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What are the value and implications of two-car households for the electric car?

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ABSTRACT

The major barriers to a more widespread introduction of battery electric vehicles (BEVs) beyond early adopters are the limited range, charging limitations, and costly batteries. An important question is therefore where these effects can be most effectively mitigated. An optimization model is developed to estimate the potential for BEVs to replace one of the conventional cars in two-car households and to viably contribute to the households' driving demand. It uses data from 1 to 3 months of simultaneous GPS logging of the movement patterns for both cars in 64 commuting Swedish two-car households in the Gothenburg region.

The results show that, for home charging only, a flexible vehicle use strategy can considerably increase BEV driving and nearly eliminate the unfulfilled driving in the household due to the range and charging limitations with a small battery. The present value of this flexibility is estimated to be on average $6000–$7000 but varies considerably between households. With possible near-future prices for BEVs based on mass production cost estimates, this flexibility makes the total cost of ownership (TCO) for a BEV advantageous in almost all the investigated households compared to a conventional vehicle or a hybrid electric vehicle. Because of the ubiquity of multi-car households in developed economies, these families could be ideal candidates for the initial efforts to enhance BEV adoptions beyond the early adopters. The results of this research can inform the design and marketing of cheaper BEVs with small but enough range and contribute to increased knowledge and awareness of the suitability of BEVs in such households.

1. Introduction

Electrified vehicles are one of the options to achieve less use of fossil fuel and reduced emissions of greenhouse gases and other pollutants from transport, especially in countries or regions with clean electricity production systems. Mainly due to expensive batteries, most battery electric vehicles (BEVs) currently available have limited ranges compared to conventional cars, and they also have the disadvantage of a relatively long charging time. Due to its comparably low operational but high fixed costs, the relative economic viability of BEVs is more advantageous with high annual driving, but this, in turn, tends to aggravate the range and charging limitations. These limitations set by the range and charging time hamper the uptake in private households, whose members highly value the option to occasionally drive longer trips, or shorter trips without necessary long stops in between. For instance, in Sweden so far (Oct 2016), around 8000 BEVs (≈0.2% of the total car fleet) have

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been sold[1]. Most of these are used as fleet vehicles or provided by business or government as "company cars" to employees, and only a few are registered on private persons. There is, though, a Swedish goal of having a "fossil-independent" vehicle fleet in 2030 (Swedish Government, 2009).

But could potential private BEV buyers beyond early adopters be two-car (or multi-car) households? There could be four reasons or options related to factors connected to the car movement patterns. Firstly, *confinement*: it has been argued that while the "first car" or "main car" is also used for the household's longer trips, such as vacation trips, the "second car" is used mainly for shorter trips such as daily commuting. Replacing a car with a more confined driving pattern with a limited-range BEV may lead to fewer unfulfilled driving occasions and thus suit the BEV better[2]. Secondly, *extension*: a BEV can be used for also fulfilling some of the driving of the other car, especially when the BEV is not used anyhow, leading to a decrease in the household's operational costs due to the lower fuel cost of a BEV. Thirdly, *backup*: the other car in the households, which is assumed to be a conventional vehicle (CV), can be used as a backup for unfulfilled driving, at least when this car is not used. Fourthly, *flexibility*: a BEV can be utilized flexibly such that a BEV is replacing both cars' driving as much as possible to maximize its driving and thus minimizing the household's operational costs, while still keeping down the unfulfilled driving with backup by the CV. The flexibility option is thus an optimized combination of choice of car and the three first options.

Although multi-car households have early been identified as potential BEV buyers, it has been difficult to quantify these three factors, their value or implications directly. Detailed data for the driving patterns of multi-car households are seldom available, markets 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. Still, for instance, Beggs and Cardell (1980) tried projecting the demand for BEVs from market data for small cars in multi-vehicle households. Calfee (1985) used survey data to predict the potential market shares for various BEVs as a second car. Kurani et al. (1996) also focused multi-car households but tried to circumvent the limitations of earlier studies and extended the survey method to include a 3-day household trip diary as well as a reflexive session based on how different BEVs could contribute to fulfilling the logged driving. They thus tried to capture and illustrate the implications of the factors and estimate the preferences. Their results indicated that a BEV with a smaller battery could be preferred in "hybrid households", i.e., households with both BEVs and conventional cars. Hidrue et al. (2011) included different types of households and did not find higher stated preferences for BEVs specifically in multi-car households, or even a slight tendency towards the opposite, while Deloitte (2010) identified multi-car ownership as a characteristic of early adopters of BEVs. Rather than showing the unimportance of multi-car households for BEVs, stated preferences may point to the immature market for BEVs and the widespread BEV ignorance among potential consumers.

Recent studies also point in various directions. Javid and Nejat (2017), using US Travel Survey Data to identify plug-in electric vehicle (PEV) buyers, claimed that the number of vehicles in the household has had no significant effect on the households PEV purchase. But the recent development in Norway beyond-early-adopters-market for BEVs has demonstrated the importance of multi-car households there. According to the survey presented in Figenbaum and Kolbenstvedt (2016), in Norway, with its unique high BEV share of around 15% of new car sales, 79% of the households having a BEV had more than one car compared to around 48% for owners of only conventional vehicles. It was even higher when excluding the long-range Tesla Model S, which to a much larger share is situated in one-car households. Coincidentally, a somewhat larger fraction of BEVs has been bought as an additional car rather than a replacement compared to other new vehicles.

Many studies have investigated the options for a BEV to replace a conventional car, but there are relatively few that have specifically looked at the options in multi-car households. Khan and Kockelman (2012) 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 the least-driven car only in multi-car households and found that for the daily driving the range limit is reached less often than in single car households. Jakobsson et al. (2016a) based analysis on Swedish daily driving distances derived from GPS-logged movements for randomly chosen cars for around two months each (Karlsson, 2013; Karlsson and Kullingsjö, 2013). They found that a BEV replacing the 2nd car only, determined as the least-driven car as stated by owners in a two-car household, results in fewer range-limited days, due to the shorter and more confined driving of the 2nd car, as well as on average lower total cost of ownership (TCO) for a BEV than when replacing the 1st car. Similar results were observed in their parallel analysis of a larger dataset for one week's driving in German households. Both these above-mentioned studies only replaced one of the household's cars and thus only investigated the confinement factor. Recently, though, Tamor and Milačić (2015) examined the flexibility option using the same Seattle data as Khan and Kockelman by analyzing the possibility of letting one BEV replace both/all cars in multi-vehicle households. 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.

We have completed a data acquisition and analysis project with the overall objective to assess the potential for a BEV replacing one of the conventional cars to viably contribute to the accomplishment of the car movements in Swedish commuting two-car households.

[1] http://elbilsstatistik.se/ Acc. Nov 24, 2016.

[2] Note that the confinement, contrary to the other options, is here not strictly defined, but more a general argument that some car movement patterns fit a range- and charge-limited BEV better than others.

2. Method and data

We first simultaneously logged both cars in Swedish commuting two-car households with GPS. The movement data is then used to estimate the potential driving by a BEV replacing one of the two conventional vehicles in the households assuming the car movement patterns are unchanged. Various BEV use strategies were analyzed to explore the flexibility made possible in two-car households. The potential driving is input to an estimate of the possible TCO gains. Finally, we discuss the implications for the viability of a BEV in comparison to a conventional vehicle or a hybrid electric vehicle (HEV) in these two-car households.

2.1. Potential driving for a BEV replacing one of the cars in a two-car household

An underlying prerequisite in this study is that a BEV has considerably lower operational cost than the conventional car and thus rationally should be the first option when driving. We estimate the BEV potential driving given by the household's logged driving and take into account, besides the BEV range and the charging location and rate, only the physical limitation induced by the movement patterns of the cars. In reality, there could be other reasons that limit the actual utilization of a BEV. Some driving may require specific equipment possibly available only in the non-BEV, such as a towing bar or a child seat. The non-BEV can be preferred in some of the driving for safety, reliability or capacity reasons. Psychological factor such as "my car and your car" and plain habits evolved when only CVs were available may inhibit the use of the cars for maximum BEV driving. Or simply, households may not be motivated enough to put efforts into maximizing the BEV use.

Fig. 1 depicts the driving in a two-car household and the potential BEV uptake. The BEV driving substitution is limited by the time overlap in the two cars' driving, the BEV range, and the charging options regarding location and rate. We assume in this study that the charging and exchange of vehicles only take place at home. Then the home-to-home driving distances and point of times for departure and arrival are the key. The overlap driving is here defined as the home-to-home (hth) trips that are simultaneously away from home at any moment. 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 accomplished by a BEV. All the overlap driving can't be fulfilled by a BEV, but maximally the driving of the car with the longest driving distance L between the common stops at home, which is always larger than the maximum of O1 and O2, see Fig. 1.

