any long trips?
  - Have you had to replan your travelling because of the limited range?
  - Are there any trips you had to completely abstain from?

General questions again.

- What did you experience as the biggest strengths of the electric car compared to a conventional car? Were any of these strengths unexpected?
- What did you experience as the biggest weaknesses to be? Were any of these unexpected?
- How large of a problem has the range limitation been for your travelling? [This was occassionally clarified by following up with:"Is it no problem at all, does it make the car unusable for your needs, is it big enough to deter you from purchase?"]
- Do you think that your view on the range limitation has changed over time?
- How large range would you wish for in an electric car?

Charging.

- How and when do you charge the car?
- Have you regularly charged somewhere else than at home?
- Have you ever charged at other people's homes?
- Is there any other location you have charged at?
- Where would you have the best use of charging stations?
- Have you planned your driving to use existing charging stations? In that case, how often?
- Have you used fast charging?
- Do you have any suggestions on what to do differently when it comes to charging infrastructure?
- Have you searched for any extra information with regards to the electric car or charging? For example from forums or news sites.
  - Do you think this extra information was useful?
- Did you use the car-net app? Do you think it was useful?

Last general questions.

- How have others reacted to you driving an electric car?
- Do you have any tips for the next group of users, or for someone who is considering buying an electric car?
- Could you imagine buying an electric car?
  - In that case, what is the main reason for this?
  - If not, what do you think needs to change for you to consider this? (car, infrastructure, price)
- Do you view electric cars more favorably or less favorably now after the trial period? We ask this specifically from your own personal situation.

Is there anything else you think that we should know?

References

Axsen, J., Kurani, K.S., 2013. Hybrid, plug-in hybrid, or electric—What do car buyers want? Energy Policy 61, 532–543.

Axsen, J., Cairns, J., Dusyk, N., Goldberg, S., 2018. What drives the pioneers? Applying lifestyle theory to early electric vehicle buyers in Canada. Energy Res. Soc. Sci. 44, 17–30.

Ballinger, B., Stringer, M., Schmeda-Lopez, D.R., Kefford, B., Parkinson, B., Greig, C., Smart, S., 2019. The vulnerability of electric vehicle deployment to critical mineral supply. Appl. Energy 255, 113844.

Biresselioglu, M.E., Demirbag Kaplan, M., Yilmaz, B.K., 2018. Electric mobility in Europe: a comprehensive review of motivators and barriers in decision making processes. Transport. Res. Part A Policy Pract. 109, 1–13.

Bühler, F., Cocron, P., Neumann, I., Franke, T., Krems, J.F., 2014. 'Is EV experience related to EV acceptance? Results from a German field study. Transport. Res. Part F Traffic Psychol. Behav. 25, 34–49.

Bunce, L., Harris, M., Burgess, M., 2014. Charge up then charge out? Drivers' perceptions and experiences of electric vehicles in the UK. Transp. Res. Part A Policy Pract. 59, 278–287.

Chordia, M., Nordelöf, A., Ellingsen, L.-W., 2021. Environmental life cycle implications of upscaling lithium-ion battery production. Int. J. Life Cycle Assess. 26 (10), 2024–2039.

Creswell, John W and Clark, Vicki L Plano (2007), 'Designing and conducting mixed methods research'.

Daramy-Williams, E., Anable, J., Grant-Muller, S., 2019. A systematic review of the evidence on plug-in electric vehicle user experience. Transport. Res. Part D Trans. Environ. 71, 22–36.

Egbue, O., Long, S., 2012. Barriers to widespread adoption of electric vehicles: An analysis of consumer attitudes and perceptions. Energy Policy 48, 717–729.

Figenbaum, E., Kolbenstvedt, M., 2016. Learning from Norwegian battery electric and plug-in hybrid vehicle users. TOI Report, Oslo.

Franke, T., Neumann, I., Bühler, F., Cocron, P., Krems, J.F., 2012. Experiencing range in an electric vehicle: understanding psychological barriers. Appl. Psychol. 61 (3), 368–391.

