EVS29 Symposium
Montréal, Québec, Canada, June 19-22, 2016

The potential for a BEV in the two-car household

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Summary

An optimization model was developed to estimate the potential for a BEV, when replacing one of the conventional cars, to viably contribute to the performance of the driving in the households. It uses data from 1 to 3 months of simultaneous GPS logging of the movement patterns for both cars in 64 commuting 2-car Swedish households. The results show that the BEV can potentially roughly double the driving and still decrease the unfulfilled driving in the household with a flexible car use strategy compared to a BEV substituting the 2nd car only, turning the BEV economics into a TCO gain.

Keywords: BEV, deployment, optimization, GPS, data acquisition

1. INTRODUCTION

Electrified vehicles are one the options to achieve less use of fossil fuel and reduced emissions of greenhouse gases and other pollutant in transport. Mainly due to the expensive battery, most battery electric vehicles (BEV) currently available have, compared to the conventional car, a very limited range together with a relatively long charging time. Due to the low operational and high fixed cost, the viability of the BEV is enhanced by high annual driving, which in turn tends to be counteracted by the charging and range prerequisites. This limitation set by the cost-range trade-off hampers the uptake in private households, which currently are used to and highly value to have the option to occasionally and effortlessly drive longer trips, or shorter trips without necessary long stops in between. For instance, in Sweden so far (Oct 2015), around 4000 battery electric cars (≈ 1 ‰ of the fleet) have been sold [1], and very few of these are registered on private persons, although, there is a Swedish goal of a "fossil-independent" vehicle fleet already in 2030 [2].

But potential early private buyers could be car-commuting many-car households. They ought to have larger possibilities to circumvent the range limitation by choice of car for longer trips or tight trip chains. Also the daily driving due to the commuting makes it more plausible to achieve a high yearly mileage of the BEV contributing to its economic viability. In Norway, with a unique high share of BEV among sold cars, around 90 % of the households buying an BEV have more than one car and the BEV soon becomes the first choice whenever possible [3].

But reasonably there are specific reasons for many-car households to have more than one car. Frequently, more than one household member commutes with car during the day. This simultaneous driving could, besides the range and recharging limitations, effectively hinder a BEV to take up much or most of the driving in the households. So how large is the potential in reality given the car movement patterns for a BEV to viably replace one of the conventional vehicles (CV) in many-car households?

There are many studies, which in various ways have investigated the options for a BEV to replace a conventional fossil-fuelled car straight off, but there are only few which specifically have looked at the options in many-car households [4-6]. Khan and Kockelman used logged car movement data from the

Seattle region for a period of around a year to analyse the possibility for a BEV (160 km range) to replace specifically the least-driving car only in multi-car households and find that for the daily driving the range limit is reached much less often than in single car households [4]. Jakobsson *et al* found from an analysis based on Swedish daily driving distances derived from logged car movements for around two months each, that a BEV replacing the 2nd car only (= stated least-driving car in two-car household) results in fewer range-limited days due to the shorter and more confined driving as well performs better economically than when replacing the 1st car only [5]. (Data for both cars in the households was not available.) The same results were achieved in their parallel analysis of a larger data set for one weeks' driving in German households. While both these mentioned studies still only replace one of the household cars straight off, recently Tamor and Milačić, using the same Seattle data as Khan and Kockelman, presented results from a study analyzing the option of letting one BEV under its range limitation replace both/all cars in multi-vehicle households, and 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 [6].

We have accomplished a project with the overall objectives to assess the potential for a BEV, replacing one of the conventional cars, to viably contribute to the performance of the car movements in Swedish commuting 2-car households based on data derived from loggings of car movements patterns in such households.

2. METHOD AND DATA

2.1 Potential for a BEV replacing one of the car in 2-car households

Figure 1 depicts the driving in a 2-car household and the potential BEV uptake. The BEV driving substitution is limited by the overlap in the driving, the range, and the charging rate. Assuming that the charging and exchange of vehicle only take place at home the home-to-home driving distances and point of times are the focus. The overlap driving is the driving that occur simultaneously; it is all the driving between common stops at home for which both cars are driving, i.e. are away from home at some time. For the non-overlap driving only one of the cars is away from home at a time between the common stops and in principle this driving can be accomplish by the BEV. All the overlap driving can not not be fulfilled by the BEV, but maximally the driving of the car with the longest driving distance between the common stops at home, see Fig 1. We define for the household the non-overlap indicator γ_N as the non-overlap driving share of its total driving, or the distances quotient (N1+N2)/(N1+N2+O1+O2) in Fig 1 notations.

