Transportation Research Part C 85 (2017) 363–376

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Electrification of the two-car household: PHEV or BEV?

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ARTICLE INFO

Keywords:
PHEV
BEV
Two-car household
TCO
EDF

ABSTRACT

In previous works, we have shown two-car households to be better suited than one-car households for leveraging the potential benefits of the battery electric vehicle (BEV), both when the BEV simply replaces the second car and when it is used optimally in combination with a conventional car to overcome the BEV's range limitation and increase its utilization. Based on a set of GPS-measured car movement data from 64 two-car households in Sweden, we here assess the potential electric driving of a plug-in hybrid electric vehicle (PHEV) in a two-car household and compare the resulting economic viability and potential fuel substitution to that of a BEV.

Using estimates of near-term mass production costs, our results suggest that, for Swedish two-car households, the PHEV in general should have a higher total cost of ownership than the BEV, provided the use of the BEV is optimized. However, the PHEV will increasingly be favored if, for example, drivers cannot or do not want to optimize usage. In addition, the PHEV and the BEV are not perfect substitutes. The PHEV may be favored if drivers require that the vehicle be able to satisfy all driving needs (i.e., if drivers don't accept the range and charge-time restrictions of the BEV) or if drivers requires an even larger battery in the BEV to counter range anxiety.

We find that, given a particular usage strategy, the electric drive fraction (EDF) of the vehicle fleet is less dependent on whether PHEVs or BEVs are used to replace one of the conventional cars in two-car households. Instead, the EDF depends more on the usage strategy, i.e., on whether the PHEV/BEV is used to replace the conventional car with the higher annual mileage ("the first car"), the less used car ("the second car"), or is used flexibly to substitute for either in order to optimize use. For example, from a fuel replacement perspective it is often better to replace the first car with a PHEV than to replace the second with a BEV.

1. Introduction

Battery electric vehicles (BEV) have the potential to reduce greenhouse gas emissions, local pollutants, and energy security concerns. However, high initial costs are hampering their introduction. These costs might be compensated for by the lower operational energy costs due to the higher energy conversion efficiency compared to the conventional fuel-propelled car. This gain will increase with more electric driving, which in turn may be hindered by BEVs range and charge limitations. In this perspective, two-car (or generally multi-car) households have been discussed as potential early adopters with the ability to more viably replace one of the two conventional cars with a BEV. The household car with the lower annual mileage has, on average, also fewer days of long-distance driving compared to the average car, and can therefore still drive a considerable annual distance with a smaller and cheaper battery, which is favorable in BEV adoption (Jakobsson et al., 2016). More important, though, is the flexibility that a two-car household makes possible. Utilization of the BEV can be increased if the BEV is used to offset as much as possible of the driving of both cars,

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http://dx.doi.org/10.1016/j.trc.2017.09.021
Received 23 March 2017; Received in revised form 22 September 2017; Accepted 22 September 2017

while its range limitation can be mitigated if the remaining conventional car takes on the household's long-range driving (Karlsson, 2017).

However, the BEV is not the only alternative for electrification of passenger cars. A plug-in hybrid electric vehicle (PHEV) has the potential to replace a substantial share of the fuel used with electricity and thus also lower the operational energy cost, without compromising the range of the vehicle (Björnsson and Karlsson, 2015). Since a PHEV does not suffer from range limitation, it can be fitted with a smaller battery that is well suited for the user's specific driving needs. This increases the possibility of reaching high battery-utilization rates, contributing to a lower total cost of ownership (TCO). However, the extra powertrain cost for the fuel engine can be substantial. A BEV only has an electrical drivetrain but is often equipped with a larger and more expensive battery to be able to manage the rare long-distance trips. Thus, both PHEVs and BEVs have relatively high investment costs. These higher investment costs can potentially be paid for by future lowered operational costs, the magnitude of which will depend on the battery range and the actual usage of the vehicle in individual households.

We used data from the simultaneous GPS logs of the movements of both cars in 64 two-car households in Sweden to compare the resulting electric drive fraction and the total cost of ownership for PHEVs and BEVs in two-car households for three different strategies for replacing one of the two conventional cars with a PHEV/BEV. This comparison promotes a better understanding of how an efficient and economically viable electrification of two-car households can be achieved, with either PHEVs or BEVs.

Vehicle technology assessment studies focusing specifically on two-car households are not prevalent. Jakobsson et al. (2016) compared measured and surveyed driving data from Sweden and Germany to show that the second car, defined as the car with the shorter annual distance traveled, in general has a more confined movement pattern with fewer long-distance driving days. They therefore concluded that the second car is better suited than the first car to be replaced by a BEV (Jakobsson et al., 2016). A study by Tamor and Milačić (2015) based on GPS logs from Seattle also showed opportunities for BEVs to more easily fit the two-car, than the one-car, household. Karlsson (2017) used the above-mentioned data set of GPS logs from 64 Swedish two-car households to assess the value, for a BEV, of the flexibility in two-car households. The study shows that it is possible for the two-car household to increase the annual driving of the BEV and at the same time reduce the number of unfulfilled trips as well as the battery range, relative to the needs in a one-for-one replacement of individual vehicles (Karlsson, 2017). The above studies all suggest that, on average, the potential benefit of a BEV is greater in a two-car household than in a one-car household.

However, the possibility that a PHEV in a two-car household could be an even better solution, financially, has not been scrutinized in much detail. Using the GPS logs from Seattle, Khan and Kockelman (2012) analyzed the potential for fuel replacement and the economic viability of electrified vehicles, and compared the results for PHEVs and BEVs, but the economic analysis is relatively brief and does not, for example, take into account the inter-day driving variation available in their data set. Tamor et al. (2013) assessed battery ranges for PHEVs and BEVs to find optimal range for the fleet. Their work included an assessment of the economic viability and the resulting electric driving in multi-car households for BEVs and PHEVs. They concluded that in many households a PHEV is a far more plausible direct replacement for a conventional vehicle than a BEV, with the potential to reduce household fuel use considerably. However, the analysis was done on a dataset that only included one of the household's vehicles, and they concluded that there is a need to analyze usage data from all vehicles in multi-car households to better quantify the potential for switching cars within households. In addition, their economic analysis only considered the cost difference due to battery size between a PHEV and a BEV (making a BEV more expensive than a PHEV), even though the extra cost for a PHEV's fuel powertrain could be considerable (Moawad et al., 2016). As far as we know, no study has analyzed the potential value (for the user) of the flexibility that a two-car household makes possible when driving a PHEV or compared a PHEV's potential fuel substitution and economic viability to that of a BEV when the battery ranges of the two vehicle types are optimized for the household, and especially not for Swedish conditions.

The current study is an extension of the work in Karlsson (2017), which exclusively addressed BEVs. Using the same data set, we model the potential electric driving of PHEVs in individual two-car households, and we can then compare the total cost of ownership (TCO) savings and fuel substitution when replacing a conventional car with a PHEV or a BEV in the studied two-car households. We address the following questions:

- Which yields the lower TCO for two-car households, replacing one of the conventional cars with a PHEV or replacing it with a BEV?
- How does the households' resulting electric drive fraction (EDF) vary depending on whether a PHEV or a BEV replaces one of the conventional cars?

