Circumventing limitations to transport energy efficiency – the electric car in two-car households

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Abstract
The electrification of vehicles may lead to considerably lower energy use in transportation due to the high energy efficiency of electric driveline. The deployment of electric cars is hampered by the limited range of current battery electric drivelines. Larger batteries are costly and require energy in production that counteracts the energy gains from the additional driving that is made possible. In multi-car households, the battery electric vehicle (BEV) may drive more while keeping the battery size down by utilising the options of replacing more than one car's driving and having a back-up for longer distances.

An optimisation model is developed to estimate the potential for a BEV, when replacing one of the conventional cars, to viably contribute to the accomplishment of the driving in two-car households. It uses data from 1 to 3 months of simultaneous GPS logging of the movement patterns for both cars in 64 commuting two-car Swedish households.

The results show that a flexible vehicle use strategy fully utilising the available options can considerably increase BEV driving, almost eliminating the driving not possible to fulfil due to the range and charge limitations. This flexibility combines with a smaller BEV battery and results in significantly better BEV economics compared to a car-for-car-only BEV substitution. We estimate the present value of this flexibility on average to around $6,000–7,000 in Swedish two-car households. The achieved fuel savings amounts to around 11 GJ/yr per household corresponding to a mitigation of around 770 kg CO_2/yr.

Introduction
Electric vehicles are one of the options to achieve less use of energy from fossil fuel and reduce the emissions of greenhouse gases (GHG) and other pollutants from transport, especially in countries or regions with a clean electricity production system. Mainly due to expensive batteries, most battery electric vehicles (BEVs) currently available have a limited range compared to conventional cars, and they also have the disadvantage of a relatively long charging time. Due to its comparably low operational costs but high fixed costs, the relative economic viability of the BEV is more advantageous with high annual driving, but this, in turn, tends to be aggravated by the range and charging limitations. These restrictions hamper the uptake in private households, who place high values on the option to occasionally drive longer trips, or shorter trips without necessary long stops in between. In Sweden so far (Oct 2016), only around 8,000 BEVs (≈0.2 % of the total car fleet) have been sold[1]. Most of them 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 a "fossil-independent" vehicle fleet by 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 related to options 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 journeys, such as vacation trips, the "second car" is used mainly for shorter trips such as daily commuting. Replacing this car with its more confined driving pattern with a limited-range

1. http://elbilsstatistik.se/ acc Nov 24, 2016.

BEV may lead to fewer unfulfilled driving occasions (UFO)[2], and thus suit the BEV better. Secondly, *extension*: the BEV can be used for fulfilling driving also of the other car in the household when the BEV is parked anyhow. Thirdly, *backup*: the other car, assumed to be a conventional internal combustion engine vehicle (ICEV), can be used as a back-up for unfulfilled driving, at least on those occasions when it happens not to be driving anyhow. Finally, *flexibility*: the BEV can be utilised flexibly such that the BEV is replacing both cars' driving as much as possible to maximise its driving and thus minimising the household's operational costs due to the lower fuel cost of the BEV, while still keeping down the unfulfilled driving with backup by the ICEV. This fourth option is thus an optimal combination of the first three.

Although multi-car households have for some time been identified as potential BEV buyers [Beggs and Cardell 1980, Calfee 1985, Kurani *et al.* 1996], it has been difficult to quantify these three factors, their value or implications directly. Detailed data for the driving patterns of multi-car households is seldom available. Market data for conventional cars does 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.

Recent studies of the current electrification also point in various directions. Javid and Nejat [2017], using US Travel Survey Data to identify plug-in electric vehicle (PEV) buyers, claim that the number of vehicles in the household has had no significant effect on the household's 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 uniquely high BEV share of around 15 % of new car sales, 79 % of the households having a BEV have more than one car compared to around 48 % for owners of only conventional vehicles. It is even higher when excluding the long-range and expensive Tesla Model S, which to a much larger share is owned by one-car households.

Many studies have investigated the physical 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 around a year to analyse the possibility for a BEV (160 km range) to replace the least-used car in multi-car households. They found that for 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 & Kullingsjö 2013]. They found that a BEV replacing the 2nd car only (i.e. the least-used 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 the BEV than when replacing the 1st car only. Similar results were observed in their parallel analysis of a larger dataset for one week's driving in German households, [Jakobsson et al. 2016a]. Both these studies mentioned above only replaced one of the household's cars and thus only investigated the confinement factor. Recently, though, Tamor and Milačić [2015] investigated the flexibility option using the same Seattle data as Khan and Kockelman by analysing the option of letting one BEV under its range limitation replace both/all cars in multi-vehicle households. They concluded that a BEV with a modest range (160 km) appears to be economically viable compared to a conventional car at costs that are likely to be achieved in the near future.