Graham-Rowe, E., Gardner, B., Abraham, C., Skippon, S., Dittmar, H., Hutchins, R., Stannard, J., 2012. Mainstream consumers driving plug-in battery-electric and plug-in hybrid electric cars: a qualitative analysis of responses and evaluations. Transport. Res. A Policy Pract. 46 (1), 140–153.

Jakobsson, N., 2019. Electrification of private mobility: driving patterns, multi-car households and infrastructure. Chalmers University of Technology. Doctoral thesis.

Jakobsson, N., Gnann, T., Plötz, P., Sprei, F., Karlsson, S., 2016. Are multi-car households better suited for battery electric vehicles? – Driving patterns and economics in Sweden and Germany. Transport. Res. Part C Emerg. Technol. 65, 1–15.

Jensen, A.F., Mabit, S.L., 2017. The use of electric vehicles: a case study on adding an electric car to a household. Transport. Res. Part A Policy Pract. 106, 89–99.

Jensen, A.F., Cherchi, E., Mabit, S.L., 2013. On the stability of preferences and attitudes before and after experiencing an electric vehicle. Transport. Res. D Trans. Environ. 25, 24–32.

Karlsson, S., 2017. What are the value and implications of two-car households for the electric car? Transport. Res. C Emerg. Technol. 81, 1–17.

Karlsson, S., 2020. Utilization of battery-electric vehicles in two-car households: empirical insights from Gothenburg Sweden. Transport. Res. Part C Emerg. Technol. 120, 102818.

— (2017b), *The variation of BEV energy use and range with climate and driving behaviour in real driving in Sweden*. Presentation at EEVC 2017, Geneva, Switzerland, March 14-16, 2017.

Khan, M., Kockelman, K.M., 2012. Predicting the market potential of plug-in electric vehicles using multiday GPS data. Energy Policy 46, 225–233.

McCollum, D., Krey, V., Kolp, P., Nagai, Y.u., Riahi, K., 2014. Transport electrification: a key element for energy system transformation and climate stabilization. Clim. Change 123 (3-4), 651–664.

Miller, J., (2020), 'Electric car cost to remain higher than traditional engines' Financial Times, Aug 31, 2020. https://www.ft.com/content/a7e58ce7-4fab-424a-b1fa-f833ce948cb7.

Nykvist, B., Sprei, F., Nilsson, M., 2019. Assessing the progress toward lower priced long range battery electric vehicles. Energy Policy 124, 144–155.

Pearre, N.S., Kempton, W., Guensler, R.L., Elango, V.V., 2011. Electric vehicles: How much range is required for a day's driving? Transport. Res. Part C Emerg. Technol. 19 (6), 1171–1184.

Plötz, P., Jakobsson, N., Sprei, F., 2017. On the distribution of individual daily driving distances. Transport. Res. B Methodol. 101, 213–227.
Rezvani, Z., Jansson, J., Bodin, J., 2015. Advances in consumer electric vehicle adoption research: A review and research agenda. Transport. Res. D Trans. Environ. 34, 122–136.
Ryghaug, Marianne and Toftaker, Marit (2014), 'A Transformative Practice? Meaning, Competence, and Material Aspects of Driving Electric Cars in Norway', 9 (2), 146.
Tamor, M.A., Milačić, M., 2015. Electric vehicles in multi-vehicle households. Transport. Res. Part C Emerg. Technol. 56, 52–60.
Turrentine, Tom, et al. (2011), 'The UC Davis MINI E consumer study'.
Whelan, G., 2007. Modelling car ownership in Great Britain. Transp. Res. Part A 41 (3), 205–219.
Williams, J.H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow, W.R., Price, S., Torn, M.S., 2012. The technology path to deep greenhouse gas emissions cuts by 2050: the pivotal role of electricity. Science 335 (6064), 53–59.
Xu, C., Dai, Q., Gaines, L., Hu, M., Tukker, A., Steubing, B., 2020. Future material demand for automotive lithium-based batteries. Commun Mater 1 (1).