2. Methods and data

An optimization model is developed to estimate the potential electric driving for a PHEV/BEV in a two-car household for different battery sizes and car usage strategies. The resulting electric mileage, and, for the BEV, also the unfulfilled household driving (i.e., driving that cannot be accomplished due to the range and charging limitations of the BEV), is then used to assign to each household a PHEV/BEV with a cost-optimal battery and to calculate the households' TCO and electric drive fraction for each vehicle usage strategy. Thus, all in all, each household is assigned six optimal battery ranges corresponding to three usage strategies for each of the two vehicle types.

2.1. Vehicle models

The PHEV traction battery is assumed to be able to deliver the power needed to propel the vehicle in a pure charge-depleting (CD) mode until its utilizable energy is consumed, and the driveline turns into the charge-sustaining (CS) hybrid mode. The specific energy use is assumed to be e_e (electricity) and e_f (fuel) [kWh/km] in CD and CS mode, respectively. The PHEV all-electric range *AER* [km] is the maximum possible distance driven in CD mode, and the battery is assumed to maintain its properties throughout the car's economic lifetime. Correspondingly, the energy use of the BEV is assumed to be characterized by the same specific energy use e_e.

A "conventional" vehicle (CV) is somewhat difficult to define since a wide variety of models are successfully marketed and sold, ranging from cars with no specific energy efficiency facilities, to simple stop/start systems, to different variants of hybrids. Here we assume the CV to be a fuel-efficient full hybrid (HEV) with the same energy use e_f as the PHEV in CS mode. In this model formulation, a certain distance covered by electric driving always corresponds to a specific amount of fuel saved.

2.2. The potential for a PHEV/BEV to replace one of the cars in a two-car household

An underlying premise in this study is that the PHEV/BEV has a considerably lower operational cost (the PHEV only when in CD mode) than the CV and thus rationally should be the first option when driving. We estimate the potential PHEV/BEV driving given by the household's logged driving and then take into account, in addition to the PHEV/BEV range and the charging location and rate, only the physical limitation implied by the movement patterns of the cars. In reality, there could be other factors that limit the actual utilization of a PHEV/BEV. Some driving may require specific equipment possibly only available in the CV, such as a child seat. The CV may be preferred for some of the driving for safety, reliability or capacity reasons. Psychological factors such as "my car and your car" and habits developed when using only fuel-propelled cars may inhibit the use of the cars for maximum PHEV/BEV driving. Or, the household may simply not be sufficiently motivated to put effort into maximizing the PHEV/BEV use. Thus, a two-car household replacing one of its conventional cars with a PHEV/BEV may in practice let the PHEV/BEV substitute for one or both of the cars' driving to varying degrees.

2.3. Usage strategies

For each individual household in the data set, we examine the electric driving resulting from three different PHEV/BEV usage "strategies," **Car1**, **Car2**, and **Both**:

- **Car1:** the PHEV/BEV is used to fulfill the first car's driving and none of second car's, where the "first car" is defined as the vehicle with the greater logged mileage during the analysis period, and the "second car" is the one with the lesser. The CV is used to fulfill the second car's driving only.
- **Car2:** the PHEV/BEV is used to fulfill only the second car's driving. The CV is used to fulfill the first car's driving only.
- **Both:** the PHEV/BEV is used interchangeably between the first and second car's driving to minimize the use of fuel (i.e., to maximize the distance driven on electricity). Switching between substituting for the first or the second car is assumed to only take place at home. The CV is used to fulfill as much as possible of the remaining driving distance.

The three replacement strategies thus correspond to substitution extremes; the Car1 and Car2 strategies do not utilize the flexibility available in a two-car household but are in practice one-for-one replacement of individual vehicles, while Both fully explores the options to maximize PHEV/BEV driving while keeping unfulfilled driving down.

2.4. Optimization of electric driving

In this section, we describe the two optimization models used to estimate the potential electric driving for a PHEV and a BEV, respectively, in each individual two-car household for different battery sizes and car usage strategies. As in and for comparison to Karlsson (2017), we assume that exchanges of vehicles only take place at home during "shared stops", charging only takes place at home, and the PHEV/BEV is plugged in whenever at home. The home-charging-only assumption is also in line with a number of earlier studies, for example, Jakobsson et al. (2016) and Khan and Kockelman (2012) and supported by actual charging behavior (Tal et al., 2014). (The implications of our assumptions are further elaborated on in the Discussion and Conclusion section.)

In the optimization, with the modelling and assumptions above, the key car movement parameters are the home-to-home driving distances and the timing of departures and arrivals. The PHEV/BEV driving is limited by the time overlap in the two cars' driving and,

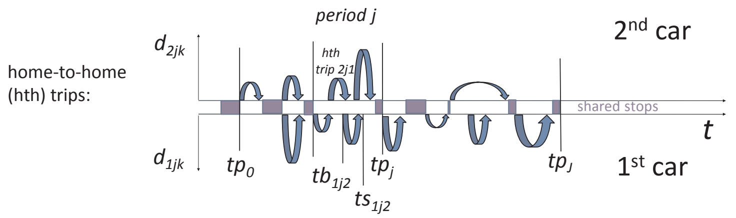

Fig. 1. A principle diagram depicting the driving by the two cars in an illustrative household. Before the shared stops j at home for the two cars ending at time tp_j, the first car has home-to-home (hth) trips 1jk of distances d_{1jk} occurring between tb_{1jk} and ts_{1jk}, which can overlap or not in time with the corresponding hth trips of the second car. And vice versa for the second car. Both cars or only one of them is driving in between the shared stops at home (from Karlsson, 2017).

in the case of a BEV, also the range and charging possibilities. See Fig. 1 for a diagram illustrating the driving by two cars in an illustrative household. For a PHEV, range limitation simply means that only the distance up to the battery range can be covered with electric driving. In the case of a BEV, the range limitation means that a BEV cannot accomplish a car's home-to-home driving (of which there may be more than one between shared stops) that is longer than the range. The charging rate limits the possibility of recharging during shorter stops at home, and thus possibly further restricts a PHEV's electric driving and a BEV's ability to fulfill a trip. The charging rate restriction thus potentially couples the household driving into mutually dependent trips.

For the Both strategy, the optimization models are given by Eqs. (1) and (3)–(14) for a PHEV and Eqs. (2) and (3)–(10) for a BEV. The models for the other two strategies are modifications of these basic relations.

