Applied Energy 143 (2015) 336–347

Contents lists available at ScienceDirect

Applied Energy

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

Plug-in hybrid electric vehicles: How individual movement patterns affect battery requirements, the potential to replace conventional fuels, and economic viability

Lars-Henrik Björnsson *, Sten Karlsson

Energy and Environment, Chalmers University of Technology, Gothenburg, SE-41296, Sweden

HIGHLIGHTS

- Economically optimal batteries are designed for 432 individual car movement patterns.
- The PHEVs' optimal battery sizes and savings vary greatly between movement patterns.
- Charging at work can economically be as important as halving the battery cost.
- Commuters are likely to be the first drivers for whom the PHEV will be cost-effective.
- A high battery-independent investment cost will slow down the introduction of PHEVs.

ARTICLE INFO

Article history:
Received 15 August 2014
Received in revised form 8 January 2015
Accepted 9 January 2015
Available online 3 February 2015

Keywords:
Battery size
GPS-logging
Individual movement pattern
PHEV viability
PHEV potential

ABSTRACT

Using GPS data logged for a representative sample of individual vehicles in private use, we assess the viability of plug-in hybrid electric vehicles (PHEVs) in Sweden for a wide range of techno-economic conditions. We determine requirements for PHEVs with the aid of a simple parameterization used to analyze the GPS data covering number of trips, driving distance per trip, and parking times, logged for 30 days or longer, for 432 conventional Swedish cars.

Good opportunities for charging and regular distances traveled between rechargings increase the potential for battery-powered driving and, along with a high annual mileage, enhance the viability of the PHEV. Therefore, commuters are likely to be the first drivers for whom the PHEV will be cost-effective. Making charging infrastructure available at work places would enhance the opportunity for this group of early adopters, as we show that charging while at work is comparable at the initial stage to halving the marginal battery costs for the average commuter.

1. Introduction

Increased electrification of personal vehicle travel has the potential to reduce greenhouse gas emissions, local pollutants, and energy insecurity. The plug-in hybrid electric vehicle (PHEV) allows for a major share of the fuel to be replaced by electricity from the grid, without compromising—as in the case of the battery electric vehicle (BEV)—the range of the vehicle. The PHEV has a smaller battery than the BEV, but it is large enough to supply energy for a significant share of the distance driven between rechargings; an internal combustion engine extends the range when the battery is empty and may also provide power in parallel with the electric motor.

For the PHEV to become a major real option on the private car market, the total economics of the PHEV would presumably have to be favorable compared to the alternatives, and especially to the (future developments of) the fuel-propelled car. Li-ion batteries, the currently dominant battery technology, are still relatively expensive, making the economic viability of the PHEV dependent on the degree to which the available energy capacity is utilized. To minimize the total cost of ownership (TCO), extra battery capacity needs to be paid for by lower operational costs of the marginal electric distance traveled (resulting from the extra battery capacity). Earlier studies have commonly focused on total battery cost without discussing the marginal cost and its effect on cost-effective battery sizing. Some studies have considered it implicitly by analyzing the total cost of ownership for a number of ex ante given battery sizes [1–6]. [6] finds the battery range to have a small impact on the TCO for a PHEV. On the contrary, [4] reaches the conclusion that short range PHEVs would reduce gasoline

* Corresponding author. Tel.: +46 31 772 31 24.
E-mail addresses: larshenr@chalmers.se (L.-H. Björnsson), sten.karlsson@chalmers.se (S. Karlsson).

http://dx.doi.org/10.1016/j.apenergy.2015.01.041
0306-2619/

consumption more per dollar spent than large range PHEVs. [1] and [2] discuss the difficulty for large batteries to offset the marginal battery cost with corresponding marginal cost savings.

To which extent an individual PHEV can replace vehicle fuel with electricity is also highly dependent on trip, road, and driving characteristics. The share of electric driving depends on driving style (aggressive/defensive driving, etc.) and on road conditions (road type, traffic situation) but even more so on characteristics such as the length of trips, duration of parking, and access to charging while parked [7]. We refer to the latter three characteristics, which will vary between countries and regions, as individual (car) "movement patterns" and focus on these in this study. PHEV studies have many times utilized statistics for the movement patterns from travel surveys or other data with statistical distributions of daily driving distances [2–5,8–19]. National and/or regional travel surveys are regularly gathered in many countries, but the focus is on the travel behavior of persons rather than the movement pattern of vehicles. The period of measurement is mostly limited to one day (as in Sweden) or sometimes up to a week [20]. While travel surveys are valuable to estimate the average travel behavior of people living in a certain region it provides less insight into the day-to-day variation in the usage of the (individual) car.

Since movement patterns vary considerably over time [21–23] it is of importance to use data covering longer measurement periods when analyzing the possible share of electric driving for the individual car [7,14,24]. There are a limited number of publicly available and highly detailed multiday data sets gathered with GPS. However most have been collected for a specific purpose, or focusing on vehicles in specific areas. Puget Sound Regional Council's 2007 traffic choices study [25] was originally conducted to analyze changes in travel behavior as a response to (hypothetical) road tolling. This data set has for instance been used to estimate total cost of ownership for BEVs and PHEVs [1,6,26]. The commute Atlanta study [27], a Georgia Tech project measuring commuters active within Atlanta metropolitan area, has been used to estimate the range requirement for BEVs and to analyze the importance of access to charging [28,29]. In Canada, Department of Geography at University of Winnipeg, has been logging 76 cars in Winnipeg to be able to, for instance, assess the prerequisites for electrification with PHEVs [30–33]. In Italy, part of the data gathered for a huge amount of cars by a private company for insurance purposes are now used to analyze various aspects of electrification in and around the Firenze and Modena regions [34–36] Also many of the electric vehicles sold so far have been subject to various measurements. Part of the EV-project [37] includes collecting travel and recharging data from privately driven Chevrolet Volt [38]. Although it is highly important to understand the actual usage of PHEVs, these very early adopters of the PHEV technology cannot be expected to be representative for the general car owner.

In Sweden individual multiday movement patterns have been logged by GPS for a number of privately driven conventional cars constituting a representative sample of Swedish driving [39,40]. The aim of this study is to use this database to explore how individual movement patterns, under various charging infrastructure and a wide range of techno-economic conditions, affect the PHEVs' optimal battery size, economic viability and potential to increase the electrification of Swedish driving.

2. Method

We estimate the energy use and economics for hypothetical PHEVs with the same individual movement patterns as the conventional cars in the database. To single out the effect of these movement patterns we intentionally leave out possible differences due to driving behavior, road and climate conditions and traffic situation etc., and focus only on trip distances and the length of pauses in between trips. For each individual movement pattern, we size the PHEV battery to minimize the TCO. We assume that the car keeps its movement pattern independently of the battery size and that the GPS-logged driving is representative of the car's whole economic lifetime. To size individual batteries optimally, we develop a framework for the analysis of how the individual car's movement pattern affects battery utilization and how different techno-economic and infrastructure conditions affect the battery-related costs and the potential fuel savings. The basic idea is that a PHEV is economically viable when, compared to an HEV, the initial extra investment costs for the PHEV are paid for by the lower energy costs made possible by using electricity from the grid rather than fuel. The potential for increased electrification of Swedish driving via PHEVs is estimated in terms of the electric driving enabled by viable PHEVs in the vehicle fleet.