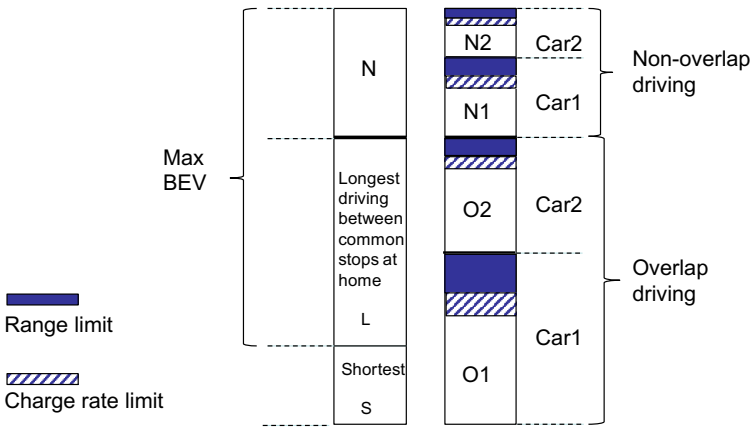

Figure 1: *Maximum possible EV uptake. The household driving is partitioned on vehicles and in time non-overlap and overlap driving. Further the overlap driving is also sorted into that car's driving which has the longest and shortest driving between common stops at home, respectively.*

To this comes the range and charging limitation. The BEV can apparently not accomplish a car's home-to-home driving (can be more than one between common stops), which is longer than the range. The charge rate limits the possibilities to fill up the battery during shorter (common) stops at home thus possibly

further restricting the BEV driving of that or the other car's next trip(s). The charge rate restriction thus potentially couples the household driving into mutually dependent trips.

2.2 Substitution modelling

2.2.1 Optimization

A mixed integer quadratically constrained programming (MIQCP) model has been developed to calculate the potential for a BEV to maximise its driving in the households given the logged driving during the analysis period. The optimization is performed for various battery ranges and charging power and for different car substitution strategies. The BEV can substitute the 1st or the 2nd car depending on their driving patterns. We define the 1st car as the car with the longest total driving distance during the analysis period. The change between substituting the 1st or the 2nd car can take place at home only. The model thus maximizes the sum of the BEV driving distances when possibly substituting the driving of the 1st and the 2nd car, alternatively, between the identified common pauses at home, see also Fig 2 for notation:

$$\underset{u,\, v_1,\, v_2}{\text{Max}} \quad \Sigma_{j,k}\left[\left(1-u_j\right) * d_{1jk} * \left(1-v_{1jk}\right) + u_j * d_{2jk} * \left(1-v_{2jk}\right)\right] \tag{1}$$

Here u_j, v_{1jk}, and v_{2jk} are binary variables {0,1}, where u_j denotes the BEV substituting the 1st car (= 0) or the 2nd car (= 1) in between the common pauses j-1 and j, and v_{xjk} denotes if the BEV driving distance is maximized.

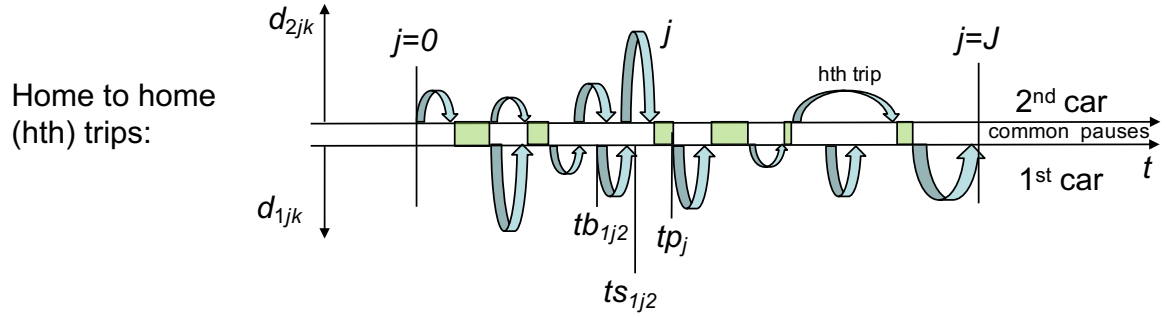

Figure 2: *A principle diagram depicting the driving by the two cars in an example household. Before the common pauses j at home for the two cars ending at point of time* tp_j*, the* 1st car *has home to home (hth) trips* 1*jk of distances* d_{1jk} *occurring between between* tb_{xjk} and ts_{xjk}*, which can overlap or not in time with the corresponding hth trips of* the 2nd car. *And vice versa for* the 2nd car. *Both cars or only one of them can be driving in between the common pauses at home.*

The optimization in Eq (1) involving choosing which car's driving to substitute between common pauses j-1 and j is subject to limitations on the battery energy content *SOC* (Eqs (2-7) due to the limited battery utilizable capacity B [kWh] and charging rate *cr* [kW] of the battery. The equations are

- battery energy:

$$0 \leq SOCb_{xjk}, SOCs_{xjk}, SOCp_{xj} \leq B \tag{2}$$

- battery energy at the start after the common pause j:

$$SOCs_{\mathrm{x}j0} = 0.99B \quad for\ j = 1 \tag{3}$$

$$SOCs_{\mathrm{x}j0} = \left(1-u_j\right) * SOCp_{1(j-1)} + u_j * SOCp_{2(j-1)} \quad \text{for } j \geq 2 \tag{4}$$