Next we consider the range and charging limitation. Range limitation is when a BEV cannot accomplish a car's home-to-home driving (can be more than one between common stops) that 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 restricts a BEV's fulfillment of one or the other car's next trip(s). The charge rate restriction thus potentially couples the household driving into mutually dependent trips.

2.2. Modeling potential BEV driving

2.2.1. Optimization

A mixed integer quadratically constrained programming (MIQCP) model has been developed to calculate the maximum BEV driving in the households given the logged movement pattern during the analysis period. The optimization is performed for various battery ranges and charging power rates and for different car substitution strategies. A 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 model thus maximizes the sum of the driving distances d_{xjk} of the BEV when it possibly accomplishes the driving of the 1st or the 2nd car, alternatively, in the periods j between the identified common stops at home, see also Fig. 2 for notation:

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

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 stops $j-1$ and j, and v_{xjk} denotes if the BEV is driving (=0) the hth trip k when substituting car x in between the common stops $j-1$ and j.

The optimization in Eq. (1) is subject to limitations on the battery energy content SOC [kWh] (Eqs. (2)–(7)) due to the limited utilizable capacity B [kWh] of the battery and charging rate cr [kW] of the battery. The equations are

– battery energy:

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

– battery energy at the start after the common stop j:

$$SOCs_{xj0} = 0.99B \quad \text{for } j = 1 \tag{3}$$

$$SOCs_{xj0} = (1-u_j)*SOCp_{1(j-1)} + u_j*SOCp_{2(j-1)} \quad \text{for } j \geqslant 2 \tag{4}$$

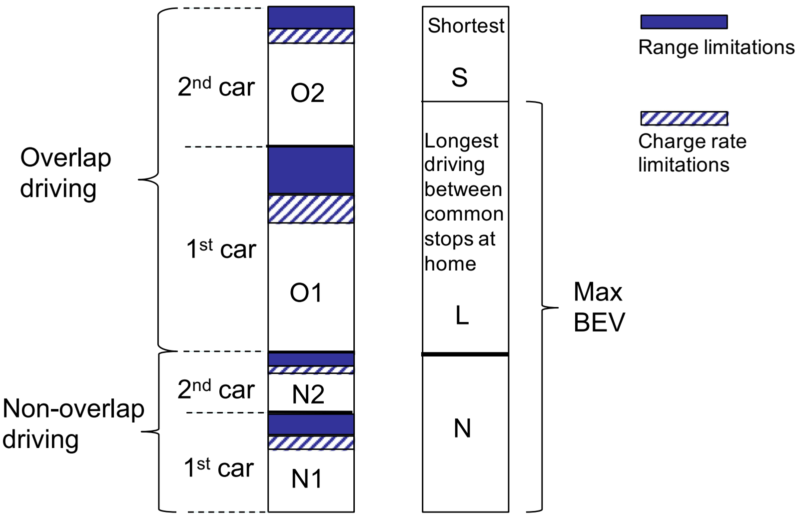

Fig. 1. Maximum possible BEV uptake in an illustrative two-car household. The household driving is partitioned between the two vehicles as well as between the in time non-overlapping and overlapping driving, denoted N and O, respectively. Further, the overlap driving is also sorted into that car's driving which has the longest (L) and shortest (S) driving between common stops at home, respectively.

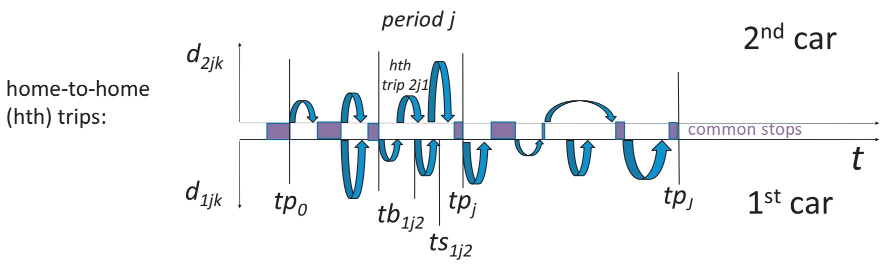

Fig. 2. A principle diagram depicting the driving by the two cars in an example household. Before the common stops j at home for the two cars ending at the point of time tp_j, the 1st car has home-to-home (hth) trips 1 jk of distances d_{1jk} occurring between tb_{1jk} and ts_{1jk}, which can overlap 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 are driving in between the common stops at home.

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

$$SOCb_{xjk} \leqslant SOCs_{xj(k-1)} + cr * (tb_{xjk} - ts_{xj(k-1)}) \quad for\ j \neq 0, k \neq 0 \tag{5}$$

– discharging (when driving) or charging (if possibly not driving) between beginning and stop of hth trip xjk:

$$SOCs_{xjk} \leqslant SOCb_{xjk} + cr * (ts_{xjk} - tb_{xjk}) * v_{xjk} - e_e * d_{xjk} * (1 - v_{xjk}) \quad for\ j \neq 0, k \neq 0 \tag{6}$$

– charging up to the point of time tp_j after last hth trip xjk before common stop j:

$$SOCp_{xj} \leqslant SOCs_{xjk} + cr * (tp_j - ts_{xjk}) \quad \text{for } j \neq 0,\ k = K_{xj} \tag{7}$$

Here tb_{xjk} and ts_{xjk} are the points of time [h] at the beginning and stop, respectively, of the hth trip xjk, and $SOCb_{xjk}$ and $SOCs_{xjk}$ are the battery energy [kWh] at these points of time. K_{xj} is the number of hth trips between the common stops $j-1$ and j. $SOCp_{xj}$ is the battery energy at the end of the common stop j. The specific battery energy use is denoted e_e [kWh/km]. Eqs. (1) and (4) contain products of two variables leading to a non-linear problem, but only quadratically constrained, though. The model is written in GAMS and uses the SCIP MIQCP solver.

Table 1
The investigated ten different car-use strategies for two-car households. (rem(Y) = remaining of distance Y).

Strategy: Number – *Used option*	Strategy: Denoted	BEV: With Fig. 1 notation	BEV: Description	CV: With Fig. 1 notation	CV: Description	Unfulfilled driving: With Fig. 1 notation
1 *confinement*	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 *confinement + backup*	Car1*			max [rem(O1 + O2)] (= all [rem(L)], then max [rem(S)]) + all [rem(N1 + N2)]	Used for a maximum of all remaining driving	[rem(S)]
3 *confinement + extension*	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 + rem(N2)]	Used for the 2nd car's remaining driving only	[rem(O1 + N1)]
4 *confinement + extension + backup*	Car1+*			max [rem(O1 + O2)] (= all [rem(L)], then max [rem(S)]) + all [rem(N1 + N2)]	Used for a maximum of all remaining driving	[rem(S)]
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 *flexibility*	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 *flexibility*	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 stops	Maximize BEV driving, but take the longest hth trip in the overlap driving only if the BEV distance gained is 3 times the induced unfulfilled driving	max [rem(O1 + O2)] + all [rem(N1 + N2)]	Used for a maximum of all remaining driving	[rem(O1 + O2)]

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, and TCO gains, for 10 different basic strategies, which to various degree explore the confinement, extension, backup and flexibility options, see Table 1.

The first four strategies all start with the BEV maximizing the replacement of the 1st car's driving and can explore any possible confinement factor. The (+)-strategies Car1+ and Car1+* also utilize the extension option by adding to the BEV driving the 2nd car's non-overlap driving, when the 1st car is not being used. The conventional car is similarly used only for the 2nd car's driving in strategies Car1 and Car1+, while the backup option is used in the (*)-strategies Car1* and Car1+* to maximize the non-BEV driving distance and thus minimize any unfulfilled driving. Strategies 5–8 are the symmetric strategies where the BEV firstly is used for maximizing the substitution of the 2nd car.

Strategies Both and Both* first maximize the BEV's driving and then utilize the CV to minimize the unfulfilled driving. Strategy Both is an unconditional maximum. Strategy Both* has the reasonably added condition that the maximization of BEV driving should not be enforced if it comes with a too large amount of unfulfilled driving distance. This could occur when some of a car's home-to-home trips between common stops can be serviced by a BEV if and only if simultaneously some of the remaining trips are skipped. In strategy Both* the BEV is allowed to choose this car's driving only if the gain in the BEV driving distance is more than 3 times longer than the distance skipped. This factor 3 is somewhat arbitrarily chosen, though, but it means that the implicit cost trade-off between the cost savings per km for driving electric and the cost added per km unfulfilled driving is a factor of 3[3]. We can conclude that both these strategies, one in a naive way and one more wisely, fully explore the confinement, extension, and backup options made possible in the two-car household.