2.1. PHEV modeling

The PHEV energy battery is supposed to be able to deliver the power needed to propel the vehicle in a pure charge-depleting (CD) mode until its useful energy is consumed, and the driveline turns into the charge-sustaining (CS) hybrid mode. We do not consider a blended CD mode in which both fuel and electricity are used for propulsion. Some PHEV models demand a blended CD mode in much actual driving (e.g., the Toyota Prius PHEV). We also assume that the battery maintains its properties throughout the car's economic lifetime.[1]

The economic performance is further affected by the specific techno-economic conditions assumed. To facilitate a focus on the effects of individual movement patterns, we assume identical (except for battery size) PHEVs, characterized by the specific energy uses e_e (electricity) and e_f (fuel) [kW h/km] in the CD and CS mode, respectively.[2] The HEV used for comparison is assumed to have the same specific fuel use of e_f. The PHEV all-electric range AER [km] is the maximum possible distance driven in the CD mode. Although the energy use in reality varies with battery size/weight, driving conditions, and properties such as speed, driving aggressiveness, terrain, load, weather and road conditions, and the use of auxiliary power (e.g., air conditioning), the specific energy uses are assumed constant, and the total energy thus only depends on the distance driven in each mode.[3]

2.2. Battery utilization

In reality the possible utilization of the PHEV battery will depend on the recharging options in the form of access to charging posts at, for example, workplaces, in public parking areas, and in private garages. There is also a need for enough time to recharge the battery before the next trip as well as a willingness to actually recharge when possible. Here the lengths of parking periods between trips are used to represent different charging options: it is assumed that the battery is recharged only and fully in every break of at least size T [h].[4]

[1] Replacing the battery before the end of the economic lifetime is likely to in most cases make the PHEV unviable in a comparison with a HEV.

[2] A complete list of the variables used in this paper is found in Appendix A.

[3] Any further specification of the car would require that we also include more details on the driving (here limited to trip distance and time between trips), such an inclusion would make it more difficult to isolate the effects of the individuality in car movement. This is further discussed in Section 2.4.

[4] This implies that the drivers are assumed to always charge when possible, in reality the charging frequency will be depending on the drivers charging habits, but our result serve to show the potential battery utilization. Driving behavior has for example been studied in [38].

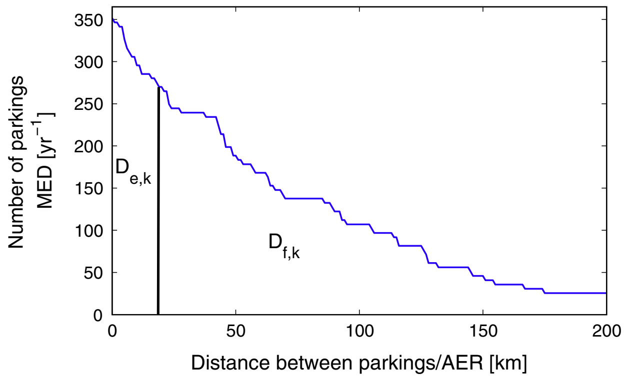

Fig. 1. The number of times per year an example vehicle k has driven a specific distance or longer between parkings of 10 h or more. It is also the resulting *MED* as a function of battery range for the individual movement pattern of car k when assuming the battery is fully charged in every parking period 10 h or more. $D_{e,k}$ and $D_{f,k}$ is then the distance traveled on electricity and fuel respectively for vehicle k.

In the analysis we focus on $T = 10$, 4 and 0.5 h. Letting the car recharge every time it stops for at least 4 h could emulate the situation when charging posts are accessed both at work and at home, whereas a 10 h stop requirement means that for most drivers the battery will only be recharged during the night. $T = 0.5$ h is a rather extreme case requiring access to a fast charging post at every place the cars stops for half an hour or longer. It simply illustrates how an omnipresent access to versatile charging facilities affects the results and is not meant to represent a feasible scenario.

For vehicle k, the resulting annual distance driven on electricity $D_{e,k}(AER_k,T)$ [km/yr], is derived by summing the distances up to the range AER of all the annual trips between rechargings [24,41]. We now introduce as a basic indicator for the expected usage of the marginal battery range, the marginal electric distance MED_k $\left[\frac{\text{km (electric driving)/yr}}{\text{km (range)}} = \text{yr}^{-1}\right]$[5] defined as the derivative of $D_{e,k}$ with respect to the range AER_k[6] (see Fig. 1 for an example):

$$MED_k(AER_k, T) \equiv D'_{e,k}(AER_k, T) \quad (1)$$

and conversely:

$$D_{e,k}(AER_k, T) = \int_0^{AER_k} MED_k(AER, T)dAER \quad (2)$$

The MED_k thus gives the extra annual electric distance made possible by an additional unit of battery range. The annual distance driven on fuel is then correspondingly denoted as $D_{f,k}$ [km/yr].

We here define the number of battery cycles BC_k [yr^{-1}] as the total yearly energy flow through the battery divided by the usable energy capacity.[7] We assume a constant specific electricity use, so:

$$BC_k = D_{e,k}/AER_k \quad (3)$$

The number of battery cycles for the whole battery of range *AER* is then the average of the *MED* in the interval [0, AER].

Fig. 1 shows the *MED* curve for the individual movement pattern of one example vehicle in the database. The *MED* can be found as the number of times per year the car drives a certain distance or longer between breaks of time *T*. The car in this example has traveled 20 km or longer 270 times per year (roughly 5 times per week on average), which means that a battery range increase from 19 km to 20 km corresponds to an additional 270 km of electric travel distance per year.

2.3. PHEV economics

The difference in TCO for the PHEV and HEV includes any extra investment costs and the annual energy cost savings. All other costs, such as maintenance costs, are assumed equal and are omitted. The (extra) annual costs C_k [\$/yr] for PHEV k comprise the annuity α [yr^{-1}] for the initial investment cost $I_{B,k}$ [\$] for the battery capacity and for the fixed battery-capacity-independent cost I_F [\$] of turning an HEV into a PHEV:

$$C_k = \alpha(I_{B,k} + I_F) \quad (4)$$

The annual operational cost reduction R_k [\$/yr] is found as the total electric distance multiplied by the specific operational cost savings r [\$/km] from using electricity instead of fuel. With the specific energy uses e_e (electricity) and e_f (fuel) [kW h/km] in the CD and CS mode, respectively and prices p_e and p_f [\$/kW h] for the electricity and fuel, respectively, we have:

$$r = (p_f e_f - p_e e_e) \quad (5)$$

$$R_k = D_{e,k} * r \quad (6)$$

The annual per range marginal operational cost reduction R_k' [\$/km,yr] is found as:

$$R'_k(AER, T) = MED_k(AER, T) * r \quad (7)$$

Assuming I_F to be a constant and the specific battery capacity cost a constant i_B [\$/kW h (nominal)] independent of battery size, the per range marginal fixed cost C' [\$/km,yr], can be found as:

$$C' = \alpha\beta^{-1} i_B e_e \quad (8)$$

where β is the battery depth of discharge [kW h (utilized)/kW h (nominal)].[8]

The specific value of the marginal electric distance for which the TCO is minimized, MED_{opt}, is the *MED* for which, on the margin, the operational cost savings equal the battery investment cost. Combining Eqs. (5), (7) and (8) we get:

$$MED_{opt} = \frac{C'}{r} = \frac{\alpha\beta^{-1} i_B}{p_f \frac{e_f}{e_e} - p_e} \quad (9)$$

The corresponding economically optimal battery range for car k is thus the *AER* that results in a $MED_k(AER,T)$ that equals the MED_{opt} (see Fig. 2).

