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How are driving patterns adjusted to the use of a battery electric vehicle in two-car households?

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Summary

We have supplied two-car households with a Volkswagen e-Golf to replace one of their conventional cars for 3-4 months and measured their driving with GPS equipment. The measurements contain data of the driving of both household cars, before, and after they obtained an EV. Our analysis focus on the uptake of driving for the EV, as well as the driving adaptation the households made when acquiring the EV. Results show a small uptake of driving for the EV and a large heterogeneity in adaptation, where some household increase the EV driving compared to the removed car, and some decrease it.

Keywords: BEV, deployment, GPS, data acquisition, passenger car

1 Introduction

Battery electric vehicles (BEVs) can reduce local and global emissions from the transport sector [1]. However, their limited driving range and high investment cost impede 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.

One such group could be multi-car households where a conventional long-range vehicle could supplement the BEV. Availability of another car has been found important in regions where BEV penetration is high. For example, in Norway, the country with the highest BEV share per capita, 91% of the BEV owners also have an additional car [2]. In this work we will focus on two-car households as a potential early majority group and analyse the suitability of the BEV in such households given the driving patterns and the BEV's range limitation.

A common line of argumentation for the use of BEVs in a multi-car household builds on two assumptions. First, the households have cars for different purposes; one car is typically used for towing, longer trips, and transporting larger number of people, while another car is used for shorter everyday trips. The latter of these cars could thus be replaced by a BEV more easily. The second assumption is that households may be able to shift trips between the cars to circumvent the range limitations of the BEV. Both of these assumptions have been analysed to an extent before. For example, Jakobsson et al, [3] show that second cars are more suitable for being replaced by BEVs. In this study a majority (70%) of second cars fulfils all their driving at a range of 220 km, while first cars need a higher range of 390 km to reach the same shares [3]. Other work has previously considered the potential for multi-car households to adopt BEVs if trips driven by the households are optimized to maximize the use of the BEV while minimizing the use of the conventional car. See for example [4-6].

However, both of the outlined approaches above consider only the extremes; the households do not shift trips between the cars at all, or they optimize the use of the BEV. Yet the question remains how much optimizing the households are actually willing or able to do and how this would impact the possibility of BEVs being adopted by multi-car households from a driving need perspective as well as from an economical perspective. These are the questions we will address in the present work.

2 Data and methods

We use two data sets of GPS measurements from western Sweden. The first set contains GPS measurements of the driving patterns of both conventional cars in 64 commuting two-car households (the comparison period) [6]. This data set contains loggings for approximately 2-3 months per vehicle. The second data set (the evaluation period) contains further measurements on 25 households selected from the original 64. These households were given a BEV (Volkswagen e-Golf with a 24 kWh battery) to replace one of their conventional cars. The collected data during this trial period contain GPS measurement of the BEV and the remaining conventional car, as well as charging data for the BEV. The evaluation period contains data for 3-4 months driving. Among the 25 households in the second data set we have selected 10 households for this analysis. Of the remaining 15, five households are still under ongoing measurements, and ten households will need additional data pre-processing before analysis.

A key feature of the data used here is that they come from households who did not themselves take the initiative to obtain an electric car. Instead a selection of the original 64 households was presented with the option of doing so, to which the vast majority answered positively, and thus, cannot be considered early adopters, but instead would represent the general population. In this sense, our study differs from other travel measurements of electric vehicle users. Note however, that since the sample size is very small in our study, the results should be considered as illustrative of possible behaviours rather than representative of car users in general.

