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## **Indicating and managing BEV range issues in two-car households**

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### **Summary**

We discuss from various perspectives the range limitation; possible indicators, different relaxation options and the actual adaptation in two-car households, using GPS-loggings of both cars simultaneously for 1-3 months in 64 two-car households, and interviews after a BEV trial in 25 of these households.

Indicators such as DRA are less useful in two-car households. Instead the flexibility in such households may drastically reduce the range issues. The actual adaptation in households shows that there are numerous reasons to why the options are not fully utilized. Still, none of the test households stated a perceived limitation due to range.

*Keywords: case study, electric vehicle, GPS, optimization, user behaviour*

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### **1 Introduction**

Battery electric vehicles (BEVs) can mitigate local and global emissions from the transport sector [1]. However, the limited driving range and the high investment cost of a larger battery reduce their utility for users. On the other hand, the low operating costs, the driving experience of the electrical engine as well as the lower environmental impact may motivate some users to adopt BEVs. Therefore, it is important to find user groups that could appreciate the strengths of the BEV while being able to mitigate its weaknesses.

By an appraisal of the possible flexibility to circumvent the range limitations, multi-car households have early been identified as potential BEV early buyers [2,3,4]. It has been difficult to directly quantify this flexibility, its value and implications, though. Detailed data for the driving patterns of multi-car households are rarely available, market data for conventional cars do not reveal demand for cars with BEV-specific attributes such as range and recharge limitations, and survey data may be unreliable because of the lack of pronounced preferences among respondents, especially those based on knowledge or experience. Recently, Khan and Kockelman used available GPS-logged car movement data from the Seattle region for a period of around a year to analyze the possibility for a BEV (160 km range) to replace specifically the least-driving car only in multi-car households [5]. Tamor and Milačić investigated the flexibility option using the same Seattle data as Khan and Kockelman by analyzing the option of letting one BEV under its range limitation replace both/all cars in multi-vehicle households [6]. They concluded that a BEV with a modest range (160 km) appears to be viable at costs that are likely to be achieved in the near future. Karlsson investigated the options for a BEV using GPS-data from Swedish two-car households and concluded that a flexible use of the BEV could viably increase driving, while keeping battery size and unfulfilled occasions down [7]. Preliminary results from a BEV trial in some of these Swedish households presented by Jakobsson et al. 2016 demonstrated various adaptation strategies in the households [8].

Here we analyse, discuss and integrate different perspectives specifically on the range limitation in two-car households. We first discuss various ways of quantifying the effects of range limitations such as days requiring adaptation, unfulfilled occasions, distance and length of time of unfulfilled trips. We identify different relaxation options available in two-car households and quantify their possible implication on the optimal range. We then compare the results of these potential measures to the actual usage in the households having a BEV at their disposal and assess the specific adaption performed in the individual household.

## 2 Method and data

We use a data set of GPS measurements from western Sweden containing simultaneous GPS measurements of the driving patterns of both conventional cars in 64 commuting two-car households [7]. The data set contains loggings for 1-3 months per vehicle. An optimization model has been developed to calculate the potential for a BEV replacing one of the cars to maximize its driving given the logged positions and points of time for the driving for various battery ranges and charging power rates and for different car utilization strategies. We evaluate and discuss various indicators on the range limitation applied to the calculated potential driving.

Later 25 households were selected from the original 64 and given a BEV (Volkswagen e-Golf my 2015 with a 24 kWh battery) to replace one of their conventional cars for a test period of 3-4 months. Interviews were performed with the 25 households before and after the BEV trial period. The focus of the prior interviews was to assess the knowledge the participants of the household had of BEVs, as well as understanding their typical car usage strategies. Such as if they use one car each or mix the car usage in-between each other; what car do they use for weekend trips, for evening trips, and so forth. The focus of the post interview was to understand their experience of the BEV usage in general. As such, the questions were of an open-ended nature where the respondents could guide the answers to the topics they felt were important. The interviews were also semi-structured in the sense that all respondents were asked the same questions in approximately the same order. Furthermore, the interview questions gradually became more close-ended toward the end of the interview to make sure that they covered topics that we wanted to discuss (in case these had not appeared during the initial open part of the interviews). The interviews average on a length of 45 minutes, and each interview typically contain two respondents (the adult members of the household), though there are a few exceptions where only one member was available, or there were additional young adults in the household present.