The optimal PHEV battery will however be of range zero if MED_{opt} is larger than MED_k for all ranges:

$$AER_{k,opt}(T) = 0, \text{if } MED_{opt} > MED_k(AER, T)\ \forall\ AER \quad (10)$$

The owner of a PHEV has the possibility to offset the higher investment cost C_k by reduced running costs R_k. The (annual) net TCO savings S_k [\$/yr] for PHEV k are given as:

$$S_k = R_k - C_k \quad (11)$$

For the case of an optimal battery $AER_{k,opt}(T)$, we can further define $D^{I}_{e,k}$ [km/yr] as the annual electric distance, which operational cost savings offset the cost for the battery-capacity-investment, see Fig 2, and get:

$$D^{I}_{e,k} = MED_{opt} * AER_{opt}(T) \quad (12)$$

[5] This is the same as the recharging frequency of the marginal battery capacity, which we in some earlier works used instead of the MED.

[6] The MED concept is denoted in the same tradition as marginal cost in economics, which is defined as the derivate of the total cost with respect to the number of goods.

[7] *Usable energy capacity* is here defined as the nominal energy capacity times the depth of discharge used for grid electricity storage.

[8] *Utilized capacity* refers to the capacity corresponding to the maximum grid electricity stored. Outside this range in state-of-charge, part of the nominal capacity can be used for the hybrid energy management.

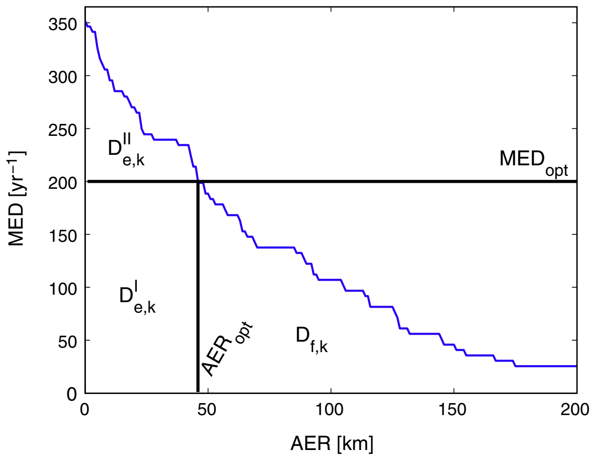

Fig. 2. For a MED curve (from Fig. 1), the optimal battery size AER_{opt} corresponding to an example MED_{opt} of 200 [yr^{-1}] (horizontal black line). $D^{I}_{e,k}$ together with $D^{II}_{e,k}$ equals the total distance driven on electricity ($D_{e,k}$) and $D_{f,k}$ is the distance traveled on fuel for vehicle k.

That is, the annuitized cost for battery-capacity-investment $C_{B,k}$ [\$/yr] is

$$C_{B,k} = r * D^{I}_{e,k} \text{ (at } AER_{k,opt}(T)) \quad (13)$$

In the continuation we call the cost reduction made available through the remaining electric distance $D^{II}_{e,k}$ [km/yr],[9] see Fig. 2, the annual battery savings $S_{B,k}$ [\$/yr]. It is useful to our analysis since it can be used to help offset the battery-capacity-independent fixed investment cost (I_F). $S_{B,k}$ is thus the remaining savings after a deduction of the annual costs for battery range. We have:

$$S_{B,k} \equiv r * D^{II}_{e,k} = R_k - C_{B,k} \text{ (at } AER_{k,opt}(T)) \quad (14)$$

2.4. Different techno-economic conditions

For each specific MED_{opt}, there are several possible combinations of techno-economic parameters, Eq. (5). For transparency, Table 1 lists several MED_{opt} and examples of the corresponding set-ups of techno-economic parameters. Generally, with development in technology, with learning and increased scale in industrial production, the MED_{opt} will decrease, i.e., go from left to right in Table 1. It can be argued that the lowering of the MED_{opt} primarily will result from decreases in costs rather than increases in savings per km of electric driving, since efficiency developments in the electric drivetrain can be assumed to be offset by efficiency gains in the competing drivetrain. In this example, the prices for fuel and electricity are set equal, and the savings per km depend on the assumed difference in energy efficiency only.[10]

What level of MED_{opt} that best represents today's situation can be discussed, but [42–47] for example report a battery price from \$450 to \$800 per kW h, which suggests that the scenarios in which MED_{opt} = 800 and 400 yr^{-1} can be thought of as fairly close to today's situation. The price has been estimated to decrease to about 250 \$/kW h by 2020 [42]. A MED_{opt} = 50 yr^{-1} would correspond to a possible future scenario in which crucial parameters have undergone considerable development.

Estimated battery costs are often given as total cost divided by the (nominal) energy capacity [\$/kW h]. But the specific cost of current PHEV batteries depends on the capacity for both power and energy. For a given power, the additional cost for energy capacity, i_B, can be considerably lower than the specific cost for the whole battery, currently indicated as 450–800 \$/kW h [42–47]. On the other hand, stated costs are often production costs and do not include mark up costs.

The extra weight from enlarging of the battery has been ignored since the weight increase will make a rather small difference to the vehicles energy demand (which would result in somewhat larger MED_{opt} for heavier batteries).[11] 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 kW h/kg) leading to less increase over time in the weight of the optimal battery, if any.

Fig. 3 shows how changes in the techno-economic parameters in Eq. (9) affect MED_{opt}, for MED_{opt} = 200 yr^{-1}. A reduction of the cost per installed battery capacity by 50% would result in a halving of the MED_{opt}, corresponding to a shift one column to the right in Table 1.

In this study we assumed the cars to all have the same specific energy use corresponding to some average conditions. In reality differences in driving behavior, ambient conditions and use of auxiliaries would result in individual parameter values e_e and e_f. As a first approximation we can assume that these varying conditions result in an equally large relative increase or decrease in energy demand per km in both CD and CS mode corresponding to an equally large relative increase (decrease) in e_e as in e_f. This would lead to an equally large increase (decrease) of the expected savings per km (r) and of the marginal battery cost (C') (see Eqs. (5) and (8)). The MED_{opt} will not change since these two effects cancel out (see Eq. (9)). The annual battery savings $S_{B,k}$ will however increase (decrease) since the savings per km have increased (decreased) (see Eq. (14)). Individual use of most auxiliary system, differences in road conditions (road gradient, wet tarmac, gravel etc.) and weather conditions etc. will therefore to a first order approximation not affect the MED_{opt} in our model. The effect of the increase or decrease of the annual battery savings $S_{B,k}$ simply tells us, as is often the case, that more energy-consuming users have more money to save from energy efficient technologies.

Heating the passenger compartment is different though. In CS mode, free waste heat from the engine can reasonably be used. However, in CD mode, for instance, according to study on BEVs [49], a battery-supplied electric heater of 4.5 kW in constant use would lead to a 16%, 35% and 64% higher energy use if following the Artemis highway, rural and urban cycle respectively, or 38% in the weighted common Artemis drive cycle (CADC). This electric heating therefore results in 19% higher and 16% lower energy use per km in Artemis exclusively urban and highway driving, respectively, compared to the CADC, or about 5% higher and 4% lower, respectively, in yearly average specific energy use when assuming the heater is used only a quarter of the year. This would in turn lead to 7% higher and 6% lower MED_{opt} for Artemis urban and highway driving, respectively. If using an electric heat pump for compartment heating, a halving of the needed electric heating power could be expected.