The electric car has a usable battery range of around 120 km, though daily variations in a number of factors, such as driving speed, temperature, and humidity, can vary the actual range from around 100 km to 140 km. We choose to use a range of 120 km for most of the comparisons made here. We use the following notation for the cars: electric car (EV) for the Volkswagen e-Golf in the evaluation period, the persistent car denotes the conventional car that is used in both data sets, and the replaced car denotes the conventional car that is used in the comparison period but is replaced by the EV in the evaluation period. Note that in some cases the households have acquired new cars in-between the two evaluation periods, thus the EV may have replaced a different car then the one actually driven in the comparison period, or the persistent car may have changed between the periods. In these cases we have designated replaced and persistent car such that the person in the household who mostly (>90% according to interview results) drove the respective car in the comparison period would drive the corresponding car in the evaluation period. This also means that the commuting distances should be consistent for the replaced-EV and persistent-persistent cars in the two data sets, assuming no changed behaviour or optimization of EV usage. Thus, we attribute the changes in commuting distances, or total distances between the EV and the replaced car to adaptations the household has made given the new situation of having one EV and one conventional car.

The analysis is two-fold. Firstly we calculate daily driving distances and compare these between the EV and replaced car, as well as in-between the EV and the persistent car in the evaluation period. Furthermore, as in Jakobsson et al., [3] we calculate the days requiring adaptation (DRA) as the number of days per month that a vehicle drives longer than the range limit. This constitutes a measure of the adaptation need for a car that is replaced with an EV.

In the second part we compare the actual EV driving to the calculated different potential total distances that are obtained for an assumed EV that uses eight different stylized driving strategies. These strategies exploit to various degree the flexibility made possible in the 2-car household. We do the calculation for various assumed ranges of the EV. The charging is supposed to occur whenever the EV is at home with a charging power at the battery of 3 kW (16A, 230V 1 phase including losses). The strategies are further outlined in the result section. For this second part of the analysis the data set used is slightly smaller, given that we need good measurements of both cars in the same household at the same time, while in the first part it is sufficient that we have many days of driving for each individual vehicle, thus, the data set is filtered for bad data a bit more in the second part.

3 Results

This section starts with analysing how large the need for adaptation would be for the households according to the DRA measure described in the methods section, followed by the adaptation according to fraction of total driving distance. This is followed up by analyses of the distribution of driving distances between the EV and replaced car, as well as between the EV and the persistent car in the evaluation period. Finally, we conclude by analysing how large part of the potential electric driving the households have actually taken up with their EV.

3.1 Household adaptation

We calculate the number of DRA using a range of 120 km for the replaced car in the comparison period. Table 1 shows that four households had no DRAs during their comparison period, while the DRA for the remaining six varied between 0.8 DRA per month to 3.6 DRA per month, the latter case constitutes a household that would have to adapt almost 1 day per week.

Table 1: Days requiring adaptation per month for the replaced car in the comparison period.

DRA per month
3.6
0
0
1.6
0
0.8
0.4
0
3.2
0.92

By extrapolating the driven distances in the two measurement periods to annual driving distances we can obtain the fraction of total household distance driven by the EV in the evaluation period and the corresponding fraction for the replaced car in the comparison period. This, as well as the fraction between them, are shown in Table 2. In most cases, the adjustments in driving due to the adoption of an EV is small, with three households lowering their driving of the EV compared to the replaced car. Among the others, there are two with low-moderate increase of driving distance (12%), and one with very large increase of driving distance (160%). In general, it cannot be said that households overall increase their driving of the EV compared to the replaced car. Similarly, Figure 1 shows the actual annual VKT for the cars in the two measurement periods, as well as the total distance driven by the different households. Here, it can be seen that the cars that were first cars, in the sense of having higher annual VKT in the comparison period, remain first cars in the evaluation period. For the second cars in the comparison period, all but one remain second cars in the evaluation period. Hence, it cannot be said that adopted EVs become first cars in these households, when using annual VKT as definition for first and second cars.

Table 2: Share of total household driving distance taken up by the EV in the evaluation period, the replaced car in the comparison period, and the fractional increase of driving for the EV compared to the replaced car.