In this paper, we focus specifically on the part of the interviews that relate to the range limitation; to what extent the range limitation has been a problem, how the trial participants have managed their driving and so forth. Therefore, we also limit the analysis to the post-trial interviews. Here, we do not seek to explain the opinions of the respondents, nor the outcomes of the trial; rather to report how the participants dealt with, and related to the range limitation. And thus, we report the results as commonly appearing themes in the interviews, with the frequency to which they appeared.

## 3 Results

Current ICEVs have so large ranges and ubiquitous fuelling opportunities that any limitations for these are not discussed. Introducing BEVs, the range and charging limitations possibly lead to unfulfilled trips in households, i.e., trips that would have been driven, had the limitations not been there. We can assume that these unfulfilled trips require some form of adaptation. The character and possible cost of these adaptations will depend on the properties of these trips and the perceived inconvenience of non-fulfilment or the actual cost of fulfilling the trips. We first identify and discuss various ways of quantifying the effects of range/charge limitations.

### 3.1 Indicating range limitations

A commonly used proxy is number of annual days requiring adaptation (DRA) or unfulfilled days. It takes its departure in a current ICEV's (unrestricted) movement pattern and assumes a BEV to fully replace the ICEV with a once-a-day full charging of the BEV. The charging assumptions are reasonable given that a large majority of charging events take place when the BEV is parked during the night, mostly at home for private cars and possibly at a daily point of departure for fleet cars. The time and power available for charging are also in most cases enough to fully compensate for the discharging due to driving earlier during the day. The number of days during a year with driving distances longer than the BEV range is thus the DRA. The

DRA is also the only “possible” and reasonable measure when the driving is given only in the form of a distribution for the daily driving distances.

When more detailed trip information is available, other measures are possible. The daily driving often consists of several hth-trips, for which charging can occur at the stops at home in between hth-trips. A measure could therefore be the number of unfulfilled home-to-home (hth) trips (UFT), which was used in [7]. Thus, while the DRA indicator per definition only includes charging once a day but not necessarily at home, the UFT indicator assumes only charging at home. If the trip info includes the trip order and the duration of the stops at home, the effect of a specified home charging rate can be evaluated and included in the UFT indicator (as was done in [7]). Longer multiday hth-trips can be divided into shorter daily distances.