- charging in the possible pause before home-to-home trip xjk (here $ts_{xj0} = tp_{j\text{-}1}$, i.e., the point of time at the end of common pause j):

$$SOCb_{\mathrm{x}jk} \leq SOCs_{\mathrm{x}j(k-1)} + cr * \left(tb_{\mathrm{x}jk} - ts_{\mathrm{x}j(k-1)}\right) \quad for\ j \neq 0, k \neq 0 \tag{5}$$

- discharging (when driving) or charging (if possibly not driving) between beginning and stop of home-to-home trip x*jk*:

$$SOCs_{\mathrm{x}jk} \leq SOCb_{\mathrm{x}jk} + cr * \left(ts_{\mathrm{x}jk} - tb_{\mathrm{x}jk}\right) * v_{\mathrm{x}jk} - e_e * d_{\mathrm{x}jk} * \left(1 - v_{\mathrm{x}jk}\right) \ for\ j \neq 0, k \neq 0 \tag{6}$$

- charging up to point of time tp_j after last trip *xjk* before common pause *j*:

$$SOCp_{\mathrm{x}j} \leq SOCs_{\mathrm{x}jk} + cr * \left(tp_j - ts_{\mathrm{x}jk}\right) \quad \text{for } j \neq 0, k = K_{\mathrm{x}j} \tag{7}$$

Here $tb_{\mathrm{x}jk}$ and $ts_{\mathrm{x}jk}$ are the points of time at the beginning and stop, respectively, of the trip x*jk*, and $SOCb_{\mathrm{x}jk}$ and $SOCs_{\mathrm{x}jk}$ are the battery energy [kWh] at these points of time. $SOCp_{\mathrm{x}j}$ is the battery energy at the end of the common pause *j*. The specific battery energy use is denoted e_e. Eqs (1) and (4) introduce products of two variables leading to a non-linear problem, but only quadratically constrained, though. The model is formulated in GAMS and uses the SCIP MIQCP solver.

2.2.2 Substitution strategies

The households may in practice use different "strategies" when substituting one of their conventional cars. We here examine the resulting BEV driving, unfulfilled driving, net revenue (NR) etc, for 10 different such strategies, see Table 1.

Table 1: The investigated 10 different strategies for household car use. (rem = remaining of)

Strategy		BEV		CV		Unfulfilled driving
		With Fig.1 notation	Description	With Fig.1 notation	Description	In Fig.1
1	Car1	max [O1+N1]	max substituting of 1st car's driving only	all [O2+N2]	used for the 2nd car's driving only	[rem(O1+N1)]
2	Car1*			max [remO1+O2] (=all [remL], then max [remS]) + all [remN1+N2]	used for maximizing all remaining driving	[remS]
3	Car1+	first max [O1+N1], then max [N2]	uses strategy Car1, + used also for 2nd car's non-overlap driving, conditional the Car1 driving is still fulfilled given range and charging limitations	all [O2+remN2]	used for the 2nd car's remaining driving only	[rem(O1+N1)]
4	Car1+*			max [remO1+O2] (=all [remL], then max [remS]) + all [rem(N1+N2)]	used for maximizing all remaining driving	[remS]
5-8	Car2 Car2* Car2+ Car2+*	symmetric to Car1 strategies above	symmetric to Car1 strategies above	symmetric to Car1 strategies above	symmetric to Car1 strategies above	symmetric to Car1 strategies above
9	Both	max [O1+O2+N1+N2]	maximize BEV driving	max [rem(O1+O2)] + all [rem(N1+N2)]	used for all remaining driving	[rem(O1+O2)]
10	Both+	max [O1+O2+N1+N2], conditional driven distance is at least 3 times larger than the unfulfilled distance when choosing a certain trip chain between two common pauses	maximize BEV driving, but take the longest hth trip in the overlap driving only if BEV distance gained is 3 times the induced unfulfilled driving	max [rem(O1+O2)] + all [rem(N1+N2)]	used for maximizing all remaining driving	[rem(O1+O2)]

The first 4 strategies all starts with the BEV focusing to replace the 1st car and so maximizing the BEV driving. The strategies 3 and 4 also reasonably add that the BEV possibly substitute the 2nd car's non-overlap driving, as the 1st car then is anyhow not driving. The conventional car is similarly used for the 2nd car's driving only in strategies 1 and 3, while it reasonably maximizes the non-BEV driving in strategies 2 and 4. Strategies 5-8 are the symmetric strategies to strategies 1-4, thus here the BEV firstly is used for substituting the 2nd car.

Strategy 9 and 10 both maximizes the BEV's driving. Strategy 9 is an unconditional maximum. Strategy 10 with the reasonably added condition that the maximization of BEV driving should not be enforced if it comes with a too large cost of unfulfilled driving, which could occur when large home-to-home distances can be covered by the BEV if simultaneously some of the home-to-home distances in actual car's driving between the common stops are skipped. Strategy 10 do not choose this skipping if the gain in BEV driving distance is not more than 3 times larger than the distance skipped. The factor 3 is rather arbitrarily chosen, though, but means that the implicit cost trade-off between cost savings for driving electric and cost for unfulfilled driving is a factor of 3[1].

We conclude there are 6 unique BEV strategies, while the 4 *-strategies (i.e., strategies 2, 4, 6, 8) involve alternative handling of the conventional vehicle, but which do not change the BEV driving potential.