We note that there are six unique BEV strategies, while four (*)-strategies (i.e., strategies 2, 4, 6, 8) involve alternative handling of the conventional vehicle but do not change the BEV driving potential. (It can influence the BEV economics, however, by affecting the number of unfulfilled occasions.)

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

2.2.3. Range and charging

The BEV range is critical for the substitution possibilities. The ranges for most of currently available BEV models are in the range of 100–150 km in normal driving. But using a lot of auxiliary power, for instance, extensive electric cabin heating when driving in a colder climate, may decrease the effective range substantially to around 60 km (Delos Reyes et al., 2016). Many car manufacturers have announced that they soon will market BEV models with considerably longer battery ranges, up to 300 km, while Tesla has even longer ranges than that. For each strategy, we, therefore, investigate 11 battery sizes B of utilizable energy [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 a BEV, Table 2. The twelfth applied range, also denoted "Inf", is a range of 2500 km assumed to mimic such a large ("infinite") battery that there is in practice no substitution restriction due to the range. With this we cover the upper theoretical physical potential for the BEV substitution options in two-car households.

The applied charging power at the battery cr [kW] is similarly varied in 7 steps between 2 kW and 25 kW, Table 2. Various voltage and current combinations possibly available in Swedish households roughly corresponding to these powers when including losses in for example the EVSE (Electric Vehicle Supply Equipment) and the on-board charger are also shown. For instance, 1*16A/230V can deliver a charging rate of 3 kW when the grid-to-battery losses are around 18%. This is on a par with the losses measured for charging of a BEV (Peugeot Ion) in Belgium (De Vroey et al., 2013). The 7 kW charging rate is also close to the maximum power of the on-board chargers of several available BEVs, such as the BMW i3 (7.2 kW), Volkswagen e-Golf (7.2 kW), Nissan Leaf (6.6 kW), as well as the upcoming Chevrolet Bolt (7.2 kW). That also means that the three highest charging rates modeled here are currently not reached if using AC charging in many available BEV models. Possible charging rates may vary with the battery SOC and is especially significant for higher charging rates and at high SOC. Combining the modeled charging rates and battery sizes gives charging C-rates (kW/kWh) between 0.02 and around 2 h^{-1}. In the modeling we have not assumed any limitation to the charging rate neither by the C-rate nor the SOC.

2.3. The TCO gains

The annual gains in TCO when substituting a BEV for one of the CVs in the household are calculated as operational cost savings minus the extra cost for unfulfilled driving minus annuitized investment cost, and for each household, strategy, range, and charging power:

$$\Delta TCO = (p_f \cdot e_f - p_e \cdot e_e) \cdot annVKT_{BEV} - \sum_{u=1}^{N_{UF}} (C_{UF} + c_{UF} \cdot d_u) - \alpha \cdot (c_B \cdot R \cdot e_e / \beta + C_{PT}) \quad (8)$$

[3] With a BEV operational cost saving of \$0.08/km (see Section 2.3), the unfulfilled distances are indirectly valued at \$0.24/km.

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

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	2	1*10A, 230 V
16	80	3	1*16A, 230 V
20	100	4	1*20A, 230 V
24	120	7	1*32A, 230 V alt. 3*10A, 400 V
30	150	10	3*16A, 400 V
36	180	16	3*25A, 400 V
42	210	25	
50	250		
50	300		
80	400		
100	500		
500	2500 (“Inf”)		

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

Techno-economic parameter	Designation	Value
Specific energy use (fuel-propelled 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
Extra fixed cost for unfulfilled trips [$/occasion]	C_{UF}	50
Extra operational cost for unfulfilled trips [$/km]	c_{UF}	0
Specific battery cost [$/kWh]	c_B	300
Battery capacity utilization [–]	β	0.9
BEV extra powertrain cost [$]	C_{PT}	Set separately
Annuity [yr^{-1}]	α	0.15

The assumed values of techno-economic parameters are summarized in Table 3. The household variables, the BEV annual kilometers traveled $annVKT_{BEV}$ [km], the number of yearly unfulfilled hth trips N_{UF} [–], and their corresponding distances d_u [km] are taken from the optimization extrapolated to a full year. A BEV is assumed to be three times more energy-efficient than a CV[4], 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 kilometer driven by a BEV the operational costs savings, $p_f \cdot e_f - p_e \cdot e_e$, are $0.08/km. The extra cost for unfulfilled (home-to-home) trips can vary considerably; there are many potential options for solving or reacting to the unfulfilled driving: from high-cost alternatives as a taxi, car renting, or using a pool car, to cheaper options such as public transport, car borrowing, or just avoid the travel. The fixed cost C_{UF} is here set equal to half of the cost of renting a midsized car for 24 h over a workday, and the extra operational costs c_{UF} is equal to zero, i.e., no additional cost above the conventional car.[5] The extra investment cost of a BEV relative to a CV is divided into the battery cost, which is proportional to the battery range R [km], and the extra powertrain cost C_{PT}, which is significant, though, only for comparison of BEVs to cars with other types of powertrains (Section 3.5). The annuity of 0.15 corresponds to, for instance, 8 years of depreciation with a discount rate of 5%.

2.4. The retrieved car movement data

The car movement data used in the analysis was derived by logging the movement patterns of both cars in two-car households with conventional vehicles simultaneously with GPS for 2–3 months. Households from 13 Swedish municipalities around and including Gothenburg were randomly drawn from the Swedish vehicle registry. Since we also tried to target two-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, we made further restrictions to households:

– which possess exactly, and only, two private cars,
– with both cars of the model year 2002 or younger,
– with both cars ≤200 kW of engine maximum power,
– with car owner(s) <65 years old.

[4] Assuming 0.6 kWh/km for a CV in real driving corresponds to 6.6 L of gasoline/100 km and emissions of 156 g CO_2/km.
[5] At one of the leading rental companies in Sweden, the renting cost for a VW Golf is $99 (790 SEK) a day plus fuel. www.avis.se. Acc. Nov 28, 2016.