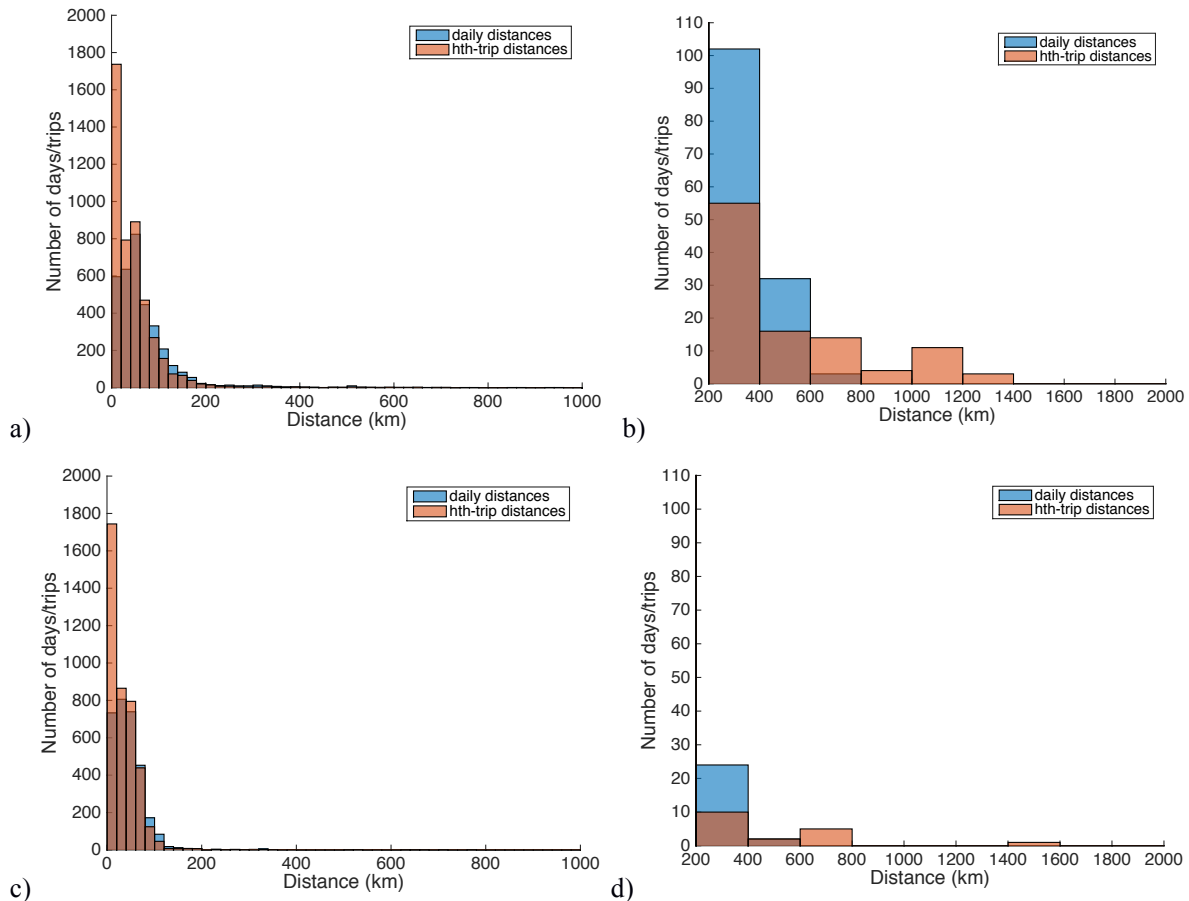


Figure 1: The distribution of daily distances and hth-trip distances for, a-b) the 1<sup>st</sup> car; c-d) the 2<sup>nd</sup> car.

The different characteristics of the two concepts are reflected in Fig 1, which shows that, for both the first and the second car in two-car households, the number of hth-trips are on average larger than the number of daily distances for short distances (< 60 km), but also for very long distances (> 600 km). Here Car1 and Car2 denote the use strategies when the BEV accomplishes the driving of the first and second car, respectively, only and no backup by the other car. It is thus the two pure single-car use strategies. The average annual DRA (i.e., charging fully once a day) and UFT (i.e., charging whenever at home) for different ranges are shown in Fig 2. For the UFT also the influence of an assumed charging rate of 3 kW is included, which is the rate commonly achieved in Swedish single-family houses [7]. The DRA indicator is larger than the UFT for ranges below 300 km, because the option to charge every time when at home occasionally makes possible driving with a BEV in total longer than the range for some days. For longer ranges, the effect demonstrated in Fig 1 gives a UFT larger than the DRA. The difference between the indicators is small though, and it is significantly smaller than the difference in each of the indicators between the first and the second car. For a given range, compared to the second car, the first car has on average about three to four times more annual UFTs. This holds as well as for DRAs, which also was shown in [8]. Some of these DRA simply come from the first car having a high annual VKT. Jakobsson et al (2016) also calculate the extra number of DRA that the first car has compared to the second independently of annual driving distance and find this to be approximately a factor of 2 for an annual VKT of 20 000 km [9]. Thus the second car has a

more confined driving pattern, with fewer long distance days for the same total VKT, compared to the first car.

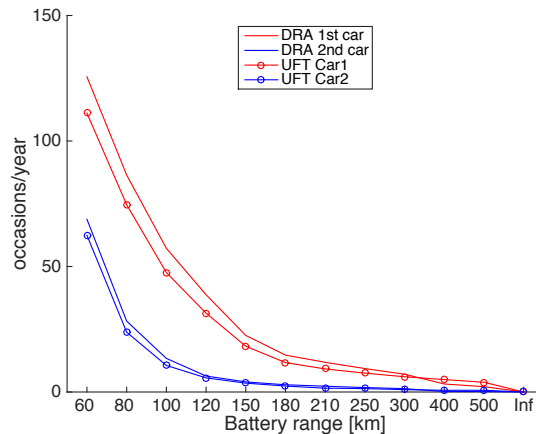


Figure 2: For the investigated two-car households, the average annual DRA and UFT (at 3 kW charging rate), for the first and second car, respectively.