Although there is an apparent direct saving in propulsion energy when replacing a fuel-propelled car with a BEV due to much higher energy efficiency at the car level, i.e., "tank-to-wheel" (TTW), there have been worries that the BEV indirect energy use is high. Firstly, the well-to-tank (WTT) energy could be higher due to the lower energy conversion efficiency in an electricity supply system relying on fuel power plants. For instance, the resulting overall "well-to-wheel" (WTW) CO_2 emission could be higher for the BEV when the electricity is produced in a condensing power plant fueled by coal. On the other hand if supplied with renewable electricity the emissions will be zero. Thus the overall WTW energy and CO_2 savings for a BEV are very dependent on the configuration of electricity system. Secondly, the production of the BEV could require more energy to produce than the conventional car. There have been several life cycle inventory (LCI) studies of BEVs and comparisons of the production of the BEV with a conventional vehicle. Peters et al. [2017] recently performed a comprehensive review of BEV LCI studies and showed that a BEV has higher production energy requirements, which mainly is due to the BEV battery.

We have used 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 and to estimate the fuel substitution options made possible in two-car households.

Method and data

The overall outline of the study is depicted in Figure 1. We use car movement patterns data from simultaneous logging of both cars in Swedish commuting two-car households with GPS. The movement data is then used to estimate the potential BEV driving made possible by the flexibility in two-car households when a BEV with various ranges replaces one of the two conventional vehicles in the households assuming the car movement patterns are unchanged. The potential BEV driving is input to an estimate of the maximum possible TCO gains for the BEV under certain techno-economic conditions. Finally, the total energy savings and fuel substitution achieved with the potential BEV driving are estimated. In the energy savings estimate, we include the direct operational energy use (TTW) and the energy required for the production of the BEV battery.

MODELLING THE BEV DRIVING FOR THREE SUBSTITUTION STRATEGIES

An underlying prerequisite in this study is that the BEV has considerably lower operational cost than the conventional car and thus, rationally, should be the first option when driving.

2. With an unfulfilled driving occasion is here meant an occasion where a demand for one of the household's trips can not be accomplished due to range and/or charging limitations of the BEV and thus will require adaptation in some form or another.

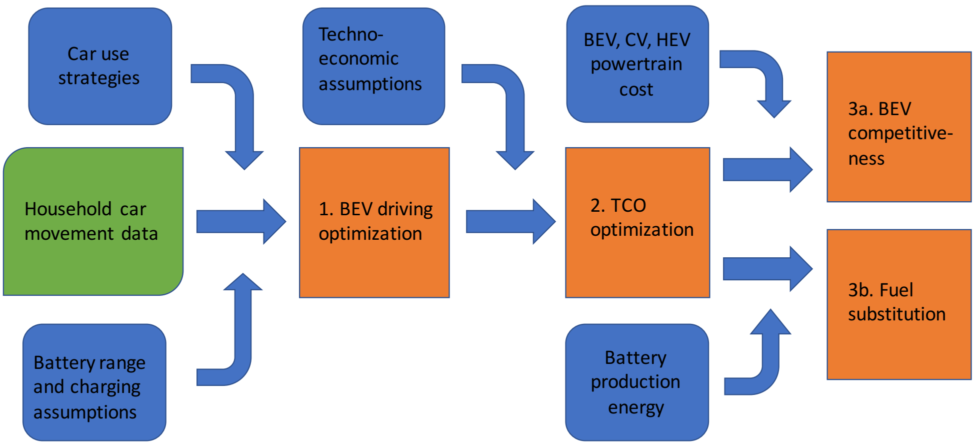

Figure 1. An outline of the method of this study with its three steps.

We estimate the BEV potential driving given by the household's logged driving and then 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 utilisation 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 pure habits evolved when using only fuel-propelled cars may inhibit the use of the cars for maximum BEV driving. Or simply, the household may not be motivated enough to put effort into maximising the BEV use.

A model was developed to calculate the potential for a BEV to maximise its driving in the households given the logged driving during the analysis period for three different car substitution strategies, Car1, Car2 and Both*. In Car1 and Car2, the BEV only replaces the driving of either the 1st or 2nd car, respectively. We define the 1st car as the car with the longest total driving distance during the analysis period.

Strategy Both* first maximises the BEV's driving by substituting the 1st or the 2nd car depending on their driving patterns and then utilise the ICEV to minimise the unfulfilled driving. The change between replacing the 1st or the 2nd car can take place at home only. But it also has the reasonably added condition that the maximisation of the 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 the BEV if and only if simultaneously some of the remaining trips are skipped. The BEV is allowed to choose this car's driving only if the gain in BEV driving distance is more than three times larger than the distance skipped. The factor 3 is somewhat arbitrarily chosen, though, but means that the implicit cost trade-off between cost savings for driving electric and cost added for unfulfilled driving is a factor of 3[3].