The optimization model given by Eqs (1-7) actually corresponds to the strategy Both only. The models for the other strategies are modifications of these basic equations and/or possibly in combinations with input restrictions derived from the output of other strategies.

2.2.3 Technical and economic prerequisites

The BEV range is important for the substitution possibilities. Current ranges for many BEV models are in the range of 100-150 km in normal driving. However, using a lot of auxiliary power for instance extensive electric heating when driving in colder climate, the range may decrease substantially. Many car manufacturers now are hinting on or announcing that they soon will market BEV models with considerably longer battery ranges, up to 300 km, and the models of the brand Tesla since some years already have even longer ranges than this. For each strategy we therefore investigate 11 battery sizes B of utilizable kWh corresponding to vehicle range options from 60 to 500 km when assuming a constant specific battery energy use e_e of 0.2 kWh/km for the BEV, Table 1. The twelfth applied range, denoted "Inf", is a range of 2500 km and is assumed to mimic such a large ("infinite") battery that there is in practice no substitution restriction due to range. We thus by this range get the upper theoretical physical potential for the BEV substitution options in the 2-car households.

Table 2: The 12 different BEV ranges and 7 different levels of charging power at the battery applied in the model.

Assumed levels of battery utilizable capacity [kWh]	Resulting BEV ranges [km]		Assumed levels of charging power *cr* to the battery [kW]	Corresponding grid supply when including grid-to-battery losses [phases*current, voltage]
12	60		1.2	1 * 6A, 230V
16	80		2	1*10A, 230V
20	100		3	1*16A, 230V
24	120		4	1*20A, 230V
30	150		10	3*10A, 400V
36	180		16	3*16A, 400V
42	210		25	3*25A, 400V
50	250			
50	300			
80	400			
100	500			
500	2500 ("Inf")			

[1] With BEV operational cost saving of 0.08 $/km from Table 2, the unfulfilled distances are indirectly valued at 0.24 $/km.

The applied charging power *cr* [kW] is similarly varied in 7 steps between 1.2 kW and 25 kW roughly corresponding to various combinations of voltage and current possibly available in Swedish households, Table 2. These power levels are (rounded) charging power rates at the battery and thus include assumed losses in for example an EVSE (Electric Vehicle Supply Equipment) and the on-board charger. For instance, 1*16A/230V can deliver a charging rate of 3 kW at the battery when the grid-to-battery losses are around 18%. This is in par with the losses measured for charging of a BEV (Peugeot Ion) in Belgium [7].

The annual gains in TCO when substituting a BEV for one of the CVs in the household are calculated as operational cost savings – investment cost – extra cost for unfulfilled driving, or for each household

$$\Delta TCO_a = \left(p_f \cdot e_f - p_e \cdot e_e\right) \cdot annVKT_{BEV} - \alpha \cdot (C_{NB} + c_B \cdot B/\beta) - \sum_k^{N_{UF}} (C_{UF} + c_{UF} \cdot d_k) \qquad (8)$$

with designation and assumed techno-economic parameters according to Table 3. The BEV is three times more energy-efficient than the CV, and the price of electricity equal to that of fuel, which could be reasonable for energy at the household level in Sweden. Thus, for each kilometre driven by the BEV the operational costs savings are 0.6*0.2-0.2*0.2 = 0.08 $/km. The investment cost of the BEV excluding battery is assumed to be equal to the conventional car [8]. The extra cost for unfulfilled (home-to-home) trips is set to a fixed cost of 50 $ per trip and no operational costs, which mean there is no extra operational cost above the conventional car. This cost is of course very ambiguous considering the many options for solving or reacting to the unfulfilled driving: taxi, public transport, car renting, car borrowing, using pool car or simply not travelling.

Table 3: Assumed (base case) techno-economic parameters for the cars and for the unfulfilled household driving.

Techno-economic parameter	Designation	Value
Specific energy use (fuel car) [kWh/km]	e_f	0.6
Specific energy use (BEV) [kWh/km]	e_e	0.2
Fuel price [$/kWh]	p_f	0.2
Electricity price [$/kWh]	p_e	0.2
Specific battery cost [$/kWh]	c_B	300
BEV extra non-battery investment cost [$]	C_{NB}	0
Annuity [yr^{-1}]	α	0.15
Battery capacity utilization [–]	β	0.9
Extra fixed cost for unfulfilled trips [$/occasion]	C_{UF}	50
Extra operational cost for unfulfilled trips [$/km]	c_{UF}	0
Number of yearly unfulfilled hth trips in the household [-]	N_{UF}	from optim.
Unfulfilled distance [km] ($k = 1,N_{UF}$)	d_k	from optim.