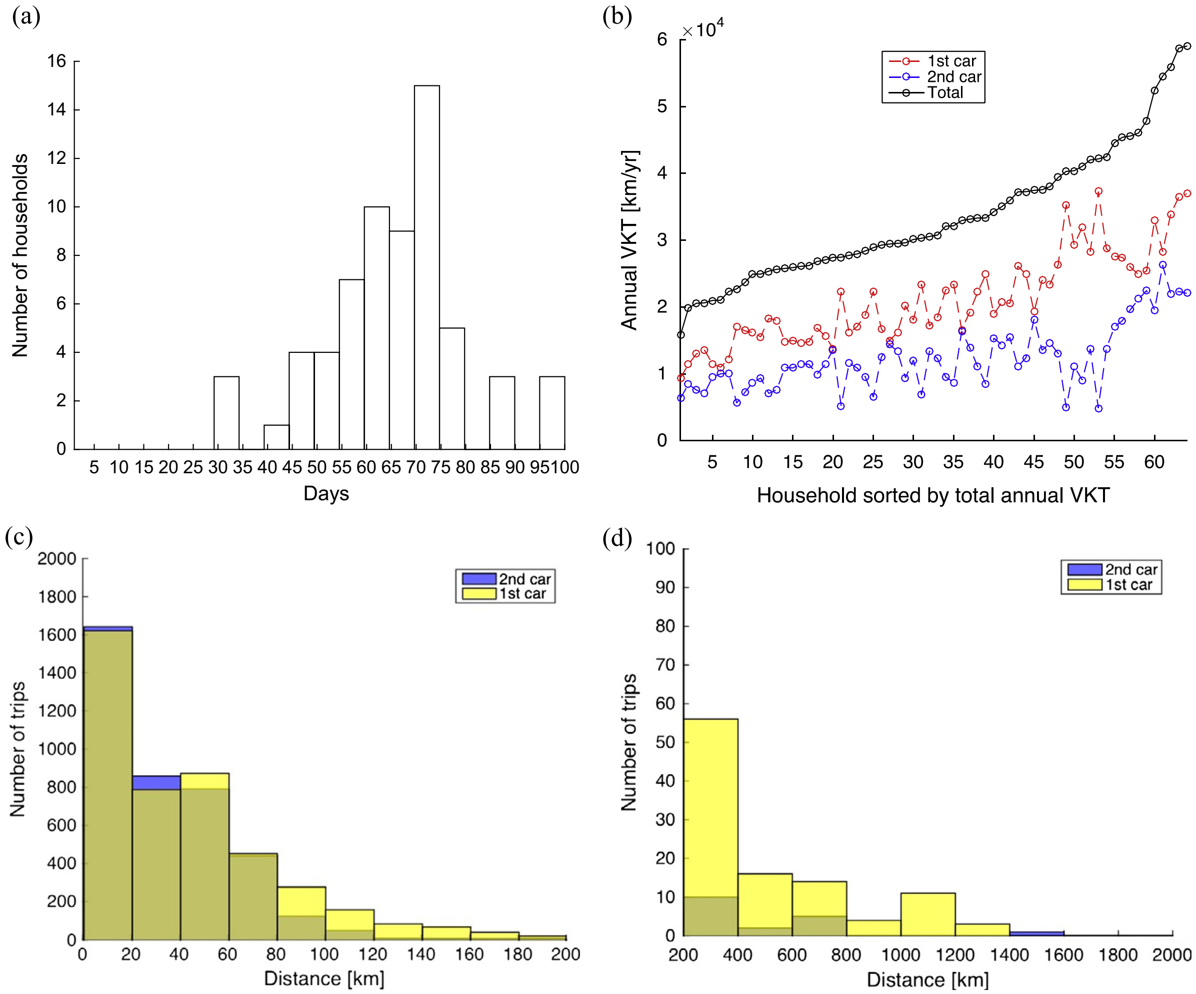

Fig. 3. For the 64 logged two-car households, (a) the length of the analysis period; (b) the distances driven during the analysis period linearly extrapolated to one year's driving sorted by total annual distance; (c and d) the distribution of home-to-home trips below and above 200 km, respectively, during the analysis period.

Of the around 331,000 private cars in the targeted region 48% belong to multi-car households and 33% to two-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 $\geq$2 actively used driving licenses,
– commuting with at least one car $\geq$10 km one way.

When a positive answer to participation was obtained (around 5% of the distributed requests) two GPS logging equipment was sent by mail to be mounted by the owner(s) themselves. The logging (timestamp, position, altitude, velocity, used satellites, and dilutions of precision) was 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 and any extraordinary event influencing the driving significantly. Around 130 households received logging equipment. We here restrict the investigation to 64 households with good data quality for both cars simultaneously for an analysis period of mostly between 1.5 and 2.5 months, Fig. 3a. 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.

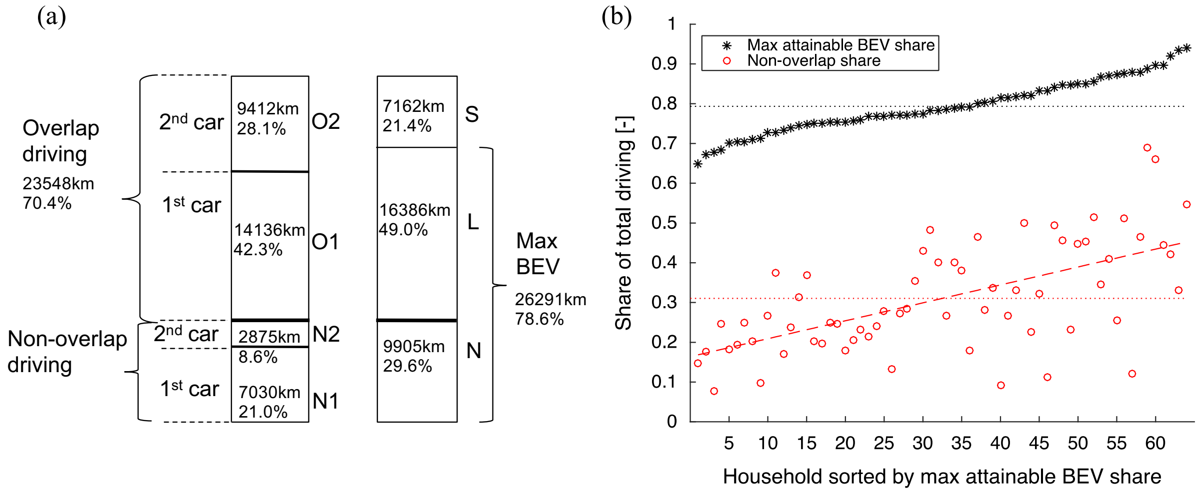

Fig. 4. For the 64 logged two-car households, (a) the average distribution of the driving (in km/yr and percentage of total driving) on overlap and non-overlap driving for the 1st and 2nd car, respectively, as well as the maximum possible BEV driving. Notation by Fig. 1 and range and charging limitations excluded; (b) the distribution of the shares of the maximum possible BEV driving and the non-overlap driving (including average and linear approximation), sorted by the maximum possible BEV driving share.

3. Results

3.1. The households' driving

The potential driving and economics for a BEV in a two-car household depend primarily on how much overall driving there is to substitute. The household distances driven during the analysis period linearly extrapolated to annual vehicle kilometers traveled (VKT) are shown in Fig. 3b. This total driving varies by almost a factor of four between about 16,000 and 60,000 km/y with an average of 33,453 km/yr. By definition, the 1st car always drives longer than the 2nd car. However, the relative driving of the two vehicles varies from close to being equal for some households to some, where the 1st car performs 88% of the driving. While the shortest annual VKT by the 1st car is around 10,000 km/yr, some of the 2nd cars have very short yearly driving corresponding to around only 10 km of daily driving in average. Fig. 3c and d shows that the 2nd car's driving is more confined in distances compared to the 1st car's driving, i.e., the hth trips are on average shorter, and the number of trips below 40 km is larger for the 2nd car. The total number of trips in the analysis period is 11% fewer for the 2nd car, while the total distance is 42% shorter, or on average 12,287 km/yr compared to 21,163 km/yr for the 1st car. Thus, the less driving of the 2nd car is mainly due to shorter home-to-home distances rather than fewer home-to-home trips. (The longest hth trip happens to belong to a 2nd car, though, as shown in Fig. 5d.)

3.2. The potential BEV driving

The potential BEV driving without any range and charging limitations is shown in Fig. 4, which also can be compared to Fig. 1. The non-overlap driving as part of the total driving for the different households varies between less than 0.1 and almost 0.7 with an average of around 0.30, see Fig. 4b. Most of the non-overlap distance belongs to the 1st car, which could be due to the more frequent driving of the 1st car, and a reflection of facts that during longer family trips only one of the cars is used which usually is the 1st car.

More than 70% (range 31–92%) of the driving is overlap driving such that a BEV physically can't fulfill all driving but has to choose which car to replace. Within this overlap driving, the average share that corresponds to the longest driving distances between the common stops of the two cars, i.e., the share denoted L, is 69.6% of the overlap driving or 49% of the total household driving. Together with non-overlap driving this gives a maximum possible BEV driving of on average 78.6% of the total driving in the households or around 26,300 km/yr, when disregarding range and charge limitations. Increased non-overlap share gives on average higher maximum possible BEV driving share (Fig. 4b). However, we did not find any significant correlation between the non-overlap driving share and the resulting share of BEV driving in the household in the optimization.

Of course, the potential BEV driving varies with the specific situations in each household. However, we will here mainly focus on the fleet average results, though. Fig. 5a gives the fleet average potential BEV driving for the six different non-redundant strategies for the BEV driving.

First, we can conclude that the influence of the charging rate is of less importance, especially at higher battery ranges. For the rate that reasonably should dominate charging in Swedish two-car households today (≈3 kW, 230V 1∗16A) and above[6],

[6] In a BEV trial in Swedish two-car households all 25 households were able to charge at home at a rate of 3 kW.

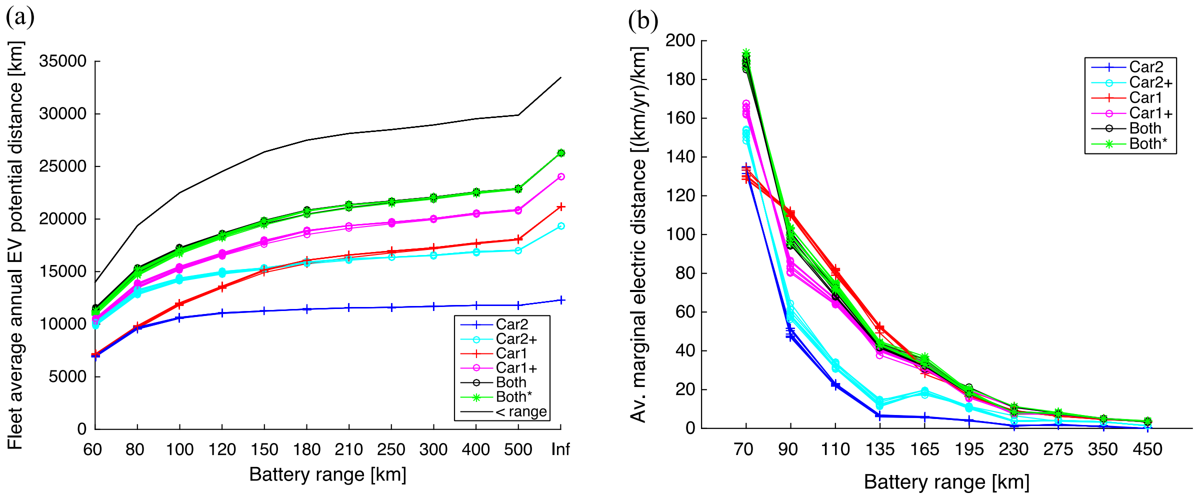

Fig. 5. For the 64 logged two-car households, as a function of battery range and charging rate (same color lines), (a) the BEV average potential distances for 6 different BEV strategies. The household annual VKT less than the range is also given; (b) the average marginal utilization of the battery, i.e., the gained BEV driving in km/yr per km additional battery range.

the charging power is on average an insignificant hurdle for the BEV uptake of the households' driving when utilizing the flexibility. For instance, in the Both∗ strategy at a range of 120 km, only 3 out of the 64 households get more BEV driving with a higher rate than 3 kW[7].