The BEV range is critical for the substitution possibilities. The ranges for most of currently available BEV models are in the interval 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 are now 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 that. For each strategy we investigate 11 battery sizes B of utilisable 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 the BEV, Table 1. The twelfth applied range, also denoted "Inf", is a range of 2,500 km assumed to mimic such a large ("infinite") battery that there is in practice no substitution restriction due to the range. We thus by this range get the upper theoretical physical potential for the BEV substitution options in two-car households.

The applied charging power is assumed to be 3 kW at the battery. This corresponds to the power currently potentially available in most Swedish households when including charging losses in, for example, the EVSE (Electric Vehicle Supply Equipment) and the onboard charger. For instance, 1*16 A/230 V can deliver a charging rate of 3 kW at the battery when the grid-

Table 1. The 12 different BEV capacities and ranges applied in the analysis.

Assumed levels of battery utilisable capacity [kWh]	Resulting BEV ranges [km]
12	60
16	80
20	100
24	120
30	150
36	180
42	210
50	250
50	300
80	400
100	500
500	2,500 ("Inf")

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

Table 2. 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 [$/kWh]	c_B	300
Battery capacity utilisation [–]	β	0.9
BEV extra powertrain cost [$]	C_{PT}	-2,000
Annuity [yr⁻¹]	α	0.15

to-battery losses are around 18 %. These losses are on par with the losses measured for charging of a BEV (Peugeot Ion) in Belgium [De Vroey *et al* 2013]. Charging with 1*16 A/230 V was also achieved in all 25 households in a Swedish ongoing BEV substitution project in two-car households.

THE TCO OPTIMISATION

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

$$\begin{aligned} \Delta TCO &= (p_f \cdot e_f - p_e \cdot e_e) \cdot annVKT_{BEV} \\ &- \sum_u^{N_{UF}} (C_{UF} + c_{UF} \cdot d_u) \\ &- \alpha \cdot (c_B \cdot R \cdot e_e/\beta + C_{PT}) \end{aligned} \qquad (1)$$

The assumed values of techno-economic parameters are summarised in Table 2. The household variables, the BEV annual kilometres travelled $annVKT_{BEV}$ [km], the number of yearly unfulfilled home-to-home trips N_{UF} [-] and their corresponding distances d_u [km] [u=1, N_{UF}] are taken from the optimisation extrapolated to a full year. The BEV is assumed to be three times more energy-efficient than the ICEV[4], and the price of electricity equal to that of fuel, which could be reasonable for energy at the household level in Sweden [IEA]. Thus, for each kilometre driven by the BEV the operational costs savings, $p_f \times e_f - p_e \times e_e$, 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 ones as public transport, car borrowing, or simply abstaining from the travel. The fixed cost C_{UF} is here set equal to half of the cost of renting a midsized car for 24 hours over a workday, and the extra operational costs c_{UF} is equal to 0, i.e., no extra cost above the conventional car.[5] The extra investment cost of the BEV relative to the ICEV is divided into the battery cost, which is proportional to the battery range R [km], and the extra powertrain cost C_{PT}. The annuity of 0.15 corresponds to, for instance, eight years of depreciation with a discount rate of 5 %.

The present value PV of the flexibility in the two-car household is estimated as the difference in the present values of the annual TCO gains for the flexibility strategy Both* and the average of the car-for-car substitution strategies, Car1 and Car2.

$$PV = \Delta TCO/\alpha \qquad (2)$$

THE FUEL REPLACEMENT

Fuel is replaced in the car use and battery production. For the car use we assume (Section 2.2.) 1 kWh electricity to the BEV substitute 3 kWh of fuel use for the ICEV. The review in Peters et al. [2017] discusses among other things various LCI estimates of the energy input required in BEV battery production. The required energy can vary with the assumed chemistry in the Li-ion batteries; different raw materials require different amounts of energy to produce, and the battery specific energy varies between the chemistries. The estimated production energy also varies with the method used in the analysis. Top-down analyses generally have given higher values for the energy input (roughly a factor 2 larger) than process-based, bottom-up analyses [Peters et al. 2017]. This difference can be due to such as different assumptions on scale and production capacity utilisation, energy partitioning on product mixes, or a more thorough inclusion of various contributing factors in the top-down approach. The average value for used chemistries in current BEVs is around 1 GJ (≈278 kWh) per kWh of battery storage capacity but varies between 0.6 and 2.1 GJ for the top-down analyses and 0.2 to 1.6 for bottom-up studies [Peters et al. 2017]. Detailed process data presented by Notter et al. [2010] shows that the overwhelming part of the energy input is in the form of fuel (oil, natural gas) and much less so of electricity. In this study we assume a value of 300 kWh per kWh in the form of fuel and no electricity for the battery production, and thus for the difference in energy input in the manufacturing of a BEV and an ICEV, respectively.