2.3 Retrieved car movement data

The car movement data used in the analysis was derived by logging with GPS simultaneously for about 2-3 months the movement patterns of both cars in 2-car households with conventional cars. Households were randomly drawn from the Swedish vehicle register. Though, to as much as possible target 2-car households with a reasonable amount of frequent and possibly simultaneous driving of cars, and with cars that could be replaced with a similar, but electric family car, the selection was restricted to households:

- within 13 Swedish municipalities around and including Gothenburg
- which possess exactly, and only, two private cars,
- with both cars of model year 2002 or younger,
- with both cars ≤ 200 kW of engine maximum power,
- with car owner(s) < 65 years old,

Of the around 331 000 private cars in the targeted region 48% belong to many-car households and 33% are in 2-car households. With the further restrictions mentioned above the number is reduced to about 37 000 or 11% of the private cars in the region. Through the participation request the households were further restricted to households

- with ≥ 2 actively used driving licenses,
- with commuting with at least one car ≥ 10 km one way.

When a positive answer to participation was obtained (around 5% of the distributed requests) two GPS logging equipment were sent by mail to be mounted by the owner(s) themselves. The logging (timestamp, position, altitude, velocity, used satellites, and were performed with 2.5 or 1 Hz. The participating households were also asked to fill in a smaller questionnaire concerning household composition, car use, commuting, towing, and home charging options. Around 130 households received logging equipment. We restrict the investigation to 64 households with good data quality for both cars simultaneously for an analysis period of mostly between 1.5 to 2.5 months, Fig 3. Good data quality means here that we have, or can reasonably reconstruct, the needed data for all trips in the analysis period in the form of distance driven, as well as departure and arrival positions and points of time.

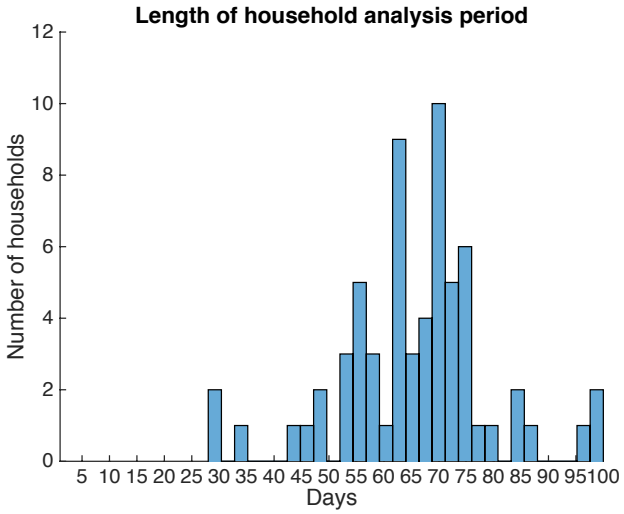

Figure 3: *The length of the analysis period for the 64 investigated 2-car households.*

3. RESULTS

3.1 The households' driving

The potential driving and economics for a BEV in a 2-car household depends much on how much overall driving there is to substitute. The household distances driven during the analysis period linearly extrapolated to annual VKTs are shown in Fig 4. This total annual driving varies with almost a factor of four between about 16000 and 60000 km/yr. By definition the 1st car always drives longer then the 2nd car. However, the relative driving of the two cars varies from close to equal for some households to some where 1st car totally dominates the driving. While the shortest annual VKT by the 1st car is around 10000 km/yr, some of the 2nd cars have very short yearly driving with around only 10 km of daily driving in average.

The non-overlap driving as part of the total driving for the different households varies between less than 0.1 and up to 0.7 with an average of 0.31, see Fig 4b. Thus 69% of the driving occurs simultaneously such that the BEV physically can not fulfil all driving but has to chose which car to replace. However, we did not find any significant correlation between the non-overlap indicator and the resulting share of BEV driving in the household in the optimization.

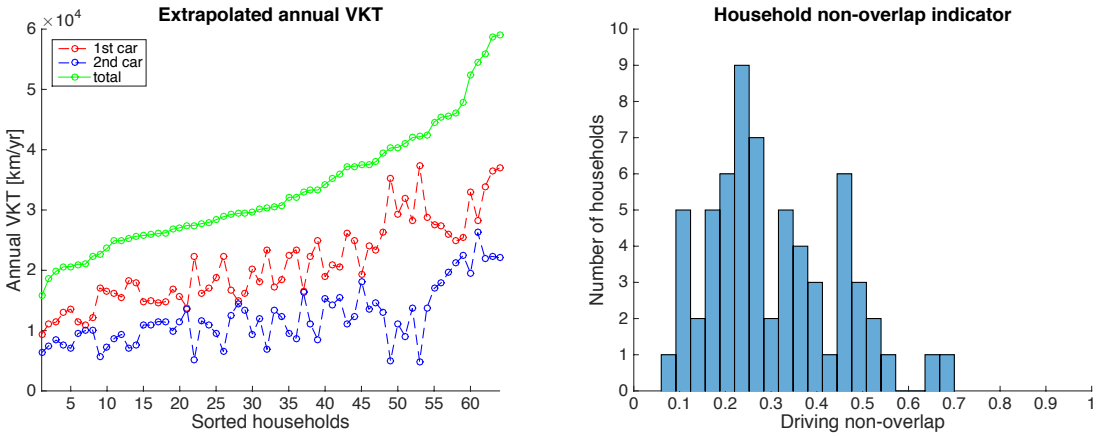

Figure 4: *For 64 logged 2-car households, a) the distances driven during the analysis period linearly extrapolated to one years driving sorted after total annual distance; b) the distribution of the non-overlap indicator.*

3.2 Potential BEV driving

Of course the results vary with the specific situations in each household. However, we will here mainly focus the fleet average results though. Figure 5a gives the fleet average potential driving by a BEV for the different strategies.