The specific energy use will however also be dependent on the type of driving. To estimate what level of variation that can be expected we exemplify by e_e and e_f in the 2014 EPA fuel economy labeling for the two most sold electric car[12] and hybrid models, the Nissan Leaf and Toyota Prius respectively [50]. The difference

[9] $D^{II}_{e,k} = D_{e,k} - D^{I}_{e,k}$.

[10] The price per kW h for gasoline is higher than the price of electricity in many nations, for example due to higher taxes, but these set-ups of techno-economic parameters are just examples of conditions resulting in different levels of MED_{opt} and alternative parameter choices, for example including a higher gasoline price, are therefore possible.

[11] According to [48] the extra weight for battery range will make the energy demand for a PHEV of 96 km range about 10% larger than the energy demand for a PHEV of 11 km range (including extra structural weight to support a heavier battery).

[12] We here use electric cars as proxy for the PHEV in CD mode since EPA does not label city and highway driving separately for PHEVs.

Table 1
Examples of techno-economic parameters and the resulting MED_{opt} values.

Techno-economic parameter	Optimal marginal electric distance MED_{opt} (yr^{-1})				
	800	400	200	100	50
Average number of times per week the marginal battery unit needs to be utilized	∼16	∼8	∼4	∼2	∼1
Annuity, α (yr^{-1})	0.15	0.15	0.15	0.15	0.15
Grid electricity SOC window, β [–]	0.5	0.5	0.55	0.65	0.75
Battery nominal capacity cost, i_B ($/kW h)	800	400	294	174	100
PHEV energy cost savings per km, $r = p(e_f–e_e)$ ($/km)	0.06 = 0.15 ∗ (0.6–0.2)	0.06 = 0.15 ∗ (0.6–0.2)	0.06 = 0.2 ∗ (0.45–0.15)	0.06 = 0.2 ∗ (0.45–0.15)	0.06 = 0.2 ∗ (0.45–0.15)

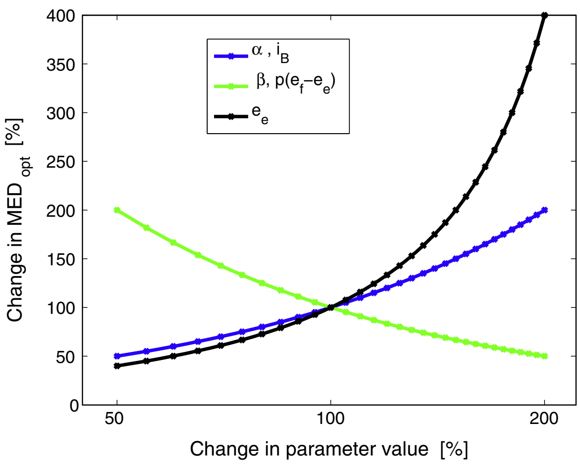

Fig. 3. Sensitivity of MED_{opt} to changes in techno-economic parameters, see Eq. (9), for $MED_{opt} = 200\ yr^{-1}$.

Table 2
Example of variations in e_e and e_f due to difference in drive cycles (EPA's city and highway cycles) and the corresponding changes in other relevant parameters normalized to EPA Combined cycle. Data from EPA's labeling of Nissan Leaf (2014) and Toyota Prius v (2014).

Parameter in our model	EPA combined	EPA city	EPA highway
e_e	1	0.90	1.13
e_f	1	0.95	1.05
r	1	0.98	1.00
C'	1	0.90	1.13
MED_{opt}	1	0.92	1.12

between EPA's combined cycle and their data on city and highway driving is shown in Table 2. In the rather extreme cases of entirely city or highway driving the change in e_e and e_f results in an 8% decrease and a 12% increase in MED_{opt}, respectively.[13] 95% of our measured vehicles have average velocities higher than the average velocity of the EPA city cycle and lower than the EPA highway cycle. 74% of the vehicles have an average speed which is more close to the average speed of combined EPA cycle than to the average speed of either the EPA city or highway cycle. It should also be noted that these type-of-driving effects work in the opposite direction to the effects of passenger compartment heating, which increases with slower driving.

The annuity also influences the total cost of ownership by annuitizing the fixed cost, I_F. The assumed annuity of 15% could for example correspond to a payback time for the extra PHEV battery and equipment of 8 years at a 5% discount rate.

[13] Similar results are achieved when for example substituting the Leaf with a Mitsubishi iMiev (2014) or substituting the Prius with a Ford Fusion Hybrid (2014). Even smaller effect on the MED_{opt} is achieved if substituting the Leaf with a Ford Focus Electric.

Two different levels, $500 and $3500, respectively, were considered for the fixed battery-capacity-independent cost, I_F. The Low I_F scenario corresponds to a situation in which the difference in the battery-capacity-independent cost between the PHEV and a competing HEV is at a minimum, corresponding to the cost for a charger and extra cabling. The High I_F is not a maximum cost scenario but a case in which larger investments are made to improve the electric drive train.

Also, possible extra costs for recharging infrastructure could be modeled through the fixed battery-capacity-independent cost. It is then reasonable that the infrastructure costs would vary with the parameter T used here; a lower T would imply a more extensive infrastructure and therefore higher costs. We have however chosen not to include the cost for infrastructure. This since it is unsettled to what extent the driver himself/herself would pay for such an infrastructure. Employers could for example provide charging at the workplace as a benefit for the employees, or as part of its environmental policy. Supermarkets and restaurants could provide free charging to attract customers. Also car drivers are as a group already through taxation paying for various road-infrastructure and charging posts could be handled in the same manner. It could however be reasonable to assume the driver has to pay for the infrastructure needed for home charging. This can then in our model be considered included under the battery-capacity-independent fixed costs I_F.

2.5. Individual car movements

Our analysis uses a data set of GPS-logged movements of 432 conventional passenger cars in private use, of model year 2002 or newer in Västra Götaland county and Kungsbacka municipality, randomly selected from the Swedish vehicle register. The region, based in southwest Sweden, has a population of about 1.6 million inhabitants and 0.7 million cars, which is about one-sixth of the total Swedish population and car fleet. The region includes Gothenburg, the second-largest town in Sweden. It is probably reasonably representative for Sweden in terms of movement patterns, car ownership, and mix of larger and smaller towns and rural areas.

The movements were logged for 1–3 months (58 days, on average). For additional information about the measurement project, see [39].

The annual driving for each vehicle is obtained by scaling the logged driving period to one year. The logs are distributed reasonably evenly across seasons from 2010 to 2012. Some of the cars have a large share of driving during a holiday period, while others have none.