THE CAR MOVEMENT PATTERNS 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 vehicles in two-car households with conventional cars. Households from within 13 Swedish municipalities around and including Gothenburg were randomly drawn from the Swedish vehicle register. Since to

4. Assuming 0.6 kWh/km for the ICEV in real driving corresponds to 6.6 litre 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 WV Golf is $99 (SEK 790) a day plus fuel. www.avis.se. acc Nov 28, 2016.

the extent possible we also targeted 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.

Of the around 331,000 private cars in the targeted region 48 % belong to multi-car households and 33 % are in 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 ≥2 actively used driving licenses,
- 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 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 to 2.5 months, Figure 2a. Good 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.

Results

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 kilometres travelled (VKT) are shown in Figure 2b. This total driving varies by almost a factor of four between about 16,000 and 60,000 km/yr with an average of 33,453 km/yr. By definition the 1st car always drives further than the 2nd car. However, the relative driving of the two cars 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.

THE POTENTIAL BEV DRIVING

Of course, the potential BEV driving varies with the specific situations in each household. However, we will mainly focus here on the fleet average results, though. Figure 3a gives the fleet average potential BEV driving for the six different non-redundant strategies for the BEV driving.

The often discussed strategy of letting the BEV replace the 2nd car only (strategy 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. Replacing the 1st car only (strategy Car1) results in a potential BEV driving increasing steadily 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 relative 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 strategy, respectively. For short ranges (60–80 km) there is almost no difference in BEV driving between substituting 1st or 2nd car, though. For a flexibility in the choice of which car to replace (strategy Both*), the BEV distance is further maximised. For medium battery ranges

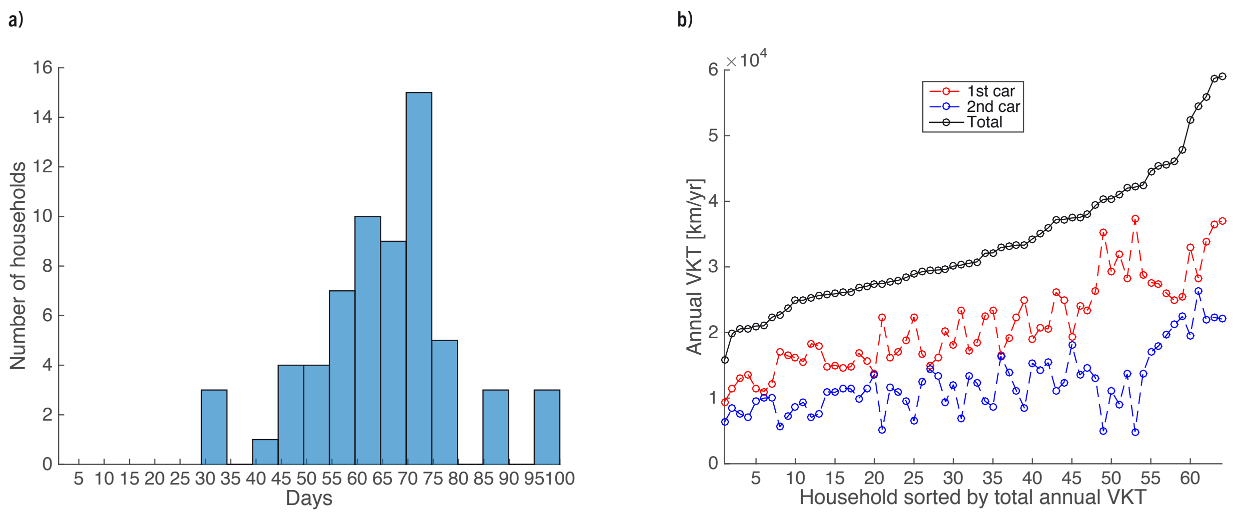

Figure 2. For the 64 logged two-car households, a) the length of the analysis period; b) the distances driven during the analysis period linearly extrapolated to one year's driving sorted by the total annual distance.