First we can conclude that the influence of the charging is a factor only for the smallest rate (1.2 kW, 230V 1*6A). For the charging rates that should dominate charging in Swedish 2-car households today (3 kW, 230V 1*16A) and above the charging power is an insignificant hurdle for the BEV uptake[2].

The often thought-of strategy of letting the BEV replace the 2nd car only (Car2) results in an annual BEV driving that saturates at around 12 000 km/yr already for midsized batteries (120-180 km), due to the confined driving of the 2nd car; it seldom drives longer out-of-range distances, which also can be seen in the small added distance for the "infinite" battery.

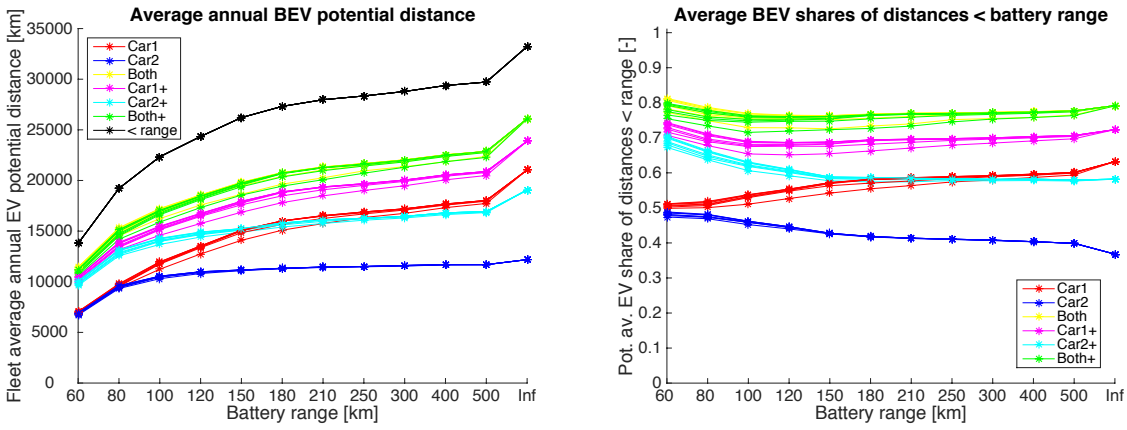

Figure 5: *For 64 logged 2-car households, as a function of battery range and charging rate (same-colour lines),* a) *the BEV average potential distances for the 6 different BEV strategies. The household annual VKT less than range is also given; b) the BEV average shares of the household driving less than range for different strategies.*

Replacing the 1st car only (Car1) results in more BEV driving, steadily increasing with the battery range reflecting the longer annual driving distances (≈ 21 000 km/yr) as well as the less confined driving of the 1st

[2] In an ongoing BEV trial in Swedish 2-car households all 25 are able to charge at home with a rate of 3 kW (ongoing own project).

car. By also allowing for replacing the 1st car when not driving the 2nd car (Car1+), the driving can be increased by about 4000 km/yr for small ranges to about 7000 km/yr for large ranges; thus more and more of the 1st car driving can be added with larger range. The Car2+ strategy gives even more BEV driving than Car1 up to 120 km range (and then about the same for larger ranges). For the symmetric strategy (Car2+) the added distance is around the same for all ranges or about 4000 km/yr.

For a total flexibility in the choice of car to substitute (Both) the BEV distance is further maximized. (The strategy Both+ gives an only marginally shorter BEV distance.) For medium battery ranges the potential BEV driving in the two-car household can be almost doubled in comparison to substitution of only the 2nd car (Both/Both+ compared to Car1). For ranges of between 100 to 180 km the potential BEV distance is between 17000 and over 20000 km/yr. In comparison to all driving in the household below a certain range, in the flexible strategies (Both/Both+), the BEV can cover 75-80% of all the household driving below that range, independently of range, Fig 5b. In comparison the Car1 strategy can cover at most close to 50% for very small ranges and no more than 40% for longer ranges.

3.3 Unfulfilled household driving

The average annual unfulfilled driving for the different strategies is shown in Fig 6. The number of yearly unfulfilled occasions (UFO) decreases rapidly with range. The Car1 strategy gives the most UFOs, almost once a week in average even for a 100 km range. The UFO for Car2 is half or less than that for Car1. However, the UFOs can be decreased considerably by using the conventional car more optimal (* - strategies). Also for the unfulfilled distances (UFD) Car1 stands out.

However, even with a limited range, by using the possible flexibility in the two-car household (Both/Both+), the non-fulfilled household driving can be minimized in occasions as well as range, while simultaneously increasing the BEV distance. For ranges of 120 km and above, the UFO and UFD are insignificant for these strategies of flexible BEV use. Thus, when considering the driving pattern only, with todays ranges of BEVs and a flexible use of the cars, the range limitation of the BEV substituting one of the cars in 2-car households is in average no major hurdle.