The difference between the first and the second car is due to the more confined driving pattern of the second car: in each household, its annual VKT is less than the first car's (per definition) leading to on average shorter mean daily distances and hth-trips, because the difference in number of trips is less pronounced. But the second car also has on average a larger share of accumulated distances (both daily distances and hth-trips) at a given share of trips, which is shown in Fig 3, depicting the Lorentz curves for the first and second cars in the different households (for the hth-trips distances only, though). The resulting Gini coefficient is accordingly on average smaller for the second car (in line with the conclusions from Jakobsson et al (2016) [9]), 0.37 (0.11-0.67), than for the first car, 0.48 (0.12-0.85), and in 2/3 of the single households, the Gini coefficient for the hth-trips is smaller for the second than for the first car.

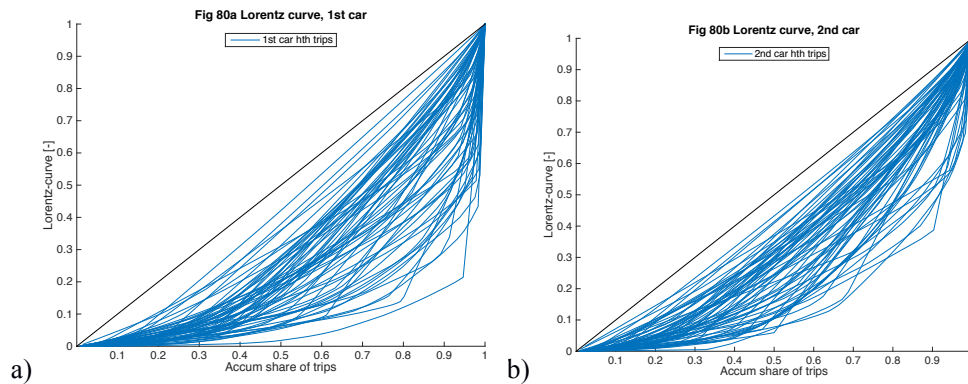


Figure 3: The Lorentz curve for hth-trip distances (share of accumulated distance of total distance) in the two-car households for a) the first car; b) the second car.

The indicators restricted to charging either once a day (for DRA), or only at home (for UFT) may be misleading in real situations when more charging options are available. Table 1 points to some performances of and principal differences between the DRA and UFT indicators for different charging options. Charging rate is not handled by the DRA which thus may underestimate the effects of a limited charging rate. On the other hand, home charging rates  $\geq 3$  kW lead to few limitations when charging at every stop at home [7]. Both indicators overestimate limitations when workplace and public charging are available.

Table 1: Performances (depicted qualitatively) of the DRA and UFT indicators at different charging options.

<i>Charging options</i>	<b>DRA</b>	<b>UFT</b>
<i>Limited charging rate at home</i>	may underestimate need for adaptation (charging to a full battery assumed in between daily distances)	can be handled by UFT if trip order and stop duration times are included in the analysis
<i>Charging more than once a day when at home</i>	may overestimate need for adaptation	handled by UFT concept
<i>Work place charging</i>	may overestimate need for adaptation	may overestimate need for adaptation
<i>Slow charging away from home within range at overnight stay, for instance, at weekends</i>	handled by DRA concept (gives 0 DRA)	overestimates need for adaptation (gives 1 UFT)
<i>Long-distance, out-of-range, vacation trip for a week</i>	gives often 2 DRA, (for the travel away from home and back, respectively)	gives 1 UFT
<i>Fast charging on a longer out-of-range trip</i>	overestimates need for adaptation	overestimates need for adaptation