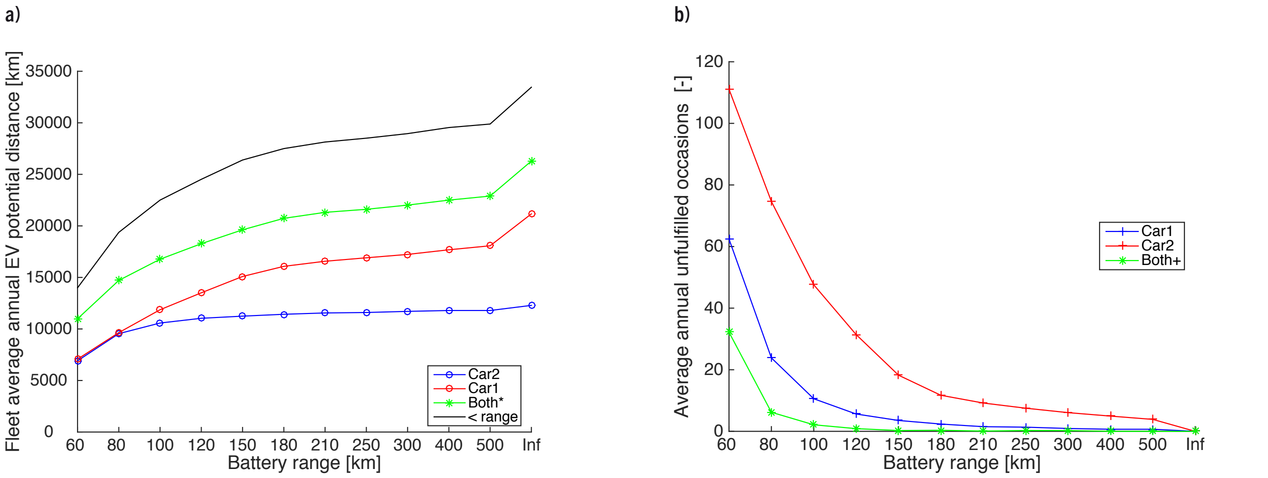

Figure 3. For the 64 logged two-car households, as a function of battery range and charging rate (equal-coloured lines), the BEV average potential distances for the three different BEV usage strategies. The household annual VKT less than the range is also given; b) the average number of annual unfulfilled driving occasions (UFO).

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* compared to Car2). For ranges of between 100 to 180 km, the potential BEV distance is between 17,000 and over 20,000 km/yr. In the flexible strategies (Both*), the BEV can accomplish 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*) the potential BEV driving is increased between 55 and 95 %.

The number of average annual unfulfilled occasions (UFO) is shown in Figure 3b. They decrease rapidly with range. The Car1 strategy, replacing 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 is considerably lower than for Car1 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). Thus, letting the BEV replaces the 1st car only gives longer BEV annual driving compared to the substitution of the 2nd car as shown in Figure 3a, but simultaneously also considerably more unfulfilled driving. Even with a limited range, by using the possible flexibility in the two-car household (strategy Both*), the unfulfilled driving can be minimised in the number of occasions, while simultaneously increasing the BEV distance. For ranges of 150 km and above, the average UFO is insignificant for this strategy of flexible BEV use. For the 150 km range and 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, respectively. And the average annual UFO is about ¼ 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 fulfilment of the driving pattern only, with today's ranges of BEVs and a flexible use of the cars, the range limitation of the BEV substituting one of the cars in two-car households is, on average, not a major hurdle.

THE VALUE OF THE TWO-CAR FLEXIBILITY

The economics of BEV depend on the applied strategy, the prevailing techno-economic conditions, BEV ranges, and charging options. The average economic performance of the different strategies compared to the average of the car-for-car strategies Car1 and Car2 (hereafter denoted Aver(1,2)) for assumed base case techno-economic parameters (Table 2) is shown in Table 3. The battery sizes are individually optimised for maximum TCO gain (Eq 1) for each household, while for simplicity a charging rate of 3 kW is assumed for all households and strategies. 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 drivings 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 different strategies in Figure 4. While the Car1 ranges are relatively evenly distributed up to 210 km, most of the 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 Car2 and Aver(1,2) or to around $700. The Both* strategy has a present value around $6,000 higher than Car2, with roughly ⅔ 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

Table 3. For the 64 logged two-car households, the average TCO gain for the different strategies in comparison to the average of strategy Car1 and Car2 (Aver(1,2)). The assumed prerequisites are: 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 ($)
Aver (1,2)	13813	0	121	0	7.5	0	0	0
Car2	11204	-209	105	160	4.3	160	111	737
Car1	16 422	209	137	-160	10.7	-160	-111	-737
Both*	18 679	389	95	262	0.25	361	1012	6747

strategy, Car1, the gain is even larger with a present value of around $7,500 on average. However, this relative higher 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 two values results in a present value of around $6,750, which is about ten times larger than the confinement value estimated above. On a household level, it varies considerably or between $2,000 and $11,000, Figure 5a.