EV	Replaced car	Fractional increase
65%	63%	2%
32%	29%	12%
52%	20%	160%
59%	59%	-1%
45%	47%	-4%
45%	42%	7%
50%	48%	3%
35%	34%	4%
58%	52%	12%
57%	63%	-8%

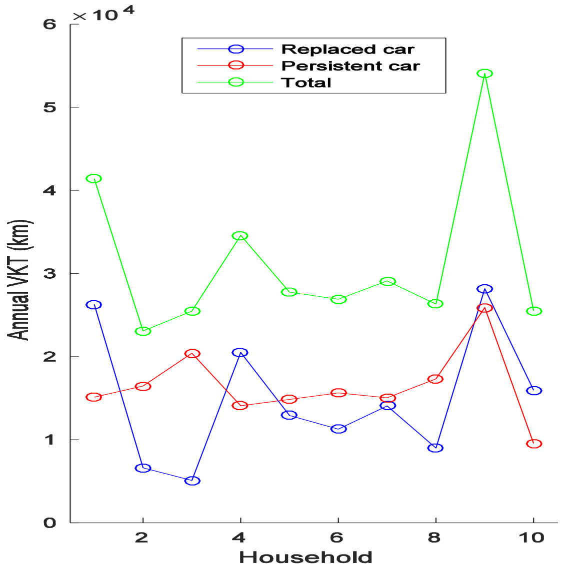

Figure 1: Extrapolated Annual VKT for the cars in the households. The left figure represents the comparison period, while the right figure is for the evaluation period.

In order to judge how much, and in what way, households have changed their driving patterns, we calculate the distribution of daily driving distances for the electric car and the replaced car, respectively, in the ten households. These results are displayed as normalized histograms in Figure 2 where the average distribution over all the households is shown in the top left figure, while the other figures contain three interesting individual results. In the top left figure we can see that there is a tendency for the EV to take driving tasks within a fairly narrow range of around 40 km to 70 km, while the persistent car increase its driving in the other ranges. Thus the electric car both reduces the amount of long distance trips (70-140 km) of the replaced car, and increases the number of short distance trips (0-30 km) of the same. This might represent both an effect of range anxiety and a wish to utilize the EV more. The top right figure shows an example of a household that to a large extent keeps the same driving distances for the EV as for the replaced car, this is also a case of a typical commuting car. The bottom left and bottom right contain households where the electric car to a large extent have increased and decreased its driving compared to the replaced cars, respectively. Most households have behaviours in-between these three examples, however the three examples show the heterogeneity of behaviour.