3. Results

3.1. Battery sizing and viability

Fig. 4a–c shows the resulting marginal electric distance MED as a function of battery capacity (expressed as AER [km]) for the three

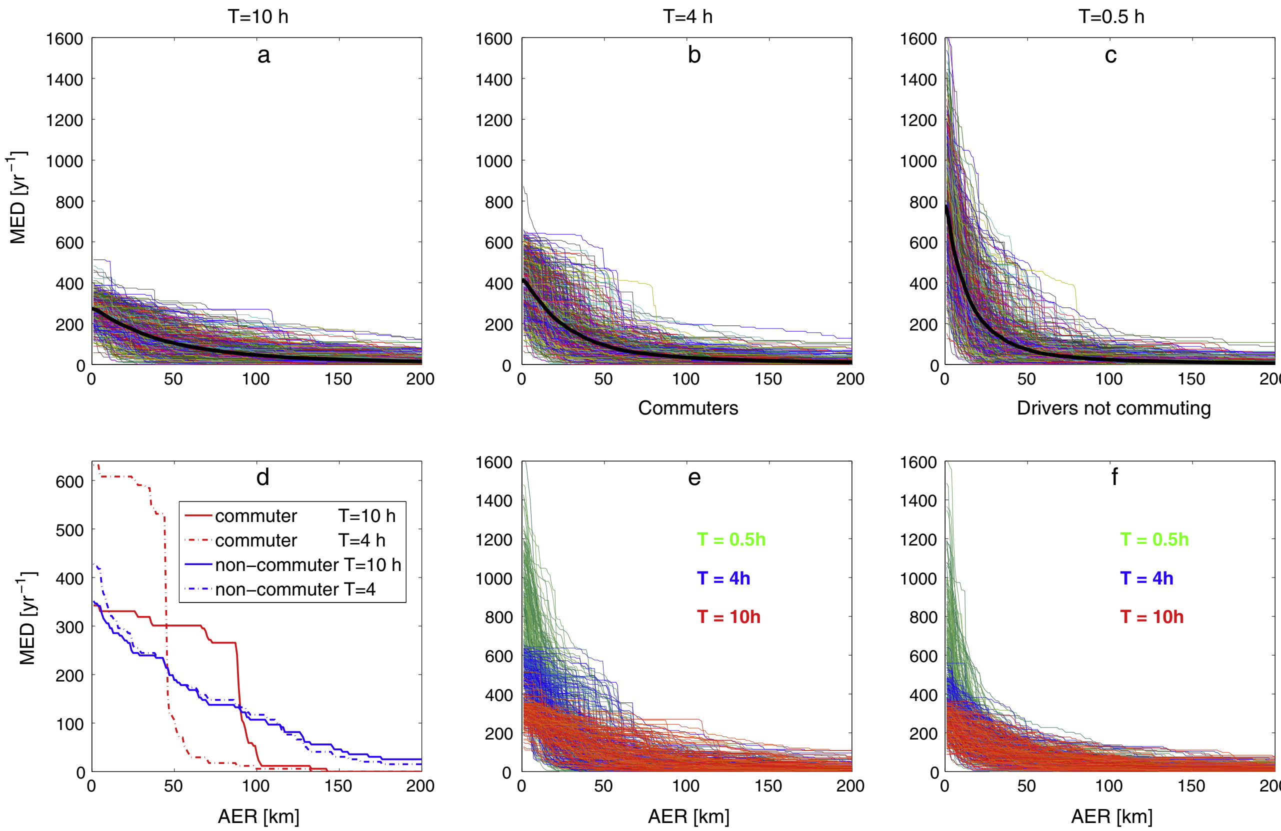

Fig. 4. (a–c) The individual marginal electric distance (*MED*) as a function of the all electric range (*AER*) and parking period *T* required to recharge the battery for the 432 cars and for the fleet average (solid black line); (d) illustrative *MEDs* for a commuter and a non-commuter for two charging options (different parking periods *T*). Note the difference in scale; (e and f) the individual *MED* as a function of the *AER* and parking period *T* for commuters (e), and non-commuters (f). The measured fleet contains 53% commuters, 35% non-commuters and 11% unknown. The number of commuters in (e) has been reduced to the same number as the non-commuters to facilitate a comparison. (The removed commuters where chosen at random.)

different charging scenarios. The individual differences in movement patterns are considerable in all three charging scenarios. In general, better charging opportunities (shorter *T*) lead to more recharging occasions, dividing the driving into shorter distances between rechargings. This results in a higher *MED* for smaller batteries and a lower *MED* for larger batteries.

The solid black lines in Fig. 4a–c give the average *MED* for the car fleet. At *AER* = 0 it corresponds to the average number of pauses longer than parking period *T*. This thus shows the average number of possible rechargings per year for different parking periods *T*. For *T* = 10 h, it is only around 270 times per year or about 0.7 times per day on average. Many cars do not drive every day, which keeps the number of possible rechargings down. Increasing the recharging options to periods of 4 h or longer raises the average number of rechargings by roughly 50%. Recharging every parking period of half an hour or more almost doubles the recharging occasions to just over two per day.

The commuters in our sample on average have a higher yearly mileage than non-commuters, about 19 and 14 thousand km, respectively, leading to, in general, higher *MEDs* for commuters. But the distribution of the movements is also important for the battery utilization, as illustrated in Fig. 4d, which shows the *MEDs* for an illustrative commuter and non-commuter with approximately the same yearly mileage and number of days driving. The individual $MED_k(AER)$ falls steeply when the movement pattern has a large number of trips of a certain length around *AER*. This can occur, for instance, when the driving is dominated by the commuting between home and work. The non-commuter's *MED* instead slowly decreases with *AER*, which is rather typical for cars not used for commuting, since they less often have a specific trip distance that dominates the pattern. A battery covering the daily round-trip commute (~90 km) could replace 95% of the fuel for the commuter but only 70% for the non-commuter. If the batteries are charged during parking periods of at least 4 h, this would lead to a larger increase in *MED* for the commuter mainly because of the possibility to charge at work. With a 44 km *AER*, the commuter would reach about 90% electric driving, while the non-commuter for the same range would only reach 45%.

The optimal battery range will depend on the current marginal battery price and on the possibilities for recharging. It is thus difficult to determine a suitable *AER* only based on the most commonly traveled daily distance.[14]

The results in Fig. 4e,f suggest that commuters, due to the work place parking, may benefit more from a PHEV than non-commuters when increasing the charging options from *T* = 10 to *T* = 4 h. However, in general, the difference is less clear-cut than in the example in Fig. 3d.

Fig. 5 shows the optimal battery size for individual cars and their corresponding yearly savings. Sizes and savings differ widely for individual movement patterns and MED_{opt}. Generally, the better the economic conditions, i.e., the shorter the *MED* needed to offset

[14] Having a steep drop in the *MED* does however mean that the corresponding *AER* would be optimal for a larger range of economic conditions. For example, in Fig. 3d when *T* = 4 h, the commuter's range would be optimal or close to optimal at the commuting distance between MED_{opt} = 500 and 100 yr^{-1}, while for the non-commuting car, the optimal battery range would go from 0 to 110 km for the same range in battery economics.