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 Figure 5b. 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 disfavours the flexibility value. A lower operational cost difference will also relatively disfavour 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.

THE IMPLICATIONS FOR THE BEV VIABILITY, ENERGY SAVINGS AND FUEL REPLACEMENT

Although the total cost of ownership (TCO) of the BEV will be considerably helped when utilising the flexibility in the two-car household, the overall viability will also depend on how the BEV compares to the alternative it replaces. We are comparing it to a conventional vehicle, an ICEV. 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), a midsize BEV without the battery can be estimated to be at least $2,000 (inclusive of 50 % markups) cheaper to produce than an ICEV in the near future. The specific fuel use in energy terms is estimated to be three times larger for the ICEV than for the BEV, Table 2.

Figures 6a and b give the resulting share of the investigated households reaching a lower TCO for the BEV compared to an ICEV, for varying extra powertrain cost C_{PT} and specific battery cost c_B, respectively. The BEV viability is roughly the same in comparison to an ICEV. At the estimated differences

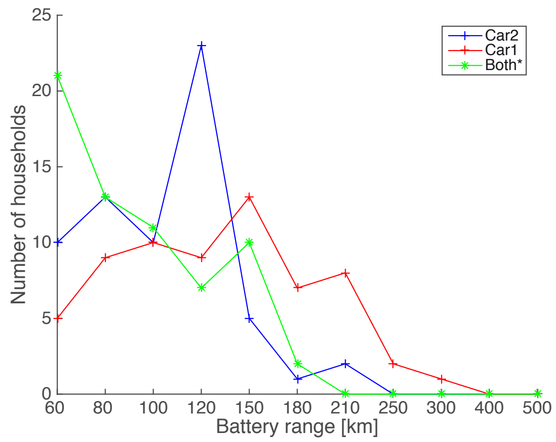

Figure 4. The optimal individual battery ranges for the three strategies.

in powertrain cost the BEV can viably compete with both the ICEV in almost all the investigated households when applying the flexible strategy, compared to only around 50 % for the Car2 strategy and even less for Car1.

The flexibility enables, as expected, the two-car household to pay an amount equal to the flexibility present value more for the BEV when comparing to the one-car strategies, Figure 6a. Expressed in battery costs, the flexibility value translates into a possible battery energy-specific cost 2–3 times larger for Both* compared to the one-car strategies to achieve the same share of two-car households with a lower BEV TCO, Figure 6b. Under the condition investigated here, the flexibility in the two-car household thus can make the more energy efficient BEV a universally viable alternative compared to the ICEV.

Figure 7a shows the achieved energy savings in the individual households. The total energy savings (av.: 2,168 kWh/yr) are comprised mainly of the operational energy savings, where according to the assumed specific energy use, for every unit of electricity three units of fuel are saved. Although a major share of the energy savings comes from the operational energy saved due to the increased BEV driving in the flexible strategy, in most households energy is also saved by the smaller battery made possible in the flexible strategy (av.: 217 kWh/yr), which sums up to one/tenth of the total energy saved. The amount of replaced fuel (av.: 3,137 kWh/yr or around 11 GJ/yr) is also in most households larger than the total energy saved.

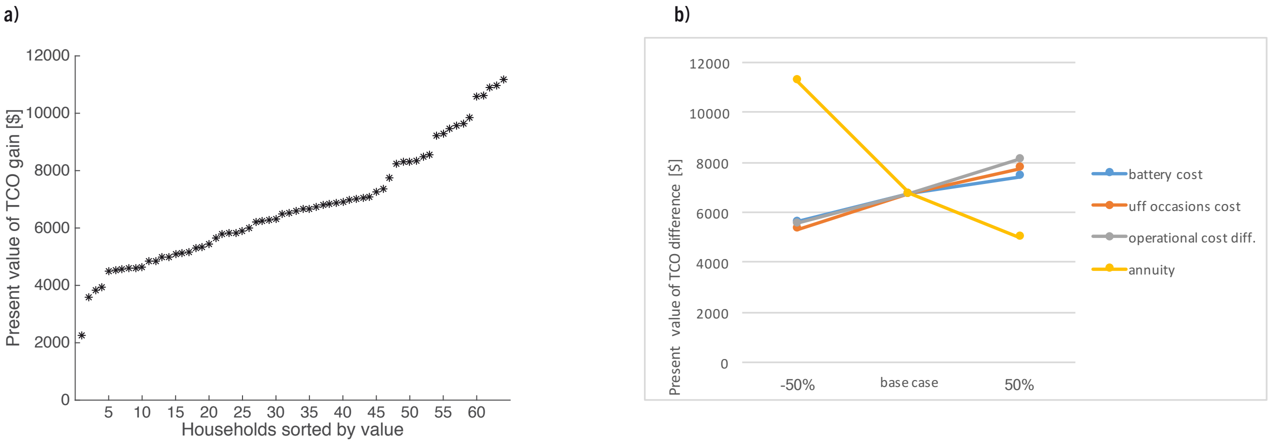

Figure 5. a) The variation between household of the flexibility value (i.e., the present value of the difference in TCO gains between the two-car strategy Both and Aver(1,2)); a) the share of households with a lower minimum TCO compared to an ICEV, b) The sensitivity of the average flexibility value to changes in annuity and to the three factors contributing to the flexibility value.*