The often supposed strategy of letting a BEV replace the 2nd car only (strategy Car2) results in an annual BEV driving that saturates at around 12,000 km/yr for midsized batteries (120–180 km), due to the confined driving of the 2nd car, that is, the share of longer distances is relatively small. Replacing the 1st car only (strategy Car1) results in a potential BEV driving steadily increasing with the battery range. This reflects the longer annual driving distances (on average ≈21,000 km/yr) as well as, the less confined driving of the 1st car, especially compared to that of the 2nd car. This can indirectly be seen in the increasing and decreasing shares of BEV driving with range for Car1 and Car2 strategies, respectively. For short ranges (60–80 km) there is almost no difference in the BEV driving between substituting 1st or 2nd car, though.

When extending Car2 strategy to also allow for replacing the 1st car when the 2nd car is not driving (strategy Car2+), the BEV driving can be increased considerably, or by about 4000 km/yr for short ranges to about 7000 km/yr for long ranges. Thus, more and more of the 1st car driving can be fulfilled with larger ranges. This Car2+ strategy also gives more BEV driving than strategy Car1 up to 120 km range, and then about the same for longer ranges. For the symmetric strategy (Car1+) the added distance compared to Car1 strategy is around the same for all ranges or about 4000 km/yr.

For a total flexibility in the choice of which car to substitute (strategy Both), the BEV distance is further maximized, and the strategy Both∗ gives an only marginally shorter BEV distance. For medium battery ranges the average potential BEV driving in the two-car household can be almost doubled in comparison to the substitution of only the 2nd car (Both/Both∗ compared to Car2). For ranges of between 100 and 180 km, the potential BEV distance is between 17,000 and over 20,000 km/yr. In the flexible strategies (Both/Both∗), the BEV can cover 75–80% of all the household driving below that range. In comparison, the Car2 strategy can cover, at most, close to 50% for very short ranges and no more than 40% for longer ranges. We can conclude that for medium to long ranges when going from a pure 2nd car substitution (Car2) to a fully flexible strategy (Both/Both∗) the potential BEV driving is increased between 55 and 95%. Roughly half of this increase is due to the non-overlap in the household driving, that is, the option to also substitute the 1st car when possible (i.e., changing from strategy Car2 to Car2+). The rest is due to the optimization made possible by the full flexibility (Car2+ → Both/Both∗).

The leveling off of BEV distance with the range in Fig. 5a is depicted in Fig. 5b, which gives the average marginal annual electric distance, that is, the extra yearly BEV distance gained by an increase of the battery range for the different strategies. The annual marginal electric distance rapidly decreases with battery size for all the Car2 strategies due to the confined driving of the 2nd car, while the decreases are less rapid for the other strategies. This also means that the gained savings from any lower operational costs per km for the BEV decrease rapidly with range. With the assumptions made in Section 2.2.3, for instance, battery costs of $300/kWh, a marginal electric distance of 110 (km/yr)/km is needed to pay back any extra battery range. This gives an average maximum viable range of 70–90 km for any strategy if only considering the operational cost savings. Still, with battery cost as low as $100/kWh, the average maximum viable range varies between 80 and 165 km.

[7] A further increase of the charging rate also has a small economic impact, see Footnote 11 in Section 3.4.

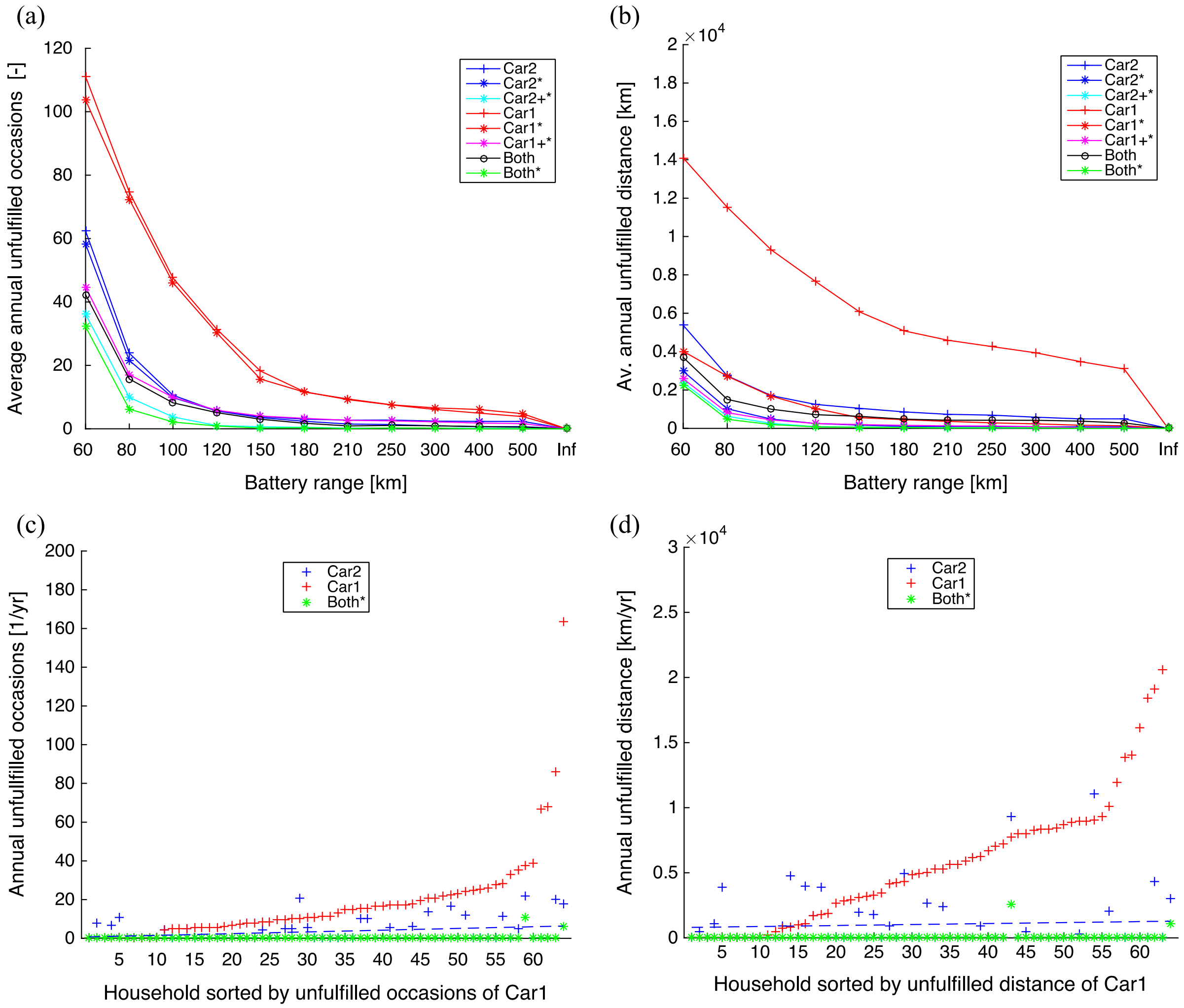

Fig. 6. As a function of battery range and at charging rate of 3 kW, (a) the average number of annual unfulfilled driving occasions (UFO); (b) the average unfulfilled distances (UFD). At a battery range of 150 km and a charging rate of 3 kW, for the strategies Car1, Car2 and Both*; (c) the number of annual unfulfilled driving occasions (UFO), sorted after UFO for the Car1 strategy; (d) the unfulfilled distances (UFD), sorted after UFD for the Car1 strategy. The linear regressions for Car2 strategy are given as dashed lines.