2.4.1. PHEV, objective function

The PHEV model replaces the driving of the first or second car with the PHEV so as to minimize the total fuel use of the household's two vehicles in J periods between the identified shared stops at home, see Fig. 1 for denotations. The given total distances for the first and second car's trip k between shared stops $j-1$ and j are denoted d_{1jk} and d_{2jk}, respectively, and tb_{xjk} and ts_{xjk} are the time points [h] at the beginning and stop, respectively, of the trip xjk, where $x=1$, $x=2$ denotes the first and second car, respectively, j denotes after which shared stop and k denotes which trip. We define u_j as a binary variable $\{0,1\}$, where $u_j=0$ and $u_j=1$ denote the PHEV substituting either the first or the second car, respectively, and variable ed_{xjk} is the corresponding electric distance travelled for car x on trip k in between the shared stops $j-1$ and j. We thus have the PHEV objective function

$$\min_{u,ed_1,ed_2} \sum_{j,k} (u_j)\cdot(d_{1jk}-ed_{1jk})\cdot e_f + (1-u_j)\cdot(d_{1jk}\cdot e_f) + (u_j)\cdot(d_{2jk}\cdot e_f) + (1-u_j)\cdot(d_{2jk}-ed_{2jk})\cdot e_f \tag{1}$$

2.4.2. BEV, objective function

A model developed in Karlsson (2017) is used to calculate the potential to maximize the driving of the BEV in the households given the logged driving during the analysis period. The model maximizes the sum of the BEV driving distances and when possible substitutes the driving of the first or second car, in J periods between the identified common stops at home:

$$\max_{u,v_1,v_2} \sum_{j,k} (1-u_j)\cdot d_{1jk}\cdot(1-v_{1jk}) + u_j\cdot d_{2jk}\cdot(1-v_{2jk}) \tag{2}$$

Here u_j, v_{1jk}, and v_{2jk} are binary variables $\{0,1\}$, where u_j denotes the BEV substituting for the first car ($=0$) or the second car ($=1$) in between the shared stops $j-1$ and j, and v_{xjk} denotes if the BEV is driving ($=0$) the home-to-home trip k when substituting for car x in between the shared stops $j-1$ and j.

2.4.3. Common constraints

The optimizations in Eqs. (1) and (2) are constrained by the battery energy content SOC [kWh] (Eqs. (3)–(10)) due to the limited utilizable capacity $AER\cdot e_e$ [kWh] of the battery and charging rate cr [kW]. The constraints are:

- battery energy:

$$0 \leqslant SOCb_{xjk} \leqslant (AER\cdot e_e) \tag{3}$$

$$0 \leqslant SOCs_{xjk} \leqslant (AER\cdot e_e) \tag{4}$$

$$0 \leqslant SOCp_{xj} \leqslant (AER\cdot e_e) \tag{5}$$

where the variables $SOCb_{xjk}$ and $SOCs_{xjk}$ are the battery energy [kWh] at start and stop of trip xjk, and $SOCp_{xj}$ is the battery energy at the end of the shared stop j.

- battery energy at the start after the shared stop $j-1$:

$$SOCs_{xj0} = 0.99(AER\cdot e_e) \quad \text{for } j=1 \tag{6}$$

$$SOCs_{xj0} = (1-u_j)\cdot SOCp_{1(j-1)} + u_j\cdot SOCp_{2(j-1)} \quad \text{for } j\geqslant 2 \tag{7}$$

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

$$SOCb_{xjk} \leqslant SOCs_{xj(k-1)} + cr\cdot(tb_{xjk}-ts_{xj(k-1)}) \quad \text{for } j\neq 0,\ k\neq 0 \tag{8}$$

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

$$SOCs_{xjk} \leqslant SOCb_{xjk} + cr\cdot(ts_{xjk}-tb_{xjk})\cdot v_{xjk} - e_e\cdot d_{xjk}\cdot(1-v_{xjk}), \quad \text{for } j\neq 0,\ k\neq 0 \tag{9}$$

- charging up to point of time tp_j after last trip xjk before shared stop j:

$$SOCp_{xj} \leqslant SOCs_{xjk} + cr \cdot (tp_j - ts_{xjk}) \quad \text{for } j \neq 0,\ k = K_{xj} \tag{10}$$

where K_{xj} is the number of home-to-home trips between the shared stops $j-1$ and j.

2.4.4. Constraints specific to the PHEV

For the PHEV, the electric distance will further be limited by the battery energy level

$$ed_{1jk} \leqslant u_j \cdot SOCb_{1jk}/e_e \text{ for } j \neq 0,\ k \neq 0, \tag{11}$$

$$ed_{2jk} \leqslant (1-u_j) \cdot SOCb_{2jk}/e_e \text{ for } j \neq 0,\ k \neq 0. \tag{12}$$

The electric distance is also limited by the trip distance for trip k in between stops $j-1$ and j

$$ed_{1jk} \leqslant u_j \cdot d_{1jk} \text{ for } j \neq 0,\ k \neq 0, \tag{13}$$

$$ed_{2jk} \leqslant (1-u_j) \cdot d_{2jk} \text{ for } j \neq 0,\ k \neq 0. \tag{14}$$

2.4.5. Solver

Because of the binary variables and quadratic terms in the constraints, both optimization problems and the objective function can be classified as Mixed Integer Quadratically Constrained Programs (MIQCP). The models were formulated in GAMS using the SCIP MIQCP solver.

2.4.6. Battery ranges

For each strategy, we investigate 11 battery ranges, varying from 20 to 210 km for the PHEV, and from 60 to 500 km for the BEV, see Table 1.

2.5. Total cost of ownership

The difference in the TCO for the PHEV and BEV relative to an HEV includes any extra investment costs and the annual running cost savings. All other costs, such as maintenance costs, are assumed equal and are omitted. The annual investment cost difference, C [\$/yr], between an HEV and a BEV or PHEV consists of the annuity α [yr^{-1}] for the extra initial investment costs $I_{B,h}$ and I_P[\$] for the battery capacity in household h and the powertrain, respectively:

$$C_h = \alpha(I_{B,h} + I_P), \tag{15}$$

$I_{P,PHEV}$ includes any investment cost that is independent of the battery range, for turning an HEV into a PHEV, such as an on-board charger, increased maximum power of the electric powertrain, and also the cost of the battery's power capacity. A BEV lacks most of the hybrid powertrain and will therefore likely be less expensive than an HEV when disregarding the cost of the battery. The $I_{P,BEV}$ thus differs by including a cost reduction related to the absence of the conventional powertrain, and the $I_{P,BEV}$ can therefore be negative. $I_{B,h}$ includes only the cost for the battery's energy capacity, according to

$$I_{B,h} = c_B \cdot AER_h \cdot e_e/\beta, \tag{16}$$

where c_B is the specific battery cost [\$/kWh], AER_h is the battery's all electric range [km] for household h, and β is the battery capacity utilization factor. We thus divide the total battery cost into a power cost and an energy-capacity cost (Santini et al., 2010).