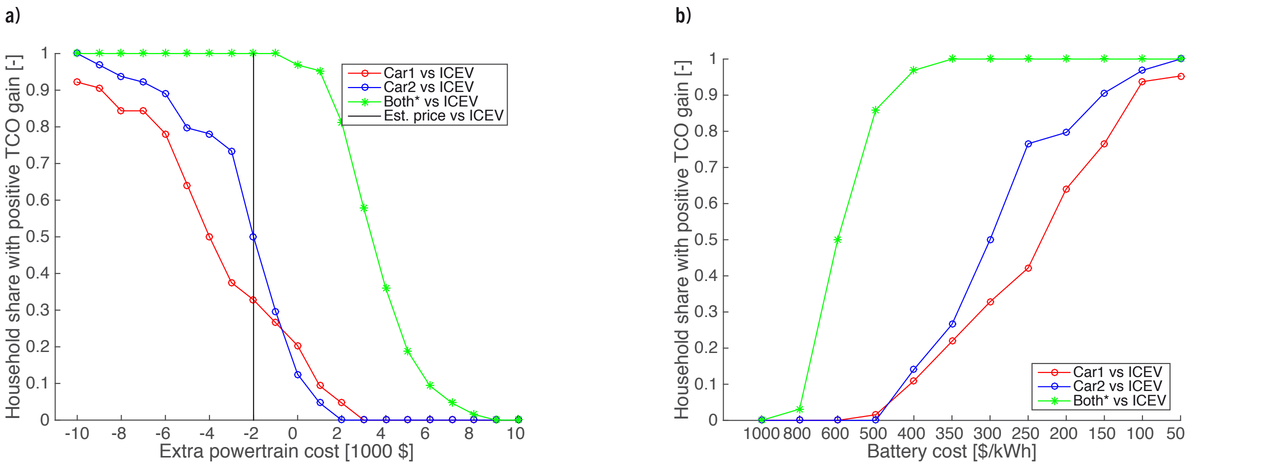

Figure 6. For the 64 logged two-car households, for the strategies Car1, Car2 and Both, a) as function of the extra powertrain cost C_{PT} at a battery specific cost of \$300/kWh; b) as function of the specific battery cost at an extra powertrain cost C_{PT} of -\$2,000 relative to an ICEV.*

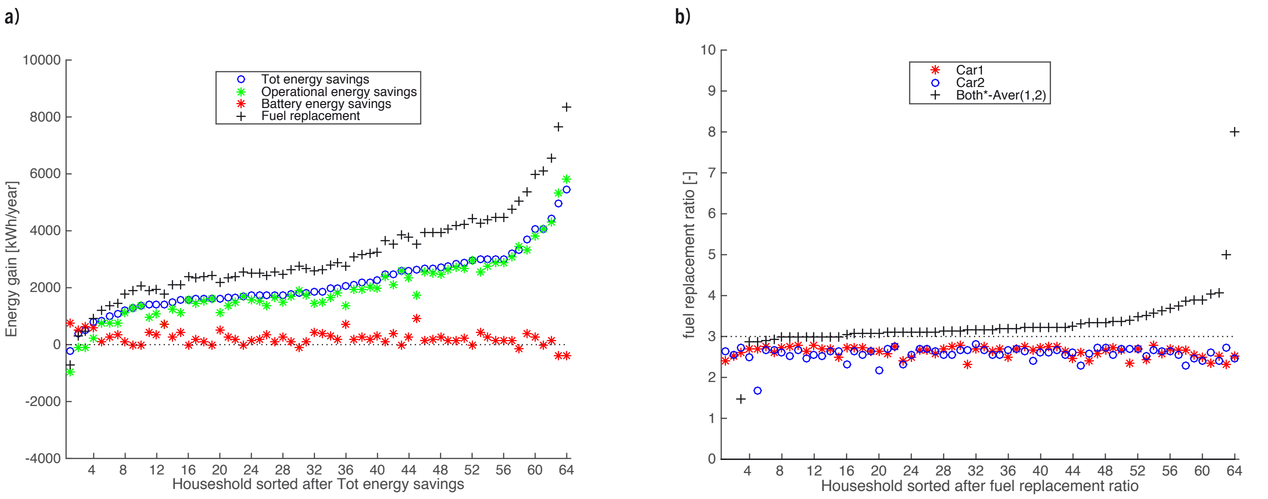

Figure 7. a) The household annual energy savings; b) The fuel replacement factor for strategies Car1, Car2, and the flexibility strategy Both minus Aver(1,2).*