### 3.2 Relaxation options in two-car households

So far we have discussed measures and performance when a BEV is used for accomplishing one and only one of the cars' driving in two-car households. As pointed to above, one of the cars can have a more confined movement pattern favoring a BEV's economic viability and accomplishment of this vehicle's driving by possibly taking up large share of the driving and avoid unfulfilled driving with a smaller battery [8]. In two-car households there are several other options than *confinement* for relief of the effects of the range limitations related to the cars' movement patterns [7]: *extension*, by which a BEV accommodates the driving of the other car in stops at home in between trip; *backup*, the other car takes the driving the BEV cannot due to range/charging limitations. By *flexibility* is meant a fully flexible choice of vehicle in the fulfilment of the households driving, by which the BEV driving can be maximized while the unfulfilled trips are kept down through the backup by the remaining conventional vehicle. Figure 4a shows that the necessary battery range to avoid any unfulfilled hth-trips is decreased dramatically for a fully flexible vehicle use (denoted Both\*) in comparison to the single-car replacement strategies, especially compared to the first cars<sup>1</sup>, with which almost half of the households has driven longer than 500 km in at least one hth-trips during the measurement period. Apparently, the households seldom drive long distances simultaneously with their two cars. This is reasonable; when the household is away together for a longer recreational trip, the other car is parked at home; when one of the household member is away on a, for instance, work-related, longer trip, the other family head probably takes care of the children and therefore stays close to home.

The resulting annual UFT for a specific range is accordingly also much lower when the flexibility is fully utilized, Fig 4b. For a range of 150 km the number of yearly unfulfilled trips are on average 18, 3.5 and 0.25 for the Car1 Car2 and Both\* strategy, respectively. Thus, for a range of 150 km the flexibility may reduce the occurrence of unfulfilled trips to on average once every fourth year, which is more than a factor of ten more seldom than for the closest single-car strategy.

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<sup>1</sup> The Both\* strategy maximize the BEV driving distance, while keeping the unfulfilled distance down. The trade-off is set such that a gain in BEV driving distance is weighted equal to an increase in the unfulfilled distance times 3.

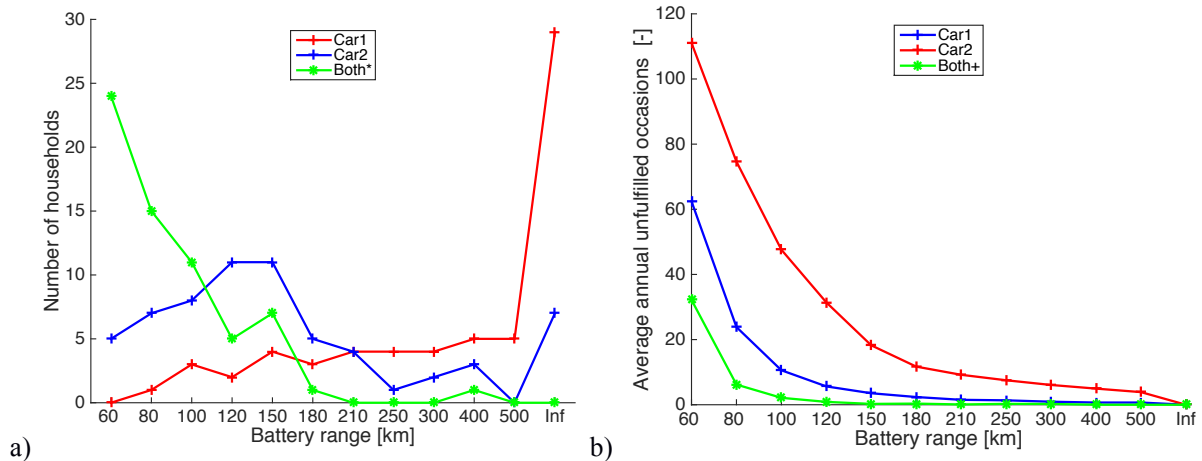


Figure 4: For different BEV use strategies, when home charging only, a) distribution of the minimum range necessary for avoiding unfulfilled hth-trips; b) average number of annual unfulfilled hth-trips.

Further hth-trip information may involve distance and duration. Figure 5 illustrates that the average distance and duration for the unfulfilled hth-trips increase with BEV range for the two single-car strategies, while in the case of a flexible car use they decrease for enough large battery ranges. Both the DRA and UFT indicator do not detect or measure the severity of the unfulfilled trips, and therefore do not note this changing character of the unfulfilled trips with range.