The annual running cost reduction R_h [\$/yr] is found as the electric distance multiplied by the specific operational cost savings r [\$/km] from using electricity instead of fuel, less the number of unfulfilled trips u_h (home-to-home trips that cannot be accomplished due to insufficient battery charge of the BEV) multiplied by the per-trip cost of unfulfilled trips c_u (BEV only). For the per-trip cost estimate, see Section 2.6 below. With the annual electric distance $D_{e,h}$ for household h, and prices p_e and p_f [\$/kWh] for electricity and fuel, we have

$$r = (p_f e_f - p_e e_e), \tag{17}$$

$$R_h = D_{e,h} \cdot r - u_h \cdot c_u. \tag{18}$$

In terms of fuel savings (i.e., $D_{e,h} \cdot r$), the marginal benefit of an extra unit of battery range diminishes with AER. Battery utilization is therefore higher for a smaller AER. For the BEV, the number of unfulfilled trips is, however, higher for a lower AER, which makes the cost-optimal battery dimensioning differ for the two vehicle types. For the purpose of considering the optimal battery size, we define the battery savings $S_{B,h}$ for household h as the annual running cost reduction from a battery investment less its

Table 1
Assessed battery ranges [km].

PHEV	20	30	40	50	60	80	100	120	150	180	210	–	–	–	–
BEV	–	–	–	–	60	80	100	120	150	180	210	250	300	400	500

Table 2
Assumed techno-economic parameters.

Techno-economic parameter	Designation	Value
Specific energy use, fuel car and PHEV in CS mode [kWh/km]	e_f	0.6
Specific energy use, BEV and PHEV in el. driving (CD) mode [kWh/km]	e_e	0.2
Fuel price [$/kWh]	p_f	0.2
Electricity price [$/kWh]	p_e	0.2
Specific battery cost [$/kWh]	c_B	300
Annuity [yr^{-1}]	α	0.15
Battery capacity utilization [–]	β	0.7–0.9
Cost for unfulfilled trips [$/occasion]	c_u	50
Charging power [kW]	cr	3

annuitized investment cost

$$S_{B,h} = R_h - \alpha I_{B,h}. \tag{19}$$

In total, a household can offset the higher investment cost C_h of a PHEV/BEV with reduced running costs R_h. The (annual) net TCO savings S_h [$/yr] for household h are given as

$$S_h = R_h - C_h. \tag{20}$$

The PHEV can reach a high share of electric driving with a relatively small and cheap battery without the cost of any unfulfilled trips. The greater battery savings, S_B, compared to the BEV can be used to offset the more expensive powertrain. We define ΔI_P as the difference in powertrain investment cost between a PHEV and a BEV:

$$\Delta I_P = I_{P,PHEV} - I_{P,BEV} \tag{21}$$

2.6. Technical and economic prerequisites

Assumed techno-economic parameters are described in Table 2. In electric mode, the PHEV is assumed to be three times more energy-efficient than the HEV. The prices for electricity and fuel are chosen as the Swedish averages over the years 2011–2015 (IEA, 2011–15). The resulting operational cost savings per km of electric driving can be found as 0.08 $/km according to Eq. (17). The extra cost for unfulfilled trips corresponds to half the daily cost for renting a car, see discussion in Karlsson (2017). The applied charging power cr [kW] is 3 kW, roughly corresponding to 16 A single phase 230 V, commonly available in Swedish households. The power level is (rounded) charging power rates at the battery and thus includes assumed losses in, for example, the EVSE (Electric Vehicle Supply Equipment) and the on-board charger. For instance, 1 • 16 A/230 V can deliver a charging rate of 3 kW at the battery when the grid-to-battery losses are around 18%. This is consistent with the losses measured when charging a BEV (Peugeot Ion) in Belgium (De Vroey et al., 2013). The battery capacity utilization factor β is assumed to be 0.7 for battery ranges up to 50 km, 0.9 for battery ranges of 100 km and above, and is interpolated linearly for battery ranges in between 50 and 100 km.

We base our estimates of the extra powertrain investment cost, I_P, for PHEVs and BEVs on a study by Argonne National Laboratory (Moawad et al., 2016). The I_P is taken as their estimate of the total cost without battery for a BEV and PHEV, respectively, less the total cost of an HEV without its battery.[1] Their technology and cost estimates are referred to as those achieved at the laboratory level with a five-year delay to production year and at large production volumes. The cost estimates for 2015, with an addition of 50% markup cost, is therefore used to roughly represent the situation in 2020 (Elgowainy et al., 2016). The resulting extra powertrain costs, $I_{P,}$ are found in Table 3.

During driving, energy use varies with driving conditions and properties such as speed, load, road conditions, etc. However, here, the specific energy uses e_e and e_f are assumed to be constant since these aspects have been found to have a relatively small influence on the vehicle's total energy consumption compared to the actual movement pattern of the car.[2] The weather can affect the BEV energy use considerably, though, see, for instance De Cauwer et al. (2015). Also, the engagement of the fuel engine in a PHEV may be dependent on the climate conditions. In this study focusing movement patterns, we have chosen to ignore these influences. The energy use is also assumed to be independent of battery size.[3] Thus, the total energy use only depends on the distance driven in CS and CD mode, respectively.

[1] In effect, some of the long-range batteries modeled will have a slightly too high marginal battery cost compared to the short-range batteries since a large energy capacity lowers the cost of battery power. However, not adding the cost of power to the powertrain cost would instead make the marginal cost for short-range batteries much too low compared to the long-range batteries.

[2] This is discussed in more detail in Section 2.4 of our earlier paper Björnsson and Karlsson (2015).

[3] According to Shiau et al. (2009), the extra battery weight will make the energy demand for a PHEV of 96 km range about 10% higher than for a PHEV of 11 km range (including extra structural weight to support a heavier battery). Also, we do not know the weight of future batteries. Lower specific battery cost will give larger optimal batteries. This cost decrease will probably mainly come as result of higher specific capacity (higher kWh/kg) leading to less increase over time in the weight of the optimal battery, if any.

Table 3
Estimated extra powertrain cost I_P for PHEVs and BEVs. Based on Moawad et al. (2016).

Powertrain	Extra powertrain cost, I_P
Power split PHEV (Prius type)	\$400
Series-split PHEV (GM Volt type)	\$2400
BEV	−\$4600

2.7. Car movement data

The car movement data used in the analysis was obtained by logging the movement patterns of both cars in two-car households simultaneously via GPS. The households were selected at random from the Swedish vehicle registry, from the Gothenburg region. The cars were required to be conventional cars of model year 2002 or newer and limited to ≤200 kW and ≤2000 kg. Through the participation inquiry, the households were further restricted to those with at least two actively used driver's licenses and at least one car commuting 10 km or more (one way). In each household, the two cars were driven by two or more persons.

We utilize data from 64 households with good data quality for both cars for a typical analysis period of between 1.5 and 2.5 months. Good data quality means that we have, or could 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 the corresponding times. For more information about the measurement project see Karlsson (2017).