3.3. The unfulfilled household driving

The average annual unfulfilled driving for the 8 different, and in this respect non-redundant, strategies is shown in Fig. 6[8]. The number of yearly unfulfilled occasions (UFO) decreases rapidly with range. The Car1 strategy, replacing the 1st car only, stands out and gives the largest UFO, for instance, around once a week on average for a 100 km range. The UFO for Car2 strategy is considerably lower than for Car1 strategy or about half at the shortest range of 60 km, and much less than that at medium and longer ranges, for instance, 3.5 and 18 occasions per year, respectively, for 150 km range (at a charging rate of 3 kW). Also for the annual unfulfilled distance (UFD) Car1 strategy stands out with, on average, almost 10,000 and 6000 km/yr at 100 km and 150 km range, respectively, while Car2 strategy results in roughly 5 times shorter unfulfilled distances. Thus, letting a BEV replace the 1st car only gives longer BEV annual driving compared to the substitution of the 2nd car as shown in Fig. 5a, but simultaneously also considerably more unfulfilled driving, both when it comes to frequency and distance.

As also can be seen in Fig. 6b, the UFDs can be decreased considerably by using the conventional car for backup and thus to minimize the UFDs once the BEV driving is given (∗-strategies compared to the corresponding non-star ones), although the UFOs for these strategies are not decreased that much or not at all.[9]

[8] The Car1+ and Car2+ strategies do not differ from Car1 and Car2, respectively, and are not shown.

[9] When the conventional car is optimally used in the (∗) - strategies, it is used to minimize the unfulfilled distance, UFD, and not the number of unfulfilled occasions, UFO.

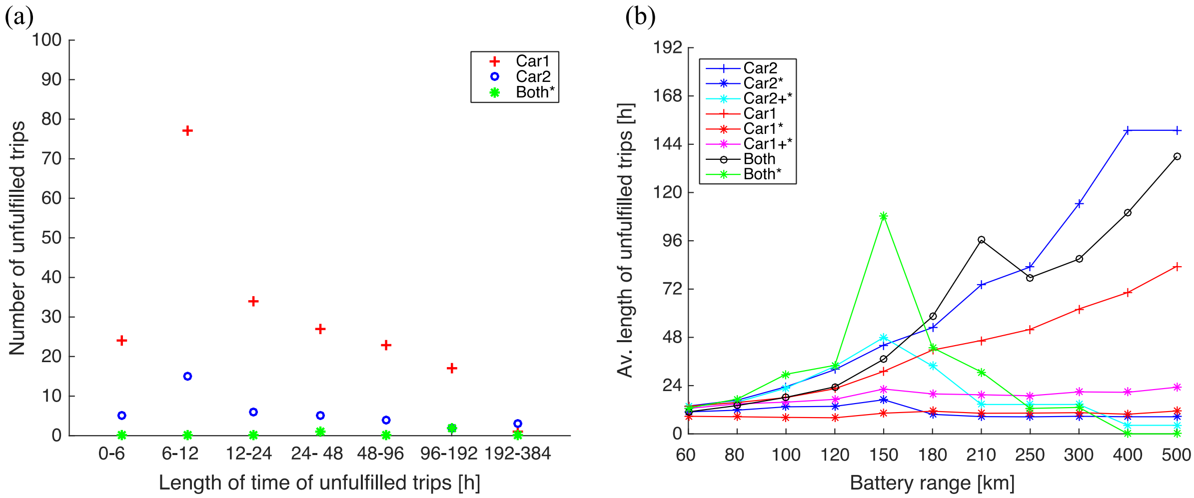

Fig. 7. (a) The distribution of unfulfilled hours (UFH) for the strategies Car1, Car2 and Both* at a battery range of 150 km and a charging rate of 3 kW during the analysis period. (b) The average trip time per unfulfilled occasion for different strategies at a charging rate of 3 kW.

Table 4
For the 64 logged two-car households, average TCO gain for the different strategies, relative to the mean of strategies Car1 and Car2. The assumed prerequisites are a charging rate of 3 kW, base case techno-economic parameters, and individually TCO-optimal battery ranges.

Strategy	BEV driving [km/yr]	TCO gain for driving [$/yr]	Battery range [km]	TCO gain for battery [$/yr]	UFO [yr^{-1}]	TCO gain for UFO [$/yr]	Total TCO gain [$/yr]	Present value of the TCO gain [$]
Car2	11,204	−209	105	160	4.3	160	111	737
Car2*	11,002	−225	99	221	4.9	128	123	820
Car2+	15,281	117	111	107	3.5	199	423	2816
Car2+*	14,493	54	91	301	1.1	319	673	4487
Car1	16,422	209	137	−160	10.7	−160	−111	−737
Car1*	16,065	180	124	−28	10	−139	13	87
Car1+	18,971	412	135	−135	11.0	−179	98	653
Car1+*	17,894	326	106	155	3.4	204	685	4565
Both	19,379	445	106	157	2.1	269	870	5800
Both*	18,679	389	95	262	0.25	361	1012	6741

However, even with a limited range, by using the possible flexibility in the two-car household wisely (strategy Both∗), the unfulfilled household driving can be minimized in the number of occasions as well as distance, while simultaneously increasing the BEV distance.[10] For ranges of 150 km and above, the average UFO and UFD are insignificant for this strategy of flexible BEV use. In the 150 km/3 kW case, for the Both∗ strategy 97% of the households has no UFO at all during the measurement period, compared to 16 and 66% for Car1 and Car2 strategies, respectively, see Fig. 7. And the average annual UFO and UFD are about ¼ and 60 km, respectively for the Both∗ strategy, which means that on average once every fourth year the driving in a household can't be fulfilled. Thus, when considering the fulfillment of the driving pattern only, with today's ranges of BEVs and a flexible use of the cars, the range limitation of a BEV substituting one of the cars in two-car households is, on average, not a major hurdle. We can also note that UFO of Car1 and Car2 are correlated among households ($R = 0.41$, $p = 0.009$), while for UFD there is no significant correlation, Fig. 7. But to the extent that it is the number of unfulfilled occasions where cost matters rather than the unfulfilled distances this UFO correlation is important.

The unfulfilled hth trips are of different lengths of time, see Fig. 7a, which shows the distribution of trip hours, or "unfulfilled hours" (UFH) (during the measurement period and for 150 km range and 3 kW charging rate). The UFHs for Car1 and Car2 strategies have roughly the same distribution, with a clear peak in occurrence for 6–12 h. 50% of the UFHs is below 12 h, while about 35% is one day (24 h) or above. For the Both∗ strategy all the three unfulfilled occasions last longer than one day. With increasing battery range the duration of the fewer unfulfilled trips left tends to increase (Fig. 7b), but for Both∗ and Car2+∗ strategies the very few occasions left for longer ranges can be kept short in duration.

[10] The not so wise BEV driving optimization strategy Both gives higher UFO and UFD.