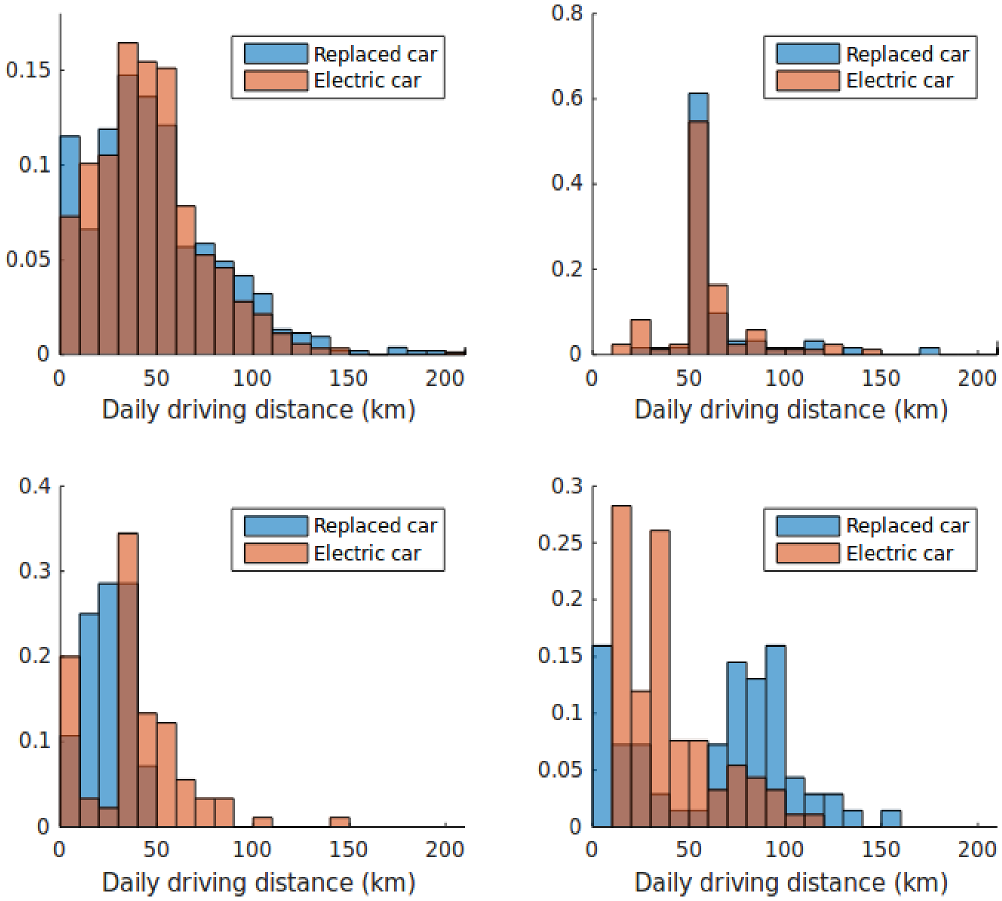

Figure 2: Distribution of daily driving distances for the EV and the replaced car. The top left figure display the average of all ten households, the other three figures display some typical results. Blue colour marks the replaced car, light brown marks the electric car, and dark brown shows overlap between the two car types.

The above result can be partly strengthened by analysing the distribution of daily driving for the electric car and compare it with the corresponding distribution for the persistent car in the evaluation period. This is displayed in Figure 3 where the top left figure contains the average over all ten households, and the other three figures contain interesting examples of household driving behaviour. The top left figure shows that the electric car tends to drive more than the persistent car in the distance region below the range limit, while the persistent car takes the very short and the long driving distances. The top left figure shows a household with a fairly even usage of the EV and the persistent car among the driving distances, while the bottom left and right shows extreme cases of using the EV for long distances below the range limit and for short distances. Again, there is a large heterogeneity in behaviour.