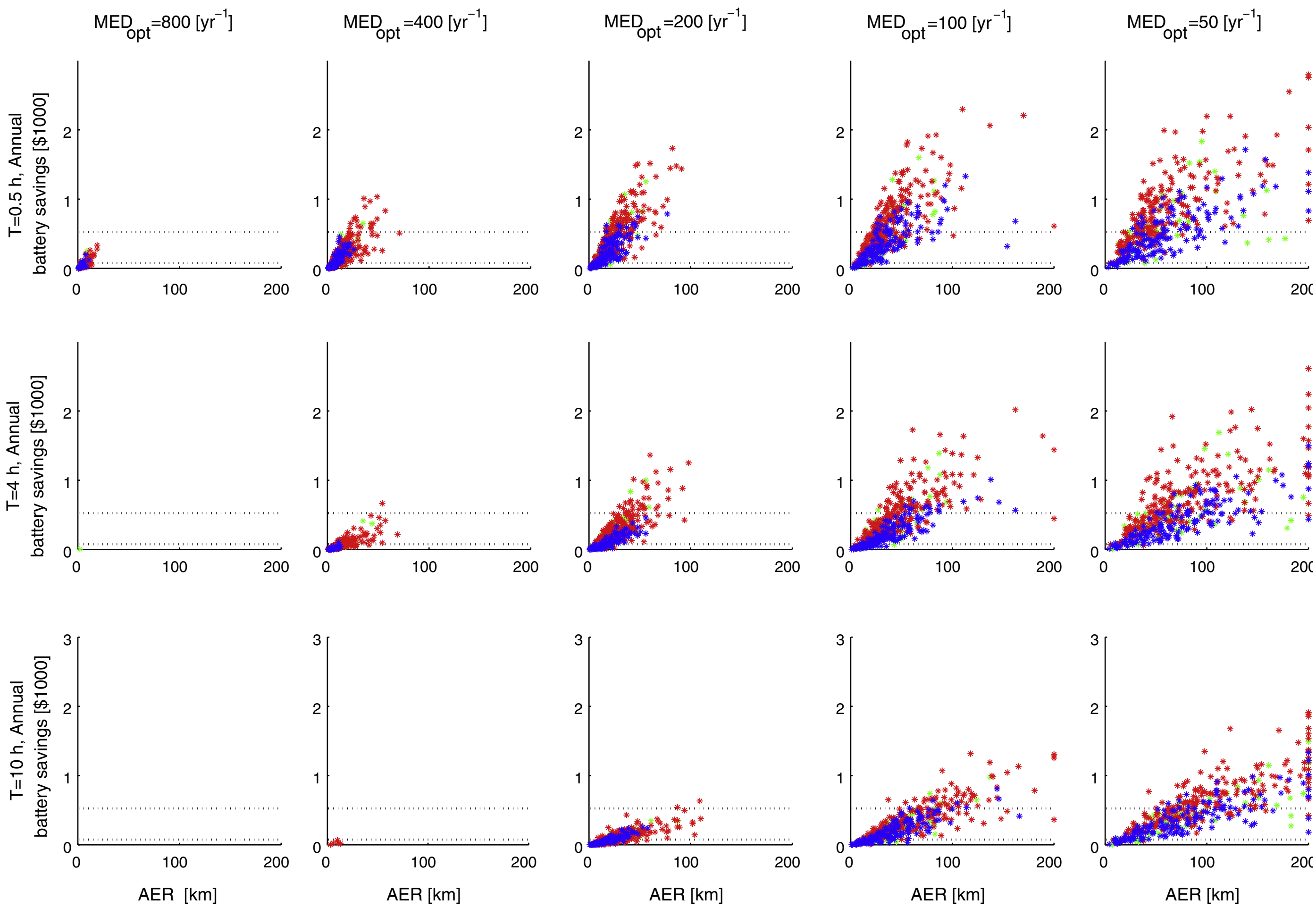

Fig. 5. Optimal battery sizes for individual movement patterns and their corresponding annual battery savings ($S_{B,k}$). Each point represents an individual movement pattern; the color of the marker indicates if the car commutes (red) or not (blue) or if commuting status is unknown (green). Results are shown for minimum marginal electric distance MED_{opt} = 800, 400, 200, 100 and 50 yr^{-1} and minimum parking period T = 10, 4 and 0.5 h. The two horizontal dotted lines indicate the savings needed to offset the Low and High I_F, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the battery investment, the more cars with batteries, the larger the batteries and the larger the savings, which are also illustrated in Fig. 9a–c depicting fleet averages.

A low MED_{opt} results in a larger variety in optimal battery sizes. For MED_{opt} = 50 yr^{-1} almost all of the cars reach enough electric distance to offset a battery investment and the optimal size varies from almost zero to 200 km, the upper limit set in the calculations. Consequently, the individual savings also vary among the movement patterns, from just above $0 to about $2800 per year.

For increased recharging options, i.e., lower T, the MED increase for smaller battery ranges means that the number of cars that can pay for the battery investments increases. The competitiveness of the PHEV thus increases with the lowering of the MED_{opt}, as well as with increased recharging options. For MED_{opt} = 800 yr^{-1}, only the most extreme recharging option, T = 0.5, allows for a number of cars to offset the battery investment.[15]

Since T = 10 h roughly corresponds to charging once per day, this charging option does not allow for a substantial number of cars to afford a battery until MED_{opt} equals 200 yr^{-1}.[16,17]

On average, the commuters reach higher savings (Fig. 6a) and constitute the majority of the first cars to be viable as PHEVs under the different charging scenarios (Fig. 5). They are also more likely to be able to offset higher levels of I_F. At T = 10 h, this is largely a result of commuters in general having larger optimal battery sizes than the non-commuters. This is shown by the small difference between commuters and non-commuters in electric distance per installed battery capacity at T = 10 h, Fig. 6b. However, at T = 4 h, the difference between the two groups is greater; even with the same optimal battery size, the commuters tend to save more on average, Fig. 6b.

Fig. 7 shows the estimated yearly mileage for all cars in the fleet and also specifically the yearly mileage for the cars that can offset different levels of PHEV investments (I_F). The average yearly mile-

[15] Except for a single movement pattern barely viable already at T = 4 h, a night-time worker whose partner uses the car during the day, resulting in a, for this sample, unusually high potential utilization of the battery.

[16] The few driving patterns that are viable already at MED_{opt} = 400 yr^{-1} manage to charge more than once per day, which is possible if, for example, the car is parked for 10 h at work.

[17] Commuting 5 days a week results in about 250 rechargings per year (disregarding vacation periods), for T = 10 h. Commuting 5 days a week with the ability to charge at work (T = 4) would double this to about 500 times a year. However, only about 80% of the commuters in our sample have more than 400 trips a year at T = 4 h. This can be due to the car owner having been on vacation, being on sick leave, changing workplace or needing to have the car repaired. Also, not all commuters drive to work 5 days a week; some could work part-time, work from home some days, etc.

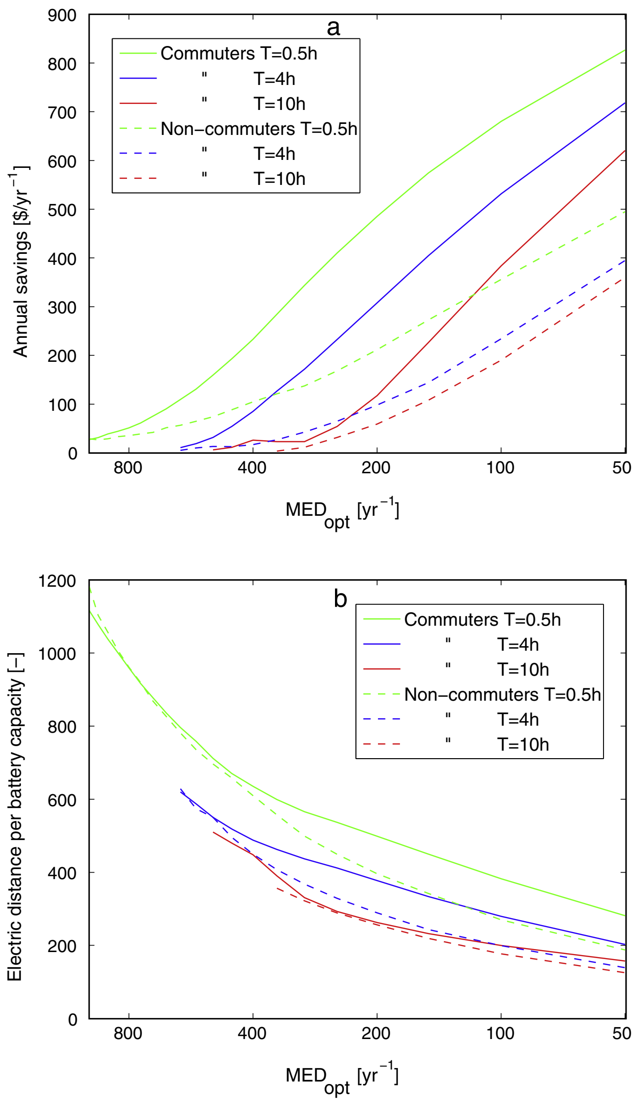

Fig. 6. For the cars viable as PHEVs, per car (a) average annual savings, (b) electric distance per installed battery capacity.

age for the measured fleet is 17,000 km, which is close to the average in 2008 for Swedish cars ⩽ 9 years of about 16,800 km, although the latter also includes cars driven for other than personal use [51].