3. Results

3.1. Potential electric driving

For a given battery range, a PHEV can reach a higher EDF than a BEV. Therefore, a PHEV can achieve a given EDF with a smaller batter range than a BEV, see Fig. 2. For the average driver, fulfilling only the first car's driving (i.e., using strategy Car1) with a PHEV that has a range of 50 km results in roughly the same EDF as using a BEV with a range of 100 km. For the two other strategies, Car2 and Both, a PHEV with a range of 60 km gives as high a fleet EDF as a BEV with a range of 100 km. Fig. 3a shows that the average number of unfulfilled trips per year for the BEV is greater with Car1 than Car2, due to the more confined driving of the second car. Also, a large share of the unfulfilled trips can be fulfilled with strategy Both. For a BEV with a 100 km battery range under Car1, about 25% of the households will face more than one unfulfilled trip per week of driving. While for a flexible strategy (Both) 25% is roughly how large share of the households that face one or more unfulfilled trips per every three months, see Fig. 3b-c.

3.2. Cost-optimal batteries

3.2.1. Battery ranges

In this section, we assign cost-optimal battery sizes to the individual households for each strategy. This is done by considering the operational cost savings r, the cost for unfulfilled trips c_u, and the investment cost for the battery range I_B. The optimal battery ranges and resulting battery savings, S_B, for individual households are shown in Fig. 4. The PHEV has a smaller optimal battery range and tends to reach greater battery savings, S_B. The greatest difference between PHEV and BEV in battery size and in battery savings can be

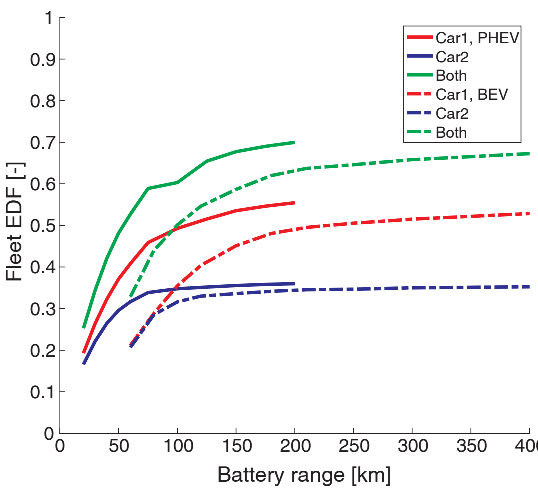

Fig. 2. Fleet-average electric drive fraction (EDF) for the PHEV and BEV under Car1, Car2, and Both.

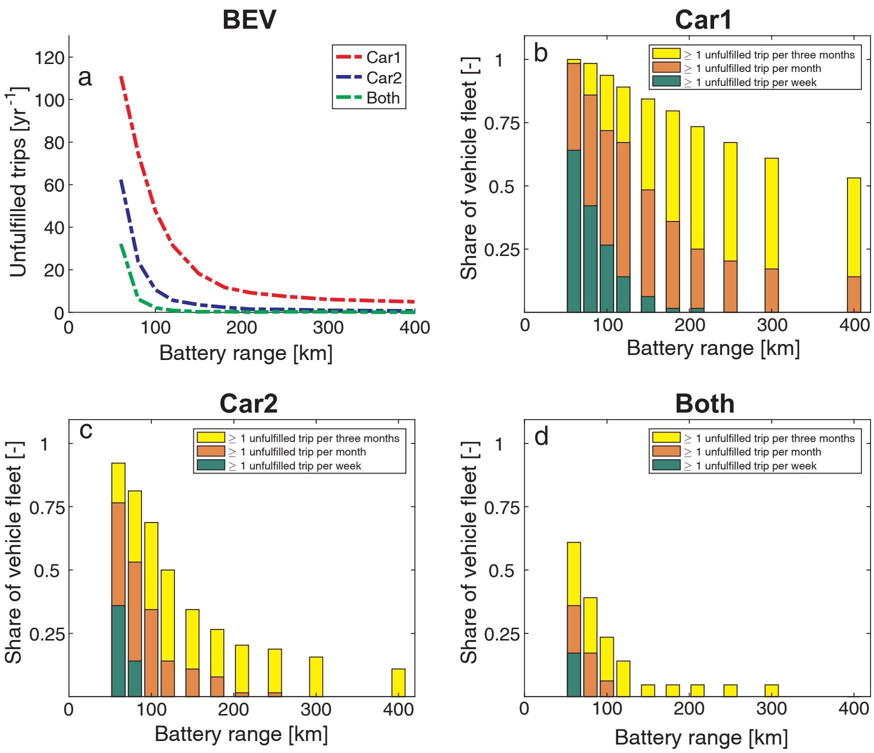

Fig. 3. (a) The average number of unfulfilled trips per household for the BEV under the three strategies. (b-c) Share of the vehicle fleet with one or more unfulfilled trips per every third month, every month and every week respectively for the three studied strategies.

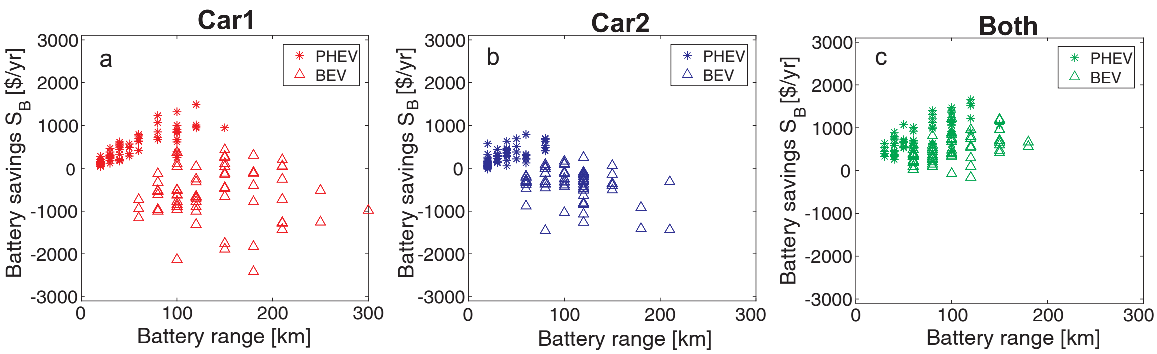

Fig. 4. The battery savings, S_B, for the cost-optimal battery range for each household for the PHEV (stars) and BEV (triangles), for each strategy, Car1, Car2, and Both.

found with Car1 and the smallest with Both, see Fig. 4.

For the PHEV, the average increase in battery savings with an optimized use of the vehicle (Both) compared to the average of the two other strategies, Car1 and Car2, is \$433/yr, Table 4, while the corresponding savings for the BEV are more than twice as large, or \$982/yr. For the PHEV, the increase in fuel cost savings when turning to the Both strategy is in general larger than the corresponding increase for the BEV, but this is partly offset by the cost increase due to the accompanied greater battery range relative to Car1 and Car2, Fig. 5. For the BEV, the number of unfulfilled trips and the related cost are reduced for the strategy Both when the other car can be used for long distance trips. This is possible while also reducing the battery range, Fig. 5. The cost reductions in strategy Both for the smaller battery and the many fewer unfulfilled trips add up to roughly the equivalent value as the value from the increase in electric driving, Table 4.