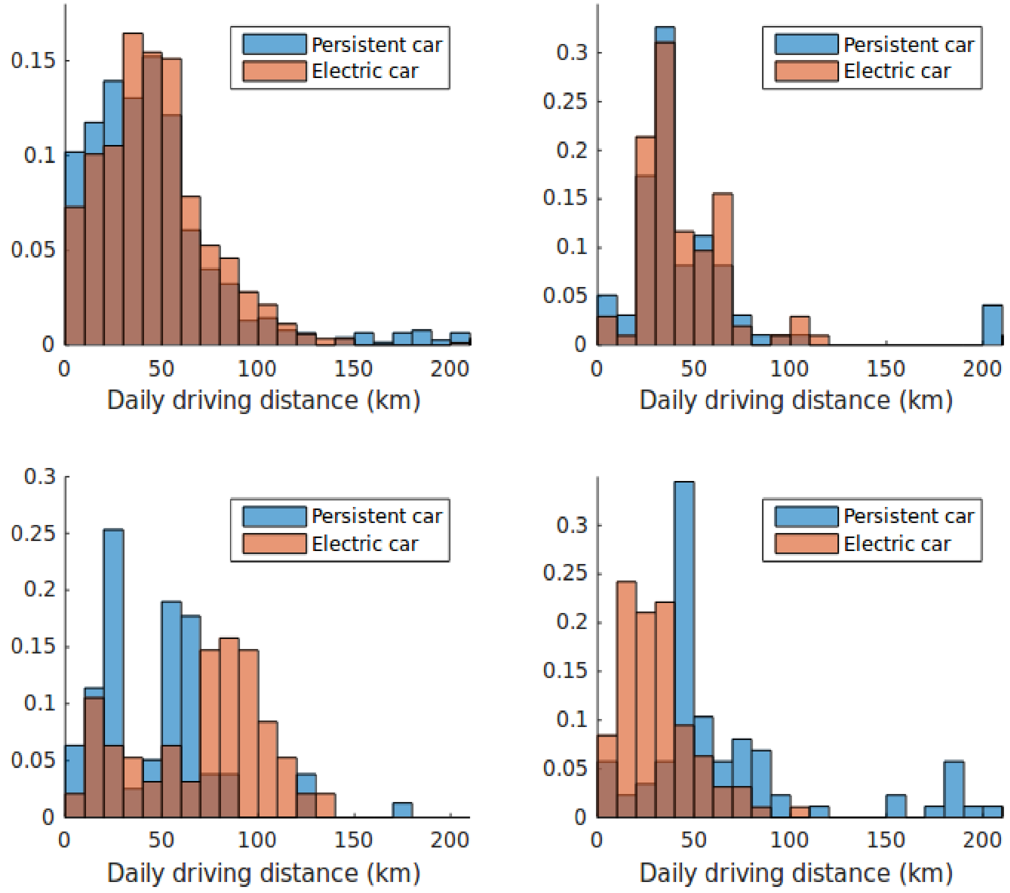

Figure 3: Distribution of daily driving distances for the EV and the concurrently used conventional car. The top left figure displays the average of all ten households, the other three figures display some typical results. Blue color marks the conventional car, light brown marks the electric car, and dark brown shows overlap between the two car types.

3.2 Potential and actual uptake of driving for the EV

The average EV driving in the ten households extrapolated to yearly driving is about 14 300 km/yr, Figure 4. This actual driving can be discussed in relation to different potentials depending on how the EV is used in the household, which car it is substituting, etc [6]. In Figure 4 the outcomes of different stylized EV use strategies are given.

The strategies are presented in Table 3. Strategies can be formulated in relation to the driving of the two conventional cars before the replacement (upper part of Table 3) or in relation to the actual driving patterns after replacement (lower part of Table 3). To the left in the table are given some strategies that only replace one car's driving, while the + strategies to the right in different ways additionally utilize the flexibility that the 2-car household gives by allowing the replacement of more than one car's driving. For Car1/Car1+ and Car2/Car2+ strategies the EV replaces primarily the 1st and 2nd car, respectively. The Both+ strategy is an optimization of the EV driving distance. (Although, here with a minor adjustment (less driving) due to an included trade-off between the maximization of EV driving and the unfulfilled driving possibly appearing when maximizing the driving.)

The Replaced car strategies in the first place fulfil the driving of the specific car which each single household chose to replace with an EV in the measurement period, a car which varied between the 1st car (4 households) and 2nd car (6 households).

The EV and EV+ strategies take departure in the actual driving in the measurement period of the EV and the persistent car but fulfil the driving of the EV in the first place. (Note that the driving of these strategies differ from the actual EV use and driving in that the calculated driving is limited by different ranges and there is no charging outside home. The charging rate is assumed to be 3 kW whenever the EV is at home, which is roughly the rate obtained at the battery including losses from the charging power (230V, 16A, 1 phase) supplied to the EV in the households.) Although the replacing EV was a specified vehicle, its range in reality varies with the driving style, traffic, climate, and use of auxiliaries, etc. Also the perceived or actually utilized range can vary between drivers and households. It can therefore be reasonable to, as in Figure 4, to make possible a comparison to an interval in range. However, here we focus on the 100 km range, which should come close to the perceived range for the actual vehicle.

Table 3: Different stylized EV usage strategies.