For the conventional car, the drivers with a high yearly mileage are the first to reach break-even for a fuel-efficient investment. When investing in a PHEV, this is not necessarily the case. Instead, there is a spread in the yearly mileage among the first cars with a battery; the drivers with a very short yearly mileage are less common in the group, though, Fig. 7. Drivers with high yearly mileage are more likely to be able to offset a higher I_F. Assuming, for instance, \$0.06/km in savings and an annuity of 0.15, about 9000 km/yr of electric driving is needed to offset an I_F of \$3500.

3.2. Battery cycling

The battery cycles per year that can be expected for the optimal battery sizes are shown in Fig. 8. As an example, at $T = 4$ h and $MED_{opt} = 400$ yr^{-1}, most cars go through fewer than 600 battery cycles per year. When allowing for charging several times per day ($T = 0.5$ h), the annual cycles can reach well over 1000, for $MED_{opt} = 800$ yr^{-1}. The MED_{opt} sets the lower bound of cycles under each economic scenario. Assuming the battery is to be used for eight years, it is thus not possible to offset the investment cost faced in the case of $MED_{opt} = 800$ yr^{-1} without reaching at least $800 * 8 = 6400$ battery cycles in total.[18]

The number of battery cycles tend to decrease with battery cost, since less expensive batteries mean that larger, less frequently cycled batteries minimize the total cost of ownership. Choosing a larger battery can lower the number of cycles per year, but this reduces the savings for the driver.

3.3. Fleet composition

In the Low I_F scenario almost every driver in the fleet can afford a battery at MED_{opt} equal to 100 or 50 yr^{-1}. But for $MED_{opt} = 200$ and 400 yr^{-1} the viability largely depends on the charging option (see Fig. 8a). For instance, for $MED_{opt} = 400$ yr^{-1}, the share of cars that can afford a battery ranges from close to 0% ($T = 10$ h) to 60% ($T = 0.5$ h). For each level of MED_{opt}, the recharging opportunities are important for the total savings and thus for the possibility to recover I_F.

In the High I_F case, a considerably smaller share of the vehicle fleet is viable as PHEVs, and the introduction of PHEVs to the market would be delayed until a lower MED_{opt} is reached. The introduction will also come at a lower pace, meaning that the number of PHEVs that becomes viable for a specified decrease in MED_{opt} is lower, Fig. 9a.

Fig. 9b shows that the average battery size increases with better battery economics but also with higher I_F. With more options for charging, the average battery size tends to decrease. The larger the MED_{opt}, the smaller the range of optimal sizes and savings. In the Low I_F case, this suggests a rather small average battery size in the first cars that are viable as PHEVs. However, in the High I_F case, many of the cars with small optimal batteries cannot offset the initial investment, and the average battery sizes are almost twice as large, Fig. 9b.

Fig. 9c shows the resulting overall potential for PHEVs to replace fuel with electricity, for the vehicle fleet. A considerable share of electric driving, 25% and 45%, for charging scenarios $T = 10$ and 4 h, respectively, is reached at $MED_{opt} = 200$ yr^{-1} in the Low I_F case. For the High I_F, the MED_{opt} needs to be as low as 100 yr^{-1} to result in 20% and 35% electric drive fractions for the two charging options, respectively. The lowering of the electric drive fraction going from Low to High I_F is in this case comparable to, or slightly worse than, a doubling of the MED_{opt}. For very favorable battery economic scenarios, there is a potential to reach above 70% and 50% of electric driving for the car fleet in the Low and High I_F case, respectively.

4. Discussion

This study considers individual vehicles' movement patterns and the possibilities, based on those patterns, for PHEV investments to be economically viable under various techno-economic conditions. We introduce the core concept of the marginal electric distance (*MED*), determined by the movement pattern and options for charging. The PHEV is assumed to be driven first in a pure CD- and then CS-mode and to have a cost in surplus of its HEV counterpart that is linearly proportional to the battery energy capacity. The techno-economic conditions that minimize the TCO are summarized in the MED_{opt} parameter, which, combined with the *MED* of the individual car, gives the optimal battery range AER_{opt}. A

[18] For the definition of battery cycles, *BC*, and discussion, see Section 2.2.

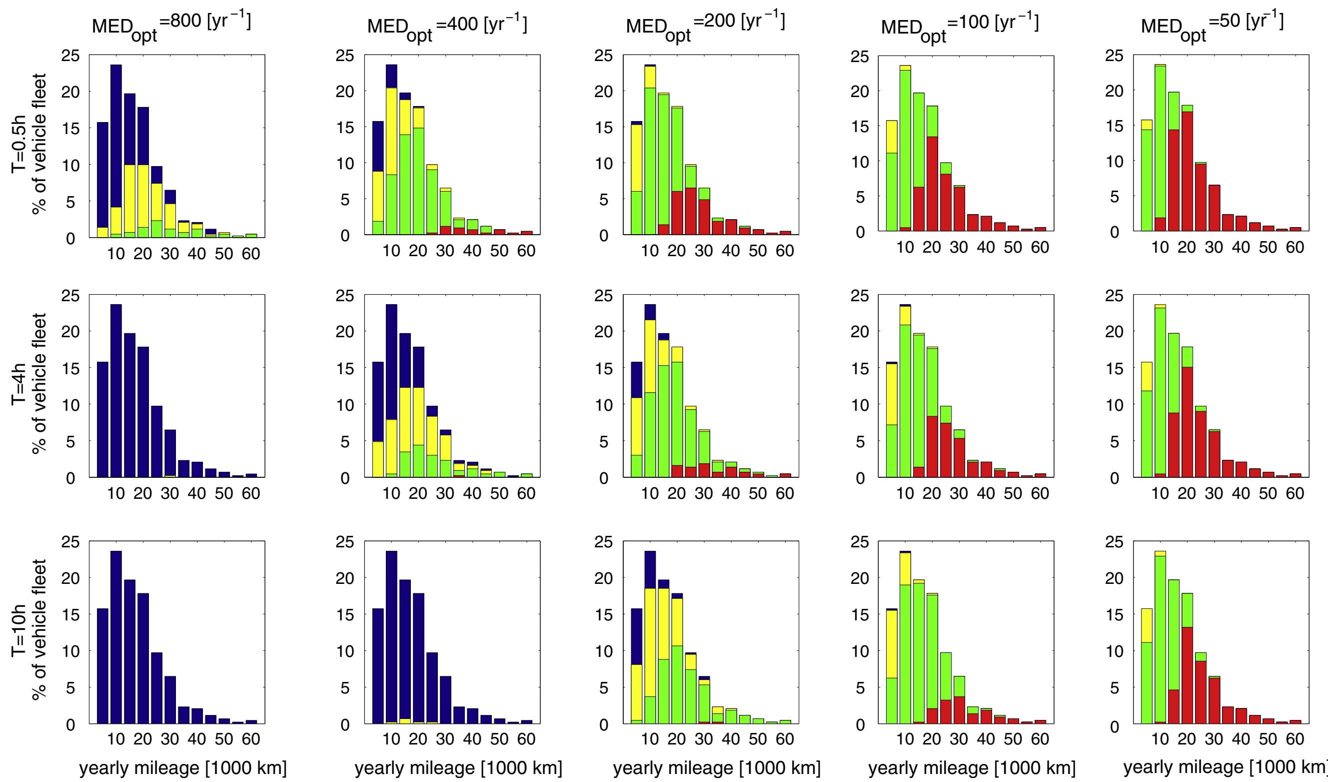

Fig. 7. Estimated yearly mileage for each car whose movement pattern cannot (blue) or can (yellow) offset a battery investment. The green and red bars represent cars that offset a battery investment and also afford the Low (500$) and High (3500$) I_F, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