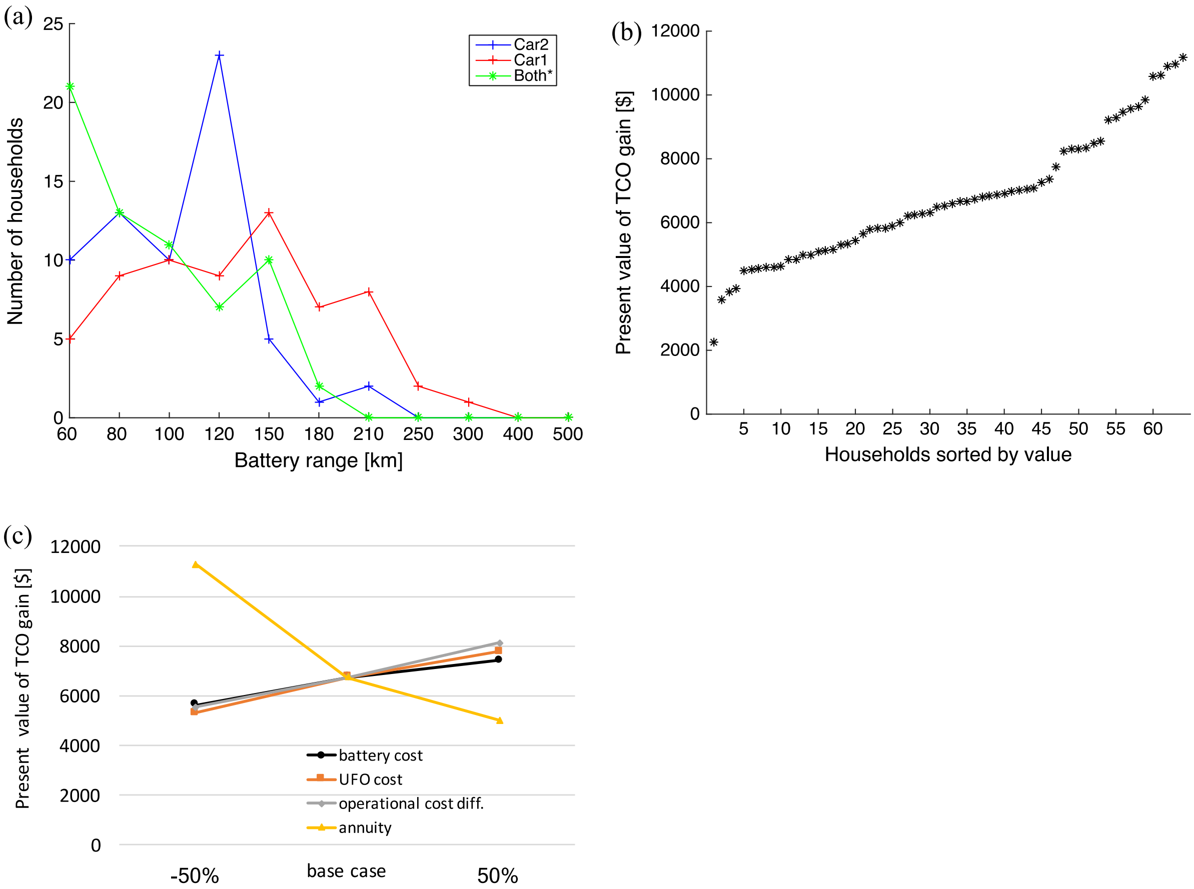

Fig. 8. (a) The optimal individual battery ranges for the three core strategies. Assumptions: a charging rate of 3 kW and individually optimal battery ranges; (b) The variation between households of the flexibility value (i.e., the present value of the difference in TCO gains between the two-car strategy Both* and the mean for the single-car strategies Car1 and Car2); (c) The sensitivity of the average flexibility value to changes in annuity and to the three factors contributing to the flexibility value.

3.4. The value of the two-car flexibility

The economics of BEVs depend on the applied strategy, the prevailing techno-economic conditions, BEV ranges, and charging options. The average economic performance of the different strategies relative to the mean for strategies Car1 and Car2 for assumed base case techno-economic parameters (Table 3) is shown in Table 4. The battery sizes are individually optimized for maximum TCO gain (Eq. (8)) for each household, while for simplicity a charging rate of 3 kW is assumed for all households and strategies.[11] Besides the battery size, the resulting BEV driving distance and unfulfilled occasions contribute to the differences in the annual TCO [$/yr]. Division of the annual gains by the annuity factor gives present values [$] of the differences (last column). For different strategies, the optimum values for each parameter vary considerably: optimal average BEV driving distances are between 11,000 and 19,400 km/yr, the battery ranges are between 95 and 137 km, and the UFOs are between once every fourth year to almost once a month. The distributions of the individually optimal battery ranges are depicted for the main strategies in Fig. 8a. While the strategy Car1 ranges are relatively evenly distributed up to 210 km, most of the strategy Car2 batteries have ranges ≤120 km. The Both∗ strategy stands out with relatively small battery ranges and none larger than 180 km.

The division of the households driving between the 1st and 2nd car is such that although the 2nd car has much less driving, the BEV TCO economics is on average better when replacing the 2nd car, due to the more confined driving making possible a smaller battery combined with fewer unfulfilled occasions. It has earlier been shown that for single-car households the BEV economics on average are in between that for the Car1 and Car2 strategies (Jakobsson et al., 2016a). Using this the present value of the confinement can be estimated as the difference in BEV TCO between strategy Car2 and the average for Car1 and Car2 strategies. This gives an estimated present value of the confinement to around $700.

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[11] Also, a further increase of the charging rate has a minor impact on the TCO gain, for instance, an increase from 3 to 4 kW gives an increase of the average annual TCO gain by $24, $9, and $10, for strategies Car1, Car 2, and Both∗, respectively.

Due to the different characteristics of the 1st and 2nd cars driving, various factors are of importance when replacing with a BEV. Comparing the different 1st car replacement strategies shows that the largest gains in TCO when replacing the 1st car are achieved through optimizing the use of the remaining CV and backup the many long trips missed by the range-limited BEV. The present value of the backup is on average around $2400 for the 1st car strategies, while the corresponding figure for the 2nd car is $900. Contrary, for the 2nd car replacement strategies better economics is mainly achieved by the extension option giving more BEV driving by the inclusion non-overlap driving from the 1st car. When utilizing both the backup and extension options roughly the same TCO is achieved whether the starting point is Car1 or Car2.

The flexibility strategy Both⁎ has the highest present value which is around $6000 higher than for Car2, with roughly 2/3 of this coming from the longer annual BEV distance made possible with the flexible strategy. An optimal smaller battery and the few unfulfilled occasions also contribute to the result. Compared to the other one-car strategy, Car1, the gain is even larger with a present value of around $7500 on average. However, this higher relative value now comes less from the increased driving, but from the smaller battery and much fewer unfulfilled occasions. Taking the present value of the flexibility as the average of these values gives a present value of around $6700, which is about 10 times larger than the confinement value estimated above. On a household level, it varies considerably or between $2000 and $11,000 (Fig. 8b).

The sensitivity of the average present value of the flexibility to the three economic factors determining the value as well as to the annuity is shown in Fig. 8c. Halving the battery cost to $150/kWh will decrease the present value by 16% due to the better options for single-car strategies to avoid their cost for their unfulfilled trips with a larger but still cheaper battery. Consequently, also a lower cost for unfulfilled trips disfavors the flexibility value. A lower operational cost difference will also relatively disfavor the flexible strategy due to its longer BEV distance driven. Finally, halving the annuity decreases the yearly relative gain for the flexible strategy, because the one-car strategies then gain more by the lowering the annual cost of the upfront investment. But the present value of the yearly differences also increases giving an overall greater advantage to the flexible strategy.

We can also note that the here assumed cost of $50 for an unfulfilled occasion ignores the length of time for the missed trip. As was seen in Fig. 7a, many unfulfilled trips last several days, which could involve extra costs. For instance, alternatively assuming an additional cost for unfulfilled trips, which adds $2/hour for every hour above 1 day (24 h) will increase the present value of the flexibility to on average $10,200 (range $2300–$23,000). However, most of the increase in the present value is due to worse TCOs for the single-car strategies and not to the flexibility strategy itself because of the so few unfilled occasions in the Both⁎ strategy.

3.5. The implications for the BEV viability

Although the TCO economics of a BEV will be improved considerably when utilizing the flexibility in the two-car household, the overall viability will also depend on how BEVs compare to the alternatives they replace. We compare to a conventional vehicle (CV) and a hybrid electric vehicle (HEV), according to Table 5. Argonne National Laboratory has in a simulation study sized various driveline technologies and estimated their current and future costs in large-scale production (100,000 + units/yr) (ANL, 2016). Using that study's estimate for mass production in 2020, (assigned as the lab costs in 2015 in the study), a midsize BEV without the battery can be estimated to be at least $2000 (inclusive of 50% markups) cheaper to produce than a CV in the near future. Similarly, compared to an HEV it is at least $5000 cheaper. The specific fuel use in energy terms is estimated to be three and two times higher for a CV and a HEV, respectively, than for a BEV.

Fig. 9a and b gives the resulting share of the investigated households reaching a lower TCO for a BEV compared to a CV and an HEV, for varying extra powertrain cost C_{PT} and specific battery cost c_B, respectively. The BEV viability is roughly the same in comparison to a CV and an HEV. The higher investment cost for an HEV is compensated for by its lower fuel costs. At the estimated differences in powertrain cost a BEV can viably compete with both a CV and an HEV in almost all the investigated households when applying the flexible strategy, compared to only around 50% for the Car2 strategy and even less, especially in comparison to an HEV, for Car1 strategy.

The flexibility enables, as expected, the two-car household to pay an amount equal to the flexibility present value more for a BEV when comparing to the one-car strategies (Fig. 9a). Expressed in battery costs, the flexibility value translates into a possible battery energy-specific cost 2–3 times larger for strategy Both⁎ compared to the one-car strategies to achieve the same share of two-car households with a lower BEV TCO (Fig. 9b).

4. Discussion

The results here confirm earlier studies of Khan and Kockelman (2012) and Jakobsson et al. (2016a) concluding that substituting 2nd car is on average more favorable both concerning unfulfilled driving and BEV TCO. They also confirm the importance of the flexibility in two-car households, the unfulfilled driving, and BEV economics pointed out by Tamor and Milačić (2015).