Ex ante (Households in comparison period)			
Strategy	**EV usage**	**Strategy**	**EV usage**
Car1	1st car's driving only	Car1+	Also uptake of the 2nd car's driving when possible
Car2	2nd car's driving only	Car2+	Also uptake of the 1st car's driving when possible
		Both+(comp.)	Maximization of EV driving from both 1st and 2nd cars' driving (but with trade-off for unfulfilled distances)
Replaced car	The in the measurement period replaced car's driving only	Replaced car+	Also uptake of the later on non-replaced (persistent) car's driving when possible
Ex post (Households in measurement period)			
Strategy	**EV usage**	**Strategy**	**EV usage**
EV	The EV's driving only	EV+	Also uptake of the non-replaced (persistent) car's driving when possible
		Both+(meas.)	Maximization of EV driving from both the EV's and the persistent car's driving (but with trade-off for unfulfilled distances)

We see from Figure 4 that the actual EV distance driven is close to the driving of the Replace+ strategy (for a 100 km range), i.e., the driving obtained when a 100 km range EV fulfils as much as possible of the replaced car's driving and then when possible the persistent car's driving, that is, when the replaced car is not driving. Thus these preliminary data indicate that the households in average use the actual EV close to the driving of the replaced car in the first place supplemented with driving of the other car when possible.

This actual EV driving is much larger than the driving possible when only replacing the 2nd car and of the same size as what could be achievable when replacing the 1st car only. However, it is also less than what is could be obtained in a full use of the flexibility available in 2-car households (Both+).

The figure shows that the actual EV has driven somewhat longer than what is possible with the simulated EV for all ranges, i.e., also for an EV having ranges longer than the actual EV. This can be explained by the fact that the simulated EV is restricted to home charging, while the actual EV in some households has driven longer distances with help of public or other charging options at places outside home.

The difference between EV and EV+ (≈ 2500 km/yr) indicates that there are occasions in the households when the EV is paused rather than used to replace the other car's driving.