The electrification can, according to the assumptions, replace fuel at a rate of three to one in the direct operational energy use. Adding the fuel used in the battery production will lower the replacement ratio below 3. Figure 7b gives the fuel replacement ratio for the individual households at minimum TCO for the BEV for the two one-car substitution strategies. The average ratios are 2.63 and 2.57 for Car 1 and Car 2, respectively. Car1 gives on average a relatively longer driving distance per range of the battery, see Table 3, which leads to a higher ratio for Car1. (The much higher number of unfulfilled occasions (UFO) gives a less favourable economy, though, as noted earlier.)

Figure 7b also depicts the replacement ratio for the flexibility; the difference between Both* and Aver(1,2). The additional operational fuel substitution in Both* is achieved with a smaller battery, which results in a marginal fuel replacement larger than 3. Some individual values are relatively high when the increase in BEV driving distance is small. The values for the first two households are below zero due to lower BEV driving in Both* compared to Aver(1,2), but the much smaller battery still contributes to a positive fuel saving. Thus, in these cases, a positive fuel replacement is achieved together with a saving in electricity for driving.

Discussion

Concerning the economics, the results here confirm earlier studies of Khan & Kuckelman [2012] and Jakobsson *et al.* [2016a] concluding that substituting the 2nd car is, on average, more favourable both concerning unfulfilled driving and TCO. They also confirm the importance of the potential flexibility in two-car households, the unfulfilled driving, and BEV economics pointed out by Tamor and Milačić [2015].

The households' average fuel savings of around 11 GJ/yr correspond to, if fossil fuel, a mitigation of around 770 kg/CO_2/yr. In Sweden where future added electricity production capacity can be assumed to be carbon neutral this decreased emissions from fuel use can be a net emission saving.

This analysis only estimates pure 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. The movement patterns may change somewhat when deploying a BEV without any particular cost or inconvenience. For instance, by delaying a trip a few minutes in some occasions it could be possible to now swap cars and thus get more BEV driving or avoid unfulfilled driving. The lower operational cost of the 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 the single households are also of great importance in practice. Thus the here assumed different ranges could be seen as the utilised 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 expensive battery capacity is translated into utilised range. Franke and Krems [2013] suggest that users are comfortable with a utilisation of around 80% of the available physical range.

In this analysis, charging has been 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 favour smaller batteries and/or more BEV driving. The possibilities for using the BEV for longer outside-the-range trips are dependent on fast charging options, which, if in place, may favour larger batteries if it is perceived as a requirement for even considering longer trips with BEVs.

We saw that the cost for unfulfilled driving influenced the BEV economics heavily with the assumed cost for unfulfilled occasions. Between single households and between various situations, the perceived cost of unfulfilled driving can vary widely, as can the alternatives available for possibly fulfilling the travel. Here it was based on half of 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 favour non-BEV powertrains. For instance, the BMW i3 with range extender is currently marketed in Sweden at a price $4,500 (SEK 36,000[6]) 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 utilisation 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 BEV 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 and operational costs. How the households will incorporate these factors into their car utilisation equations may very well change with time in a learning process at an individual, societal and technical level.

Conclusions

Obstacles to a more widespread introduction of energy efficient cars in the form 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 investigated the value of the option of flexible usage of a BEV in two-car households and the possible resulting fuel savings.

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 with which vehicle to perform the household's driving makes possible more driving using BEVs and less unfulfilled driving in the household. This

6. Announced at the brand's Swedish webpage: bmw.se, acc. Nov 23, 2016.

flexibility combines with a smaller BEV battery and results in significantly better BEV economics compared to a car-for-car-only BEV substitution. We estimate the present value of this flexibility, on average, to around \$6,000–7,000 in a Swedish two-car households, although it varies considerably between households. The possible fuel savings amount to around 11 GJ/yr per household corresponding to a mitigation of around 770 kg CO_2/yr, which in Sweden with a future CO_2-neutral electricity production capacity addition could be a net saving. Because of the ubiquity of multi-car households in developed economies, these households should be a focus target for the initial efforts to enhance BEV prevalence in the car fleets beyond early adopters. The results of this study can inform the design and marketing for cheaper BEV with smaller but enough range and be used in information campaigns aimed at increasing knowledge and awareness of the suitability of BEVs in these households.

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