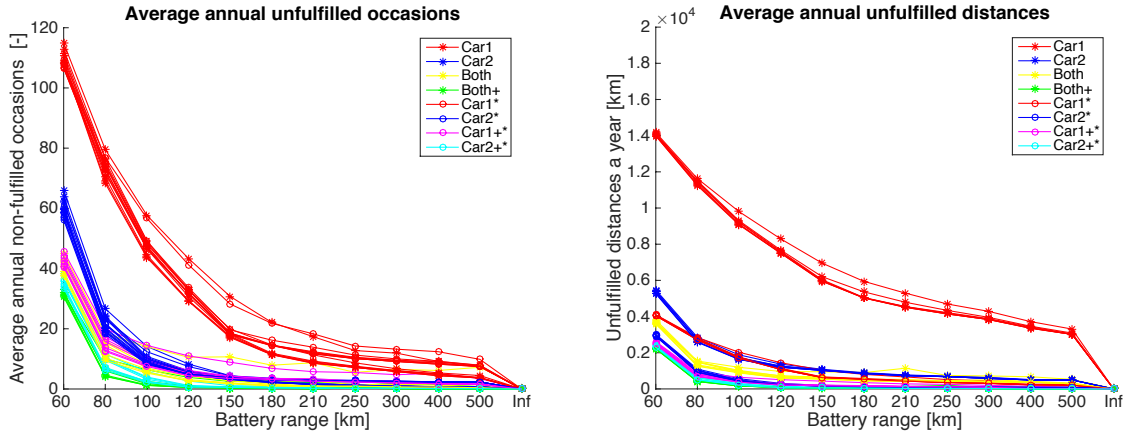

Figure 6: *For 64 logged 2-car households, as a function of battery range and charging rate a) the average number of annual unfulfilled driving occasions; b) the average unfulfilled distances.*

3.4 Possible BEV economics

The BEV economics depends besides the applied strategy on the prevailing techno-economics condition and BEV range. Figure 7a gives the average annual net revenue for the BEV in the two-car household given the assumed base case techno-economic parameters, Table 2. When substituting the 1st car only (Car1 strategy), the optimal range is larger, due to the high cost for UFOs at lower ranges, and the TCO is anyhow heavily negative for all ranges. Substituting the 2nd car gives generally a better economic viability.

A positive average net revenue is achieved only for the strategies exploring the options possible in a two-car household. The maximum BEV TCO gain in these cases is achieved already for a range of 100-120 km. For a halving of the battery prices, from 300 to 150 $/kWh, Fig 7c, the range of battery sizes for which there is a TCO gain increases considerably, although the average optimal size is not increased much. The low average optimal range for the BEV is reflecting the quickly declining marginal utilization of the battery with range, especially for the more flexible strategies, Fig 7b.

The influence of the cost for UFOs is considerable at low ranges, as seen when comparing Fig 7a to Fig 7d, which gives the TCO with no extra fixed cost for the UFOs. We realize how the single household can possibly circumvent the assumed costs for UFO/UFDs and how it values any associated inconveniences are of profound importance for the perceived BEV economic viability. However, we must also note the quick disappearance of UFO/UFD with increased range, especially when flexible vehicle strategies are applied.