3.2.2. Second-best option

For each of the three strategies, the individual household's battery savings, $S_{B,h}$, from buying a PHEV or a BEV, respectively, can be found in Fig. 6. For the PHEV, the second-best alternative to the Both strategy is most often Car1 (for 75% of the households), while for the BEV, Car1 is the second best for about half the households and Car2 for the other half (44% and 56%, respectively). The latter is primarily a result of the cost of unfulfilled trips, which in addition to their direct cost also drive up battery ranges for the Car1

Table 4
Average battery ranges, electric distances, unfulfilled trips, and the resulting annual battery savings, S_B, for the average household.

	Strategy	Electric distance [km/yr]	Savings from driving [$/yr]	Battery range [km]	Savings from battery range [$/yr]	Unfulfilled trips [yr^{-1}]	Savings from unfulfilled trips [$/yr]	Battery savings, S_B [$/yr]
BEV	Car1	16,445	1316	140	−1410	11	−571	−610
	Car2	11,292	903	110	−1128	4	−206	−405
	Both	18,940	1515	98	−1032	0.25	−8	475
	Both – mean(Car1,Car2)	5072	406	−27	237	−7.25	380	982
PHEV	Car1	14,797	1184	59	−663	0	0	520
	Car2	9160	733	37	−460	0	0	273
	Both	19,985	1599	69	−769	0	0	829
	Both – mean(Car1,Car2)	8006	640	21	−207	0	0	433

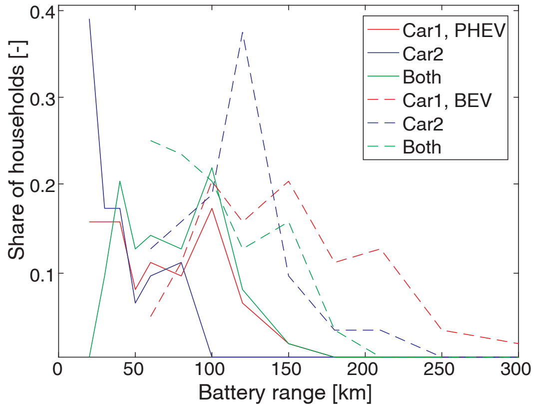

Fig. 5. Distribution of PHEV and BEV battery ranges for the individual households for each strategy.

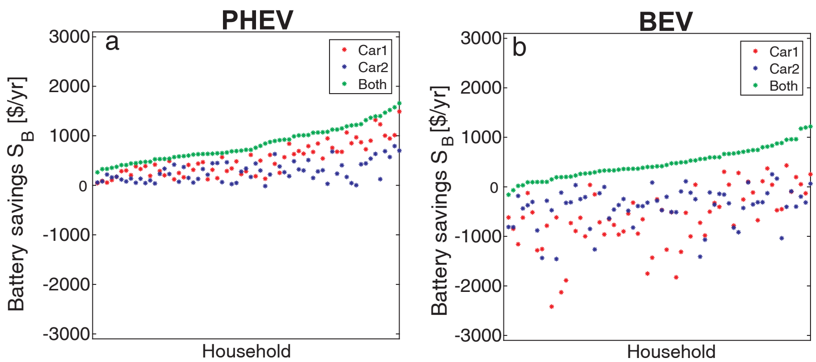

Fig. 6. The battery savings, S_B, for the cost-optimal battery range for each household for the PHEV (a) and BEV (b), for each strategy. Results are sorted by level of battery savings under the Both strategy.

strategy, see Table 4 and Fig. 5.

3.2.3. Electric drive fraction

How does the choice of vehicle technology affect the potential electric drive fraction (EDF)? The individual household's EDF can be seen in Fig. 7. For the one-car strategies (Car1 and Car2), for most households, the BEV yields a slightly higher EDF than the PHEV. On average, the BEV covers 5–7% more of the total distance than the PHEV. For the two-car strategy, Both, the difference is smaller, and the PHEV now covers about 3% more of the total driving distance than the BEV. The EDF depends less on the choice of BEV or PHEV than on the choice of strategy, Car1, Car2, or Both. Changing from Car2 to Car1, or from Car1 to Both, increases the EDF by 16 and 12 percentage points, respectively, for the average of the PHEV and BEV. From a fuel substitution perspective, it is therefore often better to replace the first car with a PHEV than to replace the second car with a BEV.

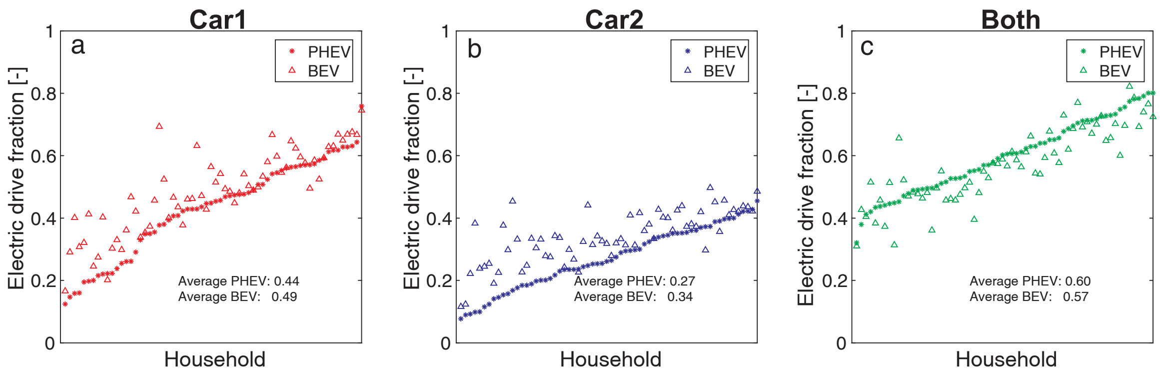

Fig. 7. The EDF (of the total household distance) for the cost-optimal battery range for the PHEV and BEV, for each household and strategy. The households are sorted by the PHEV's result for each strategy.

3.3. Total cost of ownership

To compare the full TCO of a PHEV and BEV, the powertrain cost needs to be included. Although the BEV benefits more from an optimized use of the vehicle, the PHEV will provide greater battery savings regardless of strategy, see Table 4. This advantage comes from the ability of achieving high savings on fuel costs with a relatively small battery and without the penalty of having unfulfilled trips.

On average, the PHEV's battery savings per year relative to the BEV are \$1100, \$680, and \$360, for Car1, Car2 and Both, respectively (Table 4), and can, when assuming an annuity of 15%, offset a greater PHEV powertrain investment, ΔI_P, of on average \$7300, \$4500, and \$2400, respectively. The distribution across households of the maximum powertrain investment cost difference, ΔI_P, before a BEV becomes more viable than a PHEV can be viewed in Fig. 8. The Car1 strategy offers a PHEV the greatest chance to outcompete a BEV on cost, and Both, which provides needed flexibility for the BEV, offers the least. Thus, if the households cannot or do not want to optimize the use of the vehicle, this will favor the PHEV. The differences in ΔI_P among the households are also the greatest in Car1, spanning from \$1000 to \$19,000.