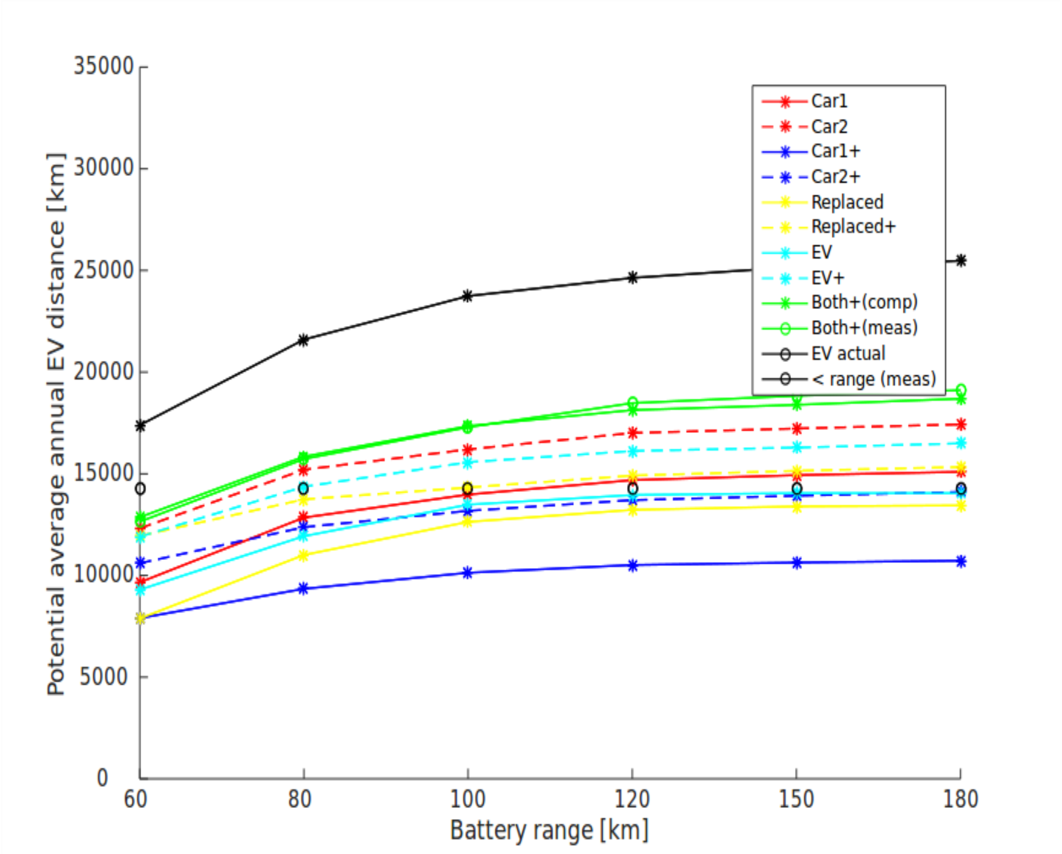

Figure 4: Potential average annual distances driven by a simulated EV adopting different stylized strategies for uptake of the driving in the 2-car household compared to the average annual distance driven

4 Discussion

The major limitation of this analysis is the sparse dataset, containing only ten households. Though further research will extend the data to 25 households, the results remain illustrative, and are not generalizable. The results however, remain relevant given that they illustrate a usage group that has seldom been measured, that is drivers of EVs that are not early adopters.

When it comes to the results of low adaptation and low usage of the possible driving uptake of the EV there are a few possible explanations. It is clear that some drivers attempt to drive the EV as a conventional car, and those that seems to maximise the driving of the EV are contrasted by those who use the EV mostly for the shortest driving distances. Especially when it comes to the EVs there is a tendency to cluster driving distances within a certain range of daily driving distances, it can be explained both by range anxiety hindering the longer trips, and a wish to utilize the environmental and economic effects, reducing the amount of short trips. It should further be noted that the total driving distance has changed between the measurement periods for some households, this may impact the results. Furthermore, an important aspect that should be considered in future work is that some measurements were done in winter, and some in summer, which affects the range of the EV.

Besides driving distance, there are other limitations of the EV that may influence the choice of which car to drive, these include the need for towing, the size of the trunk when transporting goods. Another reason in the Swedish context is the possible availability of a company car for private use. Based solely on GPS measurements, it is hard to know how often these conditions determine the choice of car for a trip, and how often it is the expected driving distance. Not accounting for this is a limitation of the present paper.

5 Conclusions

We have analysed the usage of ten EVs with an approximate range of 120 km in households that did not take the initiative to obtain the EV in question. Specifically we have analysed the usage of the EV in relation to the potential usage given the driving patterns, and how the driving behavior has changed as a result of obtaining the EV. We find that:

- There is a large heterogeneity among households in adaptation, and usage.
- In six cases there is a small increase in driving for the EV compared to the replaced car (up to 12%), in three cases there is a decline in driving distance for the EV compared to the replaced car, and in one case there is a major increase in driving for the EV compared to the replaced car (160%).
- First cars, defined by annual VKT, that are replaced by an EV remain first cars, second cars that are replaced by an EV remain second cars to a large extent (five out of six cases).
- The EV tends to take up more of the driving in the 40-70 km range compared to the replaced car. For other distances the EV reduces its driving compared to the replaced car.
- The average distance driven by the EV comes close to the possible driving when substituting the actually replaced car (varying between first and second car) supplemented with replacing the persistent car when possible.
- This resulting distance is roughly in the middle between the distances that possibly could be achieved when replacing the second car only and when fully utilizing the drive pattern flexibility in the 2-car household.

Further research is required to understand what causes some households to have a high uptake of driving for the EV, while others have low, or reduced driving compared to the replaced car.

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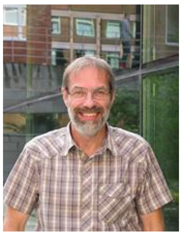

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