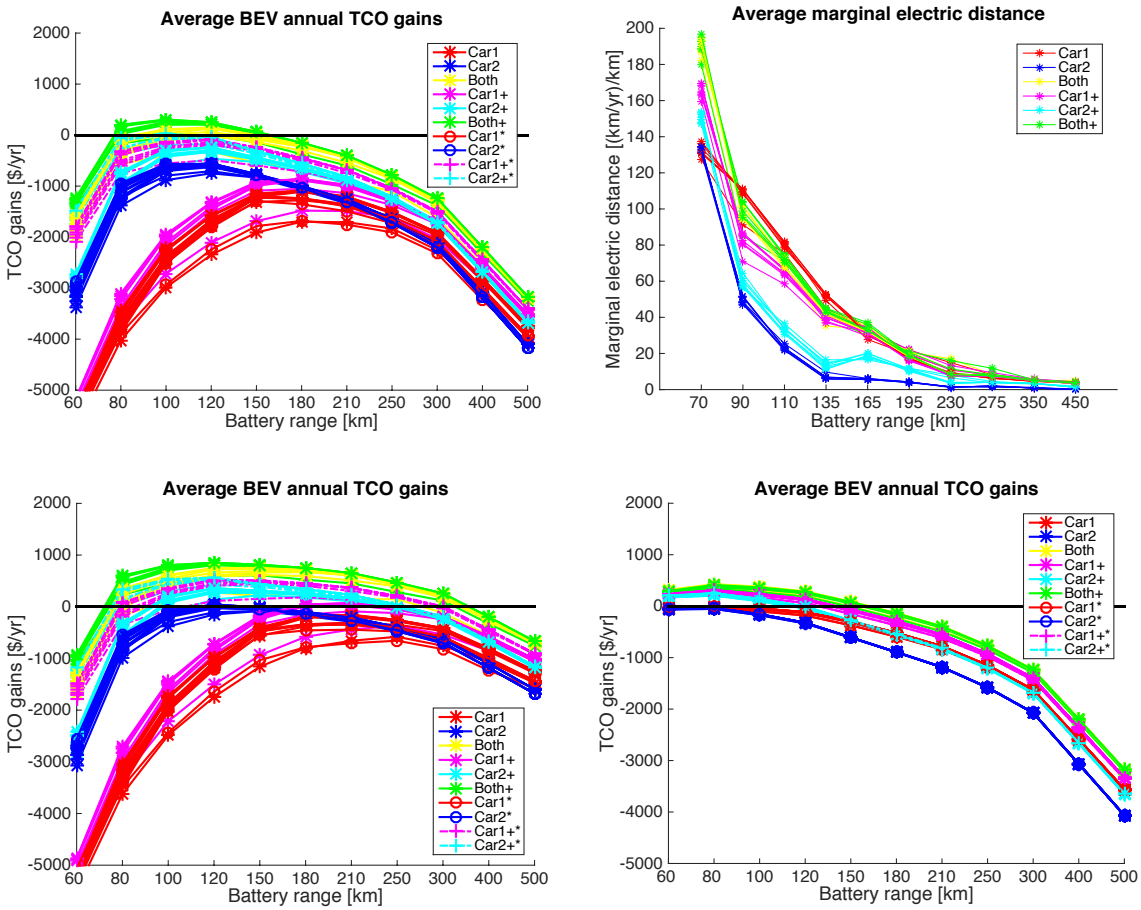

Figure 7: *For 64 logged 2-car households, the average annual net revenue for various strategies of driving by a BEV as a function of range and charging rate, for techno-economic parameter a) base case; c) battery cost =$150/kWh; d) fixed cost for unfulfilled occasions = 0; b) The average marginal utilization of the battery i.e., the gained BEV km/yr per km extra battery range as a function of range.*

4. DISCUSSION

The results here confirm earlier studies of Khan and Kuckelman and Jakobsson *et al*, studying BEV replacement of one of the cars only in the 2-car household, and concluding substituting 2nd car is more favourable both concerning unfulfilled driving and TCO [6,7]. They also confirm the importance of the

potential flexibility in the 2-car households for the potential driving of the BEV, the unfulfilled driving, and BEV economics pointed to by Tamor and Milačić [8].

The exact range of a BEV is not given. It may vary with driving conditions, urban/rural, aggressiveness, etc. Climatic conditions for instance winter coldness, will influence the use of auxiliary power and therefore the range. The comprehension of the range anxiety and the handling of it in the specific household situation are also of great importance for the in practice utilizable and utilized range of a given vehicle. The here assumed different ranges can be looked upon as the utilized ranges in the single household. This should not influence the physical analysis results as long as the ranges do not vary from trip to trip or period to period. However, for the BEV economics it is of great importance how the costly battery capacity could be translated into utilized range.

In this analysis the charging has been assumed to take place at home only. Possibilities for a household to recharge at the workplace, for instance, may influence the result considerably. It is reasonably that such options will favour smaller batteries and/or more BEV driving. The possibilities for using the BEV for the longer outside-the-range trips in the households are dependent on fast charging options. Of importance may also be the charging options at often visited places with overnight stays such as summer houses, common in Sweden.

We saw that the cost for unfulfilled driving heavily influenced the BEV economic with the assumed cost for unfulfilled occasions. It was based on the extra costs for renting a car, which normally is a high cost alternative. Between single households in certain situations the perceived value of a specific driving can vary greatly, as well as the alternatives available for possibly fulfilling the travel. To not travel may very well be an alternative with low perceived inconvenience in some cases. Lending a vehicle as well, which in this context can be seen as a flexibility in car use in between households. Other modes of transport such as public transport may be an option for some households.

This analysis has only estimated the pure physical potential for a BEV in 2-car households, i.e., only considered given car movement patterns and limitations due to range and recharging. There may be a lot of reasons for less flexibility in real households; the household members have their “own” car, only one car is used for towing or heavy load or is equipped with child seats, or simply the household is not optimizing its cars or for convenience first use the car parked closest to the street. This non-flexibility will decrease the the estimated physical potential. What the actual utilization of the potential is and what adaptations are done in real households are the questions for an on-going study in which in some of the households an EV substituting one of the cars is investigated [9].

5. CONCLUSIONS

An obstacle to a more widespread introduction of the BEV is the effects of the trade-off between range and cost due to the expensive battery. An important question is therefore where these effects can most effectively be mitigated.

Our analysis of the logged movement patterns of both cars in 2-car households has shown, that the possible flexibility introduced by the option to choose with which vehicle to perform the household driving make possible a much larger annual driving by the BEV, less unfulfilled driving and thus better BEV economics compared to substitution of one car only. Because of the ubiquity of many-car households in well-developed economies, these households could be a target for efforts to enhance the BEV prevalence in the car fleets.

Acknowledgements

We gratefully acknowledge the support from the Electric Vehicles Demonstration Program at the Swedish Energy Agency and from the Area of Advance Transport and Area of Advance Energy at Chalmers University of Technology, Gothenburg.

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