Fig. 9 depicts the share of households that optimally would choose a BEV over a PHEV at a certain powertrain investment cost difference. Fig. 9 also includes two vertical lines representing the two illustrative estimates of powertrain investment cost differences between BEV and PHEV from Table 3. The powertrain investment cost is estimated to be significantly lower for the BEV, and, if priced accordingly, an optimized use of the BEV would outcompete the PHEV on cost. If vehicle use is optimized (i.e., with the Both strategy), 97 and 100% of the households benefit more from a BEV investment, in the two illustrative cases, respectively, see the green line and the two vertical dashed lines in Fig. 9. However, if the households cannot or do not want to optimize the use of the new vehicle, the BEV outcompetes the PHEV on TCO for a much smaller share of them, especially for the Car1 strategy, with the BEV only having a lower TCO than the PHEV in 23% and 45% of the households, for the two illustrative powertrain investment cost differences. In general, the Car1 strategy favors the PHEV, while the Car2 strategy favors the BEV. The first car is more commonly used for long-distance trips, for which a BEV needs to be equipped with a relatively large and expensive battery to avoid/reduce the cost for unfulfilled trips. Under these circumstances, it can be less expensive to invest in a PHEV with a slimmed battery but a higher powertrain cost. The second car is used less often for long-distance trips, and the extra powertrain cost for a PHEV is therefore less often justified since the household can manage with a BEV with a relatively short range. However, there are differences among the individual households, and, as discussed earlier, it is not always the case that a PHEV performs best under Car1 and a BEV best under Car2, Fig. 6. When the PHEV/BEV is used in the second best strategy, between 50% and 80% of the households would benefit more from driving a BEV, depending on the powertrain cost of the PHEV, black line, Fig. 9. The chosen strategy will thus make a considerable difference to the competition between the two vehicle types.

Fig. 9 depicts how large a share of the households would benefit more from a BEV or a PHEV depending on the ΔI_P. However, it is possible that neither would be viable compared to an HEV. The powertrain cost estimates in Table 3 can be used for an illustration. At these cost levels, about 60, 80, and 100% of the households would benefit financially with a BEV under Car1, Car2, and Both, respectively. Correspondingly, for a Prius-like PHEV, the shares of households that manage to reach viability are a bit higher, 97, 83, and 100%, while at a higher powertrain cost similar to a Volt-like PHEV, the number of households reaching viability is reduced to 60, 31, and 94%. If households can choose between a BEV, a Prius-like PHEV, and an HEV under Car1, Car2, and Both, about 98, 94, and 100% of the households, respectively, would benefit more from buying a BEV or PHEV compared to an HEV. The fleet EDF would be similar to when all households are forced to choose a BEV or a PHEV (decreases by 0.17 and 0.67 percentage points under Car1 and Car2, respectively). If households instead can choose between a BEV, a Volt-like PHEV, and an HEV, then about 76, 83, and 100% of households would be better off with a BEV or a PHEV compared to an HEV under Car1, Car2, and Both, respectively. The fleet EDF would then be somewhat lower compared to when all households are forced to choose a BEV or PHEV (about 5 and 3.5 percentage points under Car1 and Car2, respectively). The households that would benefit more from driving an HEV are in general not achieving the electric distance needed to offset the extra investment cost of a PHEV or a BEV and therefore only affect the fleet EDF to a limited extent.

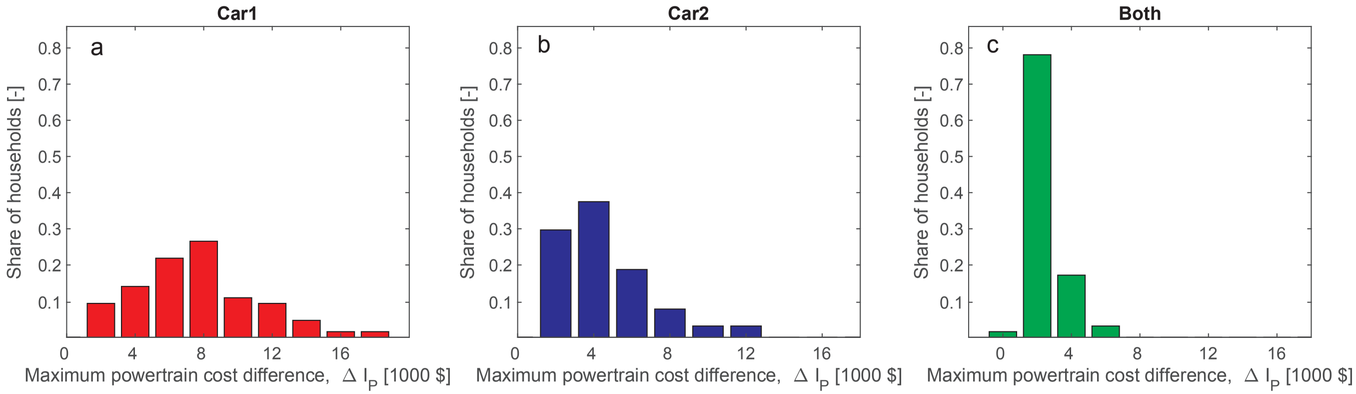

Fig. 8. The distribution of maximum powertrain investment cost difference, ΔI_P, allowing the PHEV to be more viable than the BEV for the individual households under the studied strategies.

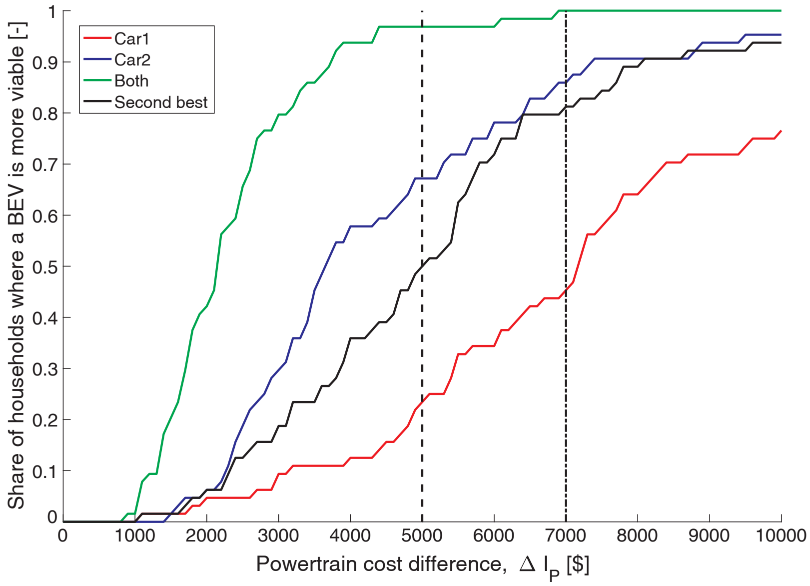

Fig. 9. Share of households for which the TCO for a BEV is less than for a PHEV, as a function of the powertrain investment cost difference, ΔI_P, between PHEV and BEV, for each of the three strategies, Car1, Car 2, and Both, as well as for the "second best" strategy (see text). Estimates of the difference in powertrain investment cost between the PHEV and the BEV are included for reference.