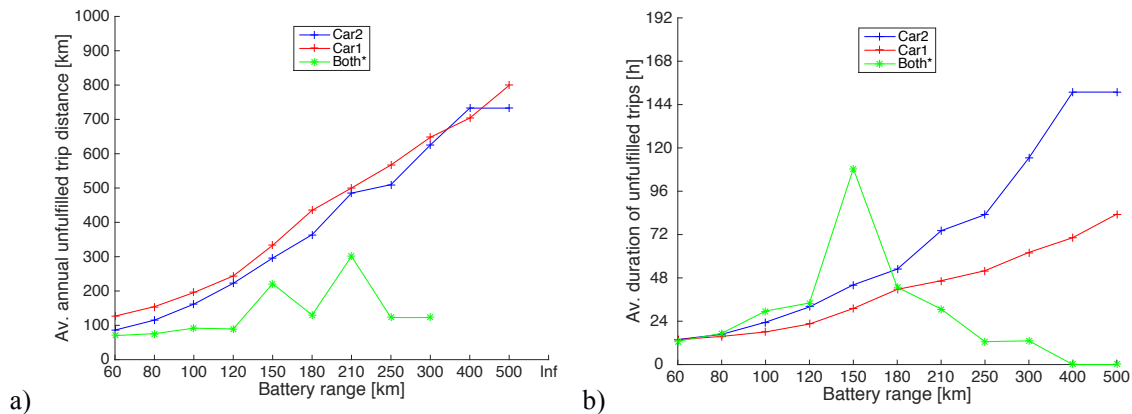


Figure 5: For unfulfilled hth-trips for different BEV use strategies, a) average distance; b) average duration.

### 3.3 Actual adoption and adaptation in households

The interview data provides us with the option to assess the actual adoption within the households as a complement to the calculated potential ones above. In this section we set out to first give an overview of the experience of using a BEV for three months, and then attempt to identify how the households have adapted to the range limitation and if there are support for the strategies described above.

It should be noted that the overall experience of using the BEV was strongly positive with 20 households stating a positive or strongly positive experience, 4 households had mixed feelings, and 1 made no clear statement (zero households reported an overall negative experience). With regards to negative aspects, the range limitation was stated by 12 households as the biggest negative factor, while 3 households stated that no particular negative aspect was present. A factor that was mentioned by many households, and ranked as the major negative aspect by 2 households was the uncertainty in the cars internal range estimate (which typically start on an estimated 190 km, but in practice only averaged 120 km in total driving according to several respondents). This uncertainty in how far the car actually can travel contributes to an overall

uncertainty feeling concerning the BEVs reliability<sup>2</sup>. Ten of the households used the BEV over 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.

With regards to how the driving trips are planned in-between the cars in a household, we can find support for several different strategies. In all the households, both cars are used for commuting. Thus, in a normal day, both cars are used for work trips, but the household have a choice of assigning the cars to work trips of different lengths. They further have choices about which car to use for extra evening or weekend trips.

Of the in total 25 households, 18 stated that they used the BEV more compared to the car it replaced. This varied from choosing the BEV for extra evening trips ad hoc as these trips were to be initiated, to doing a full daily planning of the car use at the breakfast table where the BEV use would be maximized. The full planning was done on regular basis by one household, and another frequently drove the BEV until it was close to out of charge. These two households thus support the existence of a strongly flexible car use strategy. The remaining 16 of the 18 households can be said to employ an 'extension' strategy as they had replaced one of their conventional cars with a BEV plus adding trips to the BEV from the other conventional car if it was possible to do so ad hoc.

Among the 7 households that 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 block 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 were random to some degree, and planning to some degree. A further three households performed no mixing of the car usage in-between the household adults, that is, one person always drove the BEV, and the other always used the conventional car.

One strategy to deal with the range limitation is to charge the car at other places than at home and at work during days with a lot of driving. Within our sample with an average of three months measurements, 11 households never charged away from home and work, 10 households charged up to a few times away from home and work, and the remaining three charged several to many times away from home and work. This hints at that charging at public stations is a viable strategy for a sizeable part of the sample, while the remainder uses these only given easy access and a strong need.