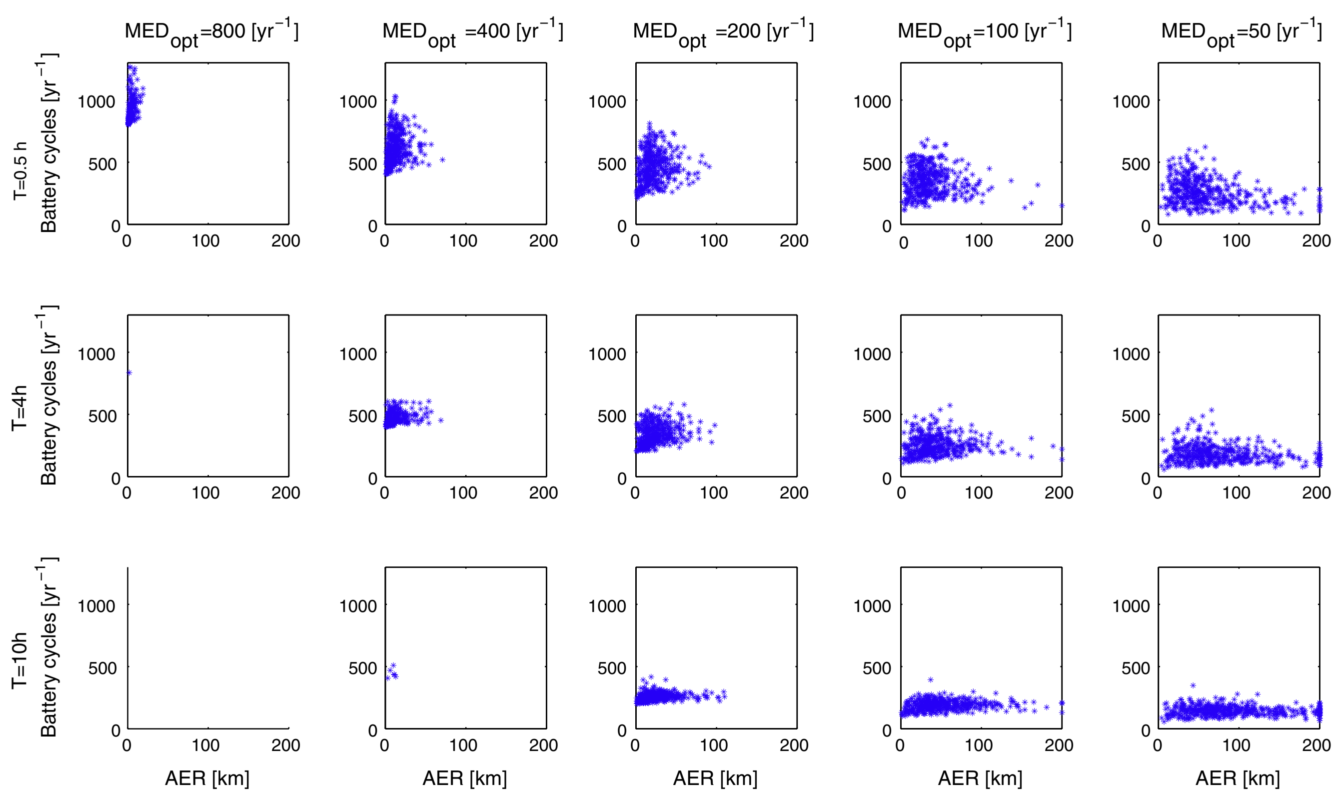

Fig. 8. Number of battery cycles per year for individually optimized battery sizes for different charging options and techno-economic conditions.

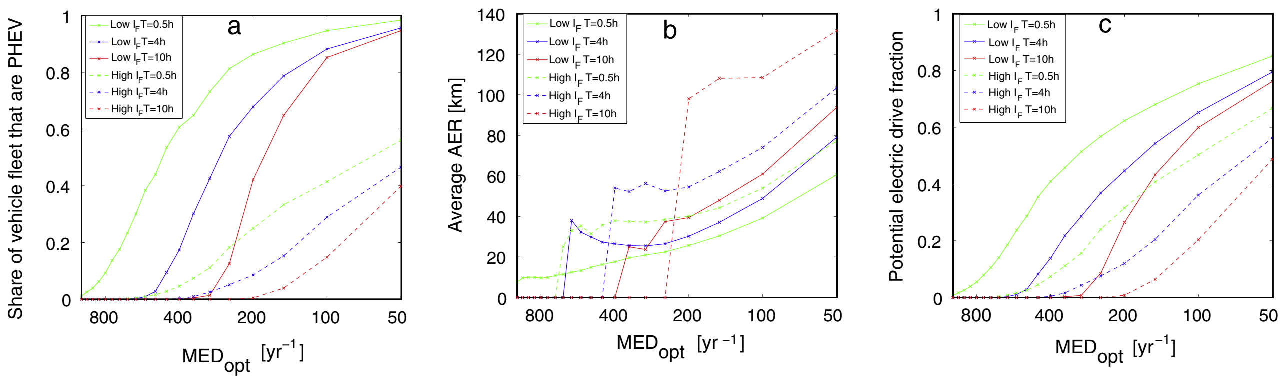

Fig. 9. (a) PHEV share of car fleet (of 432 cars), (b) average *AER* among viable PHEVs, (c) potential electric drive fraction for the car fleet. When assuming low I_F and high I_F respectively, as a function of the viability parameter MED_{opt} and charging options.

parameter I_F is included to handle an initial cost difference between the PHEV and the assumed alternative in the TCO estimate, here thought of as an HEV or efficient CV. This cost difference is meant to represent the costs of the necessary charging equipment and any driveline power enhancement when turning from the alternative to a PHEV. With this approach, we dimensioned the individual battery and assessed the viability and fuel substitution potential for PHEVs in Sweden under a large range of techno-economic conditions. The study's perspective complements many earlier studies, which focused on evaluating specific PHEV models rather than individual driving (often forced to do so by a lack of detailed movement data).

The method involves some simplifications. The movement patterns used do not cover the entire lifetime of the vehicle. Thus, they leave out effects such as changing movement patterns due to change of owner, changing travel needs in the household, and seasonal variations in the driving. We have also assumed the PHEVs to be fully charged after each break of time *T*. Limiting the charging power in our analysis would somewhat lower the utilization of large batteries when $T = 0.5$ h and to some extent also when $T = 4$ h.

Further, it is to be remembered that we here focus