4. Discussion and conclusions

The flexibility made available in two-car households does not generally benefit PHEVs over BEVs. On average, the PHEV could achieve about $430/yr in increased battery savings, S_B, from an optimized use of the vehicle, which is less than half as much as the almost $1000/yr for the BEV.

But could the PHEV still be more viable than the BEV in two-car households? Battery savings, S_B, are higher for PHEVs, since they can reach the same fuel reductions with smaller batteries. However, these savings must partly be used to offset the more expensive PHEV powertrain cost. Using estimates of the powertrain costs at high production volumes in 2020, the results showed that when the use of the PHEV/BEV is optimized over both cars in the household, the PHEV will be less viable than the BEV.

There are a number of circumstances indicating that the PHEV could be a tougher competitor than what our model results suggest at first, but there are also factors pointing in favor of the BEV. The two overarching results above relied on four basic assumptions; optimized use of the vehicles in the households, estimated mass productions cost at year 2020, current Swedish energy costs, and home charging only.

If the use of the BEV is not optimized, then the PHEV will be a tougher competitor, as was seen in Fig. 9. For instance, if the households cannot or do not want to switch vehicles within the household this will favor the PHEV. We have assumed zero cost for switching within the household to be able to determine the upper potential of an optimized use of the vehicles. If the cost of switching is perceived so high that car switching is avoided, this would favor the PHEV over the BEV.

The sizing of the batteries was determined by the economic optimization. However, the opportunity to use the PHEV for long-range driving may hold an (option) value in itself, in the same way that buyers of BEVs could value extra range to keep range anxiety at a distance. Buying a 150 km battery instead of a 100 km battery would, with our assumed battery cost of $300/kWh, correspond to an extra cost of roughly $4000 for the BEV (less some benefit from additional fuel substitution and reduced number of unfulfilled trips). Another option for curing range anxiety is to equip the BEV with an emergency engine as in the case of the BMW i3, which in Sweden comes at an extra cost of about $5000 (BMW Sverige, 2016).[4,5] Both aspects would skew the economic comparison in favor of the PHEV. How much extra people would be willing to pay is difficult to estimate and is likely to vary greatly across individuals.[6]

A lower battery cost will favor the BEV more than the PHEV because of its greater battery range. Since the price for battery energy capacity is anticipated to decrease, it is likely that BEVs will perform better compared to PHEVs over time.

The operational cost savings per km of electric driving used in our analysis are based on average energy prices in Sweden from 2011 to 2015. The cost savings are relatively high (0.08 $/km) compared to some other countries, for instance the US and Germany.

[4] Assuming 1 USD = 8 SEK.

[5] The BMW i3 REX could be seen as a PHEV version of the ordinary BMW i3, but the range extender is considerably weaker than the electric powertrain and has been considered an emergency engine (Inside EVs, 2012).

[6] There are some studies concerning consumers' willingness to pay for extra battery range. Dimitropoulos et al. (2013) showed that consumers are willing to pay between $41 and $47 per km of extra battery range. However, the review is solely based on stated preference studies, which are less reliable when assessing emerging technologies as BEVs (Al Alawi and Bradley, 2013).

(Sweden has higher fuel and electricity prices than the US and lower electricity prices than Germany). With average energy prices from the US and Germany, the operational cost savings per km, based on Eq. (17), would be roughly 50 and 75%, respectively, of the Swedish cost savings per km (IEA, 2011–15). In general, the more electric kilometers traveled, the greater the loss when the cost savings per km is lowered. Fig. 7 shows that BEVs will result in a higher share of electric driving under Car1 and Car2, while PHEVs and BEVs will reach about the same share of electric driving under Both. This suggests that under Car1 and Car2, PHEVs would be somewhat favored compared to BEVs by lowered operational cost savings, while under Both, it is more ambiguous which vehicle type would be favored.

We have assumed the same level of maintenance costs for PHEVs and BEVs. In reality, the BEV is likely to have lower maintenance costs. Propfe et al. (2012) estimated the difference in repair and maintenance costs between a PHEV and a BEV to about 1 cent per km.[7] When driving 15,000 km per year this would correspond to an annual cost difference of $150, which with an annuity of 15% corresponds to an investment cost of about $1000.

We assumed home charging only although the utilization of (especially short ranged) batteries is likely to increase from better charging opportunities. The second most common long-time parking is in general at work. For commuters, charging at work can be as valuable as a halving of the battery price for the PHEV (Björnsson and Karlsson, 2015). The battery range could be halved while retaining almost the same share of electric driving. The BEV's battery utilization could be increased analogously, but at the expense of an increased cost for unfulfilled driving. Workplace charging would therefore benefit PHEVs more than BEVs. A Californian charging behavior study showed that the second most common charging point apart from home-charging for Chevrolet Volt and Toyota Prius and Nissan Leaf was workplace charging. The average frequency for workplace charging was found as 15, 11 and 4% per commute respectively (Tal et al., 2014). This suggests that omitting charging away from home should have a comparably small impact on our results. On the other hand, we have assumed that PHEV owners always charge while in reality the charging behavior can be difficult to foresee. For example, Tal et al. (2014) showed that the Toyota Prius PHEV was less likely to charge away from home compared to the Chevrolet Volt although its shorter battery range should increase the need for additional charging. If PHEV drivers choose to not always charge and instead run the car more on fuel this would obviously have a negative impact on the PHEV's economic performance. Overnight charging out of home, for instance by weekends, will probably favor BEVs with their larger batteries. Fast charging infrastructure along major roads is supposed to mostly concern BEVs, while PHEVs with their smaller batteries are supposed to find it too inconvenient to stop for charging as often as is required on longer trips. However, the here estimated optimal batteries sizes for the BEVs are also relatively small, possibly making it inconvenient also for their drivers to accomplish longer trips relying on fast charging along the road.

Finally, and maybe somewhat hopefully, we can remind ourselves of our third overarching result, that even if PHEVs were to take the place of BEVs in the two-car household, under the assumptions made, this would in general not significantly hamper the share of electric driving in the vehicle fleet.

Acknowledgements

We gratefully acknowledge the support from the Electric Vehicles Demonstration Program at the Swedish Energy Agency, Sweden (project numbers 35880-1 and 35880-2) and from Chalmers Energy Initiative, Area of Advance Transport and Area of Advance Energy at Chalmers University of Technology, Gothenburg, Sweden.

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[7] Assuming 1 USD = 1 EUR.

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