With regards to the measures DRA and UFT, it is important to note how often they occur in practice, given the many more ways a household can deal with unfulfilled driving compared to what we can assess in the data<sup>3</sup>. One household stated that having a range-limited car was a contributory factor to refrain from doing one trip that they otherwise might have done, but that there were other contributing factors to avoid this trip as well. This might thus constitute either a DRA or a UFT in practice. In all other cases the households have managed to solve their driving need with various strategies, meaning that DRA and UFT have been a minimal to non-existent problem in practice. However, some households had to do larger replannings, including switching cars away from home (one stated instance), borrowing a car from someone else (three households stated a few instances), or renting a car while on vacation (one instance). Furthermore, on a direct question of how large a problem the range limitation had been, a majority of 15 households stated that the problem had been minor, 3 that the problem normally was minor, but could be major in winter, 2 that it was large enough to hesitate before a purchase, but that it had worked well in practice, 2 that the uncertainty in range was too big of a problem, and 3 that the range limitation was a medium-big to 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 and UFT in the GPS data analysis may overstate the problems of using a BEV in a multi-car household, where a combination of confined driving and flexibility for at least one of the household's cars exists.

Another way to assess the possibility of DRA and UFT is to ask the respondents how often they drive the two household cars long distances at the same time. This question was posed in the pre-trial interviews for 11 households, and out of these, 8 responded that it never happened, while 3 were unsure if it had never happened or might have happened once or twice. Thus, this further reinforce the conclusion that DRA and UFT calculations from the GPS data overstate the problems of using a BEV in a multi-car household.

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<sup>2</sup> The Volkswagen e-Golf has a NEDC range of 190 km, while it has 134 km in the US EPA rating.

<sup>3</sup> For instance, simply moving the driving in time can help a lot, but can't be assessed in the GPS data analysis part.



In summary, we find support for the analyzed strategies; confinement, extension and flexibility within our trial measurement, however extension is by far the most common, and flexibility the most uncommon. Further we find very few to none unfulfilled trips entirely due to the use of the BEV, though the presence of a BEV may play a contributory role in declining to do longer trips. Furthermore, the range is, on average, not experienced as a major problem, though there are households for which it is too big of a barrier.

## 4 Discussion and conclusions

We have investigated different aspects of the management of BEV range in two-car households with the help of two datasets of car movements and interviews with BEV users. If the flexibility made possible in two-car households is utilized, earlier used indicators applied on the movements of the single car, such as days requiring adaptation (DRA) and unfulfilled home-to-home trips (UFT), are misleading as indicators for the ability and economy of the BEV in two-car households. Two-car households are identified as an important group for the introduction of BEVs beyond early adopters: Karlsson (2017) showed that the value in Sweden of two-car households for the BEV is on average around \$7000, when the flexibility is fully used, and over half of Swedish cars are in multi-car households [7]. Also, in the currently most developed BEV market, the Norwegian, an overwhelmingly big share of BEVs are situated in multi-car households [10]. In this perspective, the current almost ubiquitous rush for longer range in marketed cars may be both unnecessary and counterproductive in that it increases BEV cost and environmental impact from the vehicle production.

Our measurement on and interviews with real households testing a BEV suggested that the real uptake and adaptation to a BEV in many two-car households may not fully utilise the flexibility inherent in their car movement patterns, though. Households may still for various reasons be left in old car utilization pattern not recognizing or appreciating the bigger difference in operational cost between their cars when having access to a BEV. From that perspective, when initially a closer to car-for-car replacement strategy prevails, the single-car-based range indicators may still be of relevance also in two-car households. There are good reasons to assume, though, that by time in a ripening market the flexibility will be more exploited.

In the long run, to achieve a deep decarbonisation of transport, the electrification needs to go beyond a BEV replacement of one of the cars in multi-car households. How this next step will be achieved, by yet another BEV, or by any other option possibly available, such as a PHEV, a biofuel or fuel cell vehicle, public transport, new travel patterns, car pooling, or shared autonomous vehicles, is too early to settle.

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