This analysis only estimates physical flexibility potentials for BEVs in two-car households, i.e., assuming the same car movement patterns in space and time and limitations due to the range and recharging without any adaptation or changes. When deploying a BEV, the movement patterns may change somewhat without any cost or inconvenience. For instance, by delaying the trip starts a few minutes on some occasions, it could be possible now to swap cars and thus get more BEV driv-

Table 5
Estimated cost and fuel use differences for a mass-produced BEV without battery compared to a conventional vehicle and hybrid electric vehicle in the near future. For the rest of the parameters, the base case (Table 3) is assumed.

	Conventional vehicle (CV)	Hybrid electric vehicle (HEV)
BEV Extra powertrain cost, C_{PT} [\$]	−2000	−5000
Specific fuel use, e_f [kWh/km]	0.6	0.4

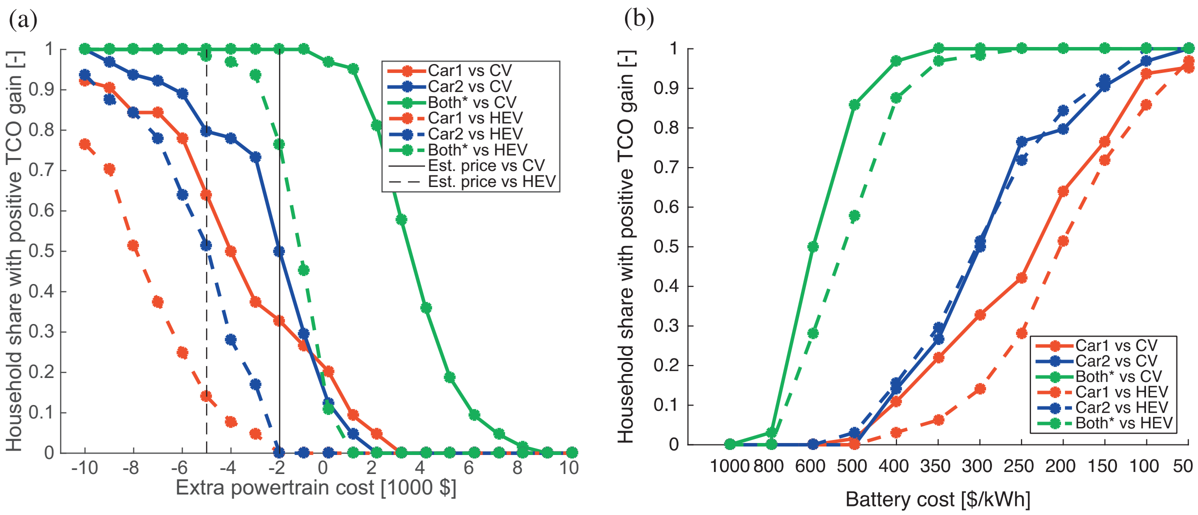

Fig. 9. For the 64 logged two-car households at a charging rate of 3 kW, for the strategies Car1, Car2 and Both*, the share of households with a lower minimum TCO compared to a CV and an HEV, respectively, (a) as a function of the extra powertrain cost C_{PT} at a battery specific cost of \$300/kWh; (b) as a function of the specific battery cost at an extra powertrain cost of-\$2000 and −\$5000 compared to a CV and an HEV, respectively.

Table 6
Current price differences in Sweden between two BEVs and the corresponding CV or HEV. Prices are announced prices [in SEK] at each brand's Swedish web page (volkswagen.se and hyundai.se, both accessed Nov 23, 2016).

BEV – CV alt HEV	Price difference [USD] ([SEK])	Price difference w/o battery at 500/300 USD/kWh [USD]	Estimated price difference w/o battery at mass production [USD]	Current Swedish BEV subsidy [USD]
VW: e-Golf (24 kWh) vs gasoline Golf 1.2 Bluemotion w aut. transm. (DSG)	22,500 (180,000)	10,500/15,300	−2000	5000
Hyundai Ionic ComfortEco: BEV (28 kWh) vs HEV	15,250 (122,000)	1250/6850	−5000	5000

ing or avoid unfulfilled driving. The lower operational cost of a BEV may also lead to a rebound effect resulting in more driving in the household (Stapleton et al., 2016).

The actual range of a BEV can vary with driving conditions, urban/rural, aggressiveness, climatic and road conditions, etc. The actual BEV range and the handling of it in single households are also of great importance in practice. Thus, the assumed different ranges could here be looked upon as the utilized ranges in a single household. This should not influence the results of the physical analysis as long as the ranges do not vary from trip to trip or over time. However, for the BEV economics, it is of great importance how the battery capacity is translated into actually utilized range. Franke and Krems (2013) suggested that users are comfortable with a utilization of around 80% of the available physical range.

In this analysis, charging is assumed to take place at home only. Possibilities for a household to recharge at, for instance, the workplace may influence the results considerably. Of importance may also be the charging options at often visited places with overnight stays such as vacation houses that are common in Sweden. It is reasonable to expect that such options will favor smaller batteries and/or more BEV driving. The possibilities for using BEVs for longer outside-the-range trips in the households are dependent on fast charging options, which, if in place, may favor larger batteries if it is perceived as a requirement for even considering longer trips with BEVs.

We saw that the cost for unfulfilled driving strongly influenced the BEV economics with the assumed cost for unfulfilled occasions. Between single households and between various situations, the perceived cost of unfulfilled driving can vary greatly, as can the alternatives available for possibly fulfilling the travel. Here it was based on half the extra costs for renting a car one day, which can be considered as a high-cost alternative. On the other hand, the willingness to pay upfront for the option to avoid any unfulfilled occasion can be considerable and will favor non-BEV powertrains. For instance, the BMW i3 with range extender is announced in Sweden at a price $4500 (36,000 SEK[12]) higher than the i3 without range extender and has taken a considerable share of the i3 market.

As already mentioned, there could be a lot of reasons for less flexibility in real households than the purely physical ones focused here. Any such inflexibility will contribute to the deviation from the here estimated movement-pattern-based flexibility potential and also reduce competitiveness against conventional and plug-in hybrids vehicles. What the actual utilization of the flexibility potential is and what adaptations are done in real households are questions for an on-going study, in which, including some of the households logged in this study, the actual EV substituting strategies are investigated (Jakobsson et al., 2016b). Whatever the results of this trial, it is also a learning process for multi-car households when BEVs introduce new factors into their car utilizations, such as the limitations in range and charging, and the increased difference in energy costs. How the households will incorporate these factors into their car utilization equations may very well change with time in a learning process at an individual, societal and technical level.

We show the viability of BEVs in two-car households compares to CVs and HEVs for prices (= production costs + 50% markups) estimated to be achieved in mass production. Note that, however, today BEVs are not marketed at these competitive prices yet. Table 6 gives two examples of midsize models, each with different powertrains but the same glider. The VW e-Golf BEV is currently priced $12,000–$17,000 (dependent on assumed battery price) more expensive than estimated near-future mass production would suggest. The newly launched Hyundai Ionic BEV is similarly $6000–$13,000 more expensive. For a mass market, these prices to customers have to come down. It has been argued that prices for new technologies can be hold up until increased production experience and competition lead to a "shakeout" period in which market prices fall faster than production cost (OECD/IEA, 2000).

5. Conclusions

Obstacles to a more widespread introduction of BEVs beyond early adopters are the effects of actual range, charging limitations, and expensive batteries. An important question is therefore where these effects can most effectively be mitigated. We investigate the value of the possible flexibility in two-car households.

Our analysis of the logged movement patterns of both cars in Swedish two-car commuting households shows that the flexibility introduced by the option to choose which vehicle to perform the household's driving makes possible more driving by BEVs and less unfulfilled driving in the household. This flexibility combines with a smaller BEV battery and results in a significantly better BEV economics compared to a car-for-car-only BEV substitution. We estimate the present value of this flexibility is on average around $6000–$7000 in Swedish two-car households, although it varies considerably between households. Because of the ubiquity of multi-car households in developed economies, these households could be a target for the initial efforts to enhance BEV adoptions in the car fleets beyond early adopters. The results of this research can inform the design and marketing of cheaper BEVs with small but enough range and contribute to increased knowledge and awareness of the suitability of BEVs in such households.

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Glossary

BEV: battery electric vehicle
CV: conventional (internal combustion engine) vehicle
HEV: hybrid electric vehicle
PEV: plug-in electric vehicle
GPS: global positioning system
TCO: total cost of ownership
UFO, UFD, UFH: unfulfilled occasions, distances, and hours, respectively
VKT: vehicle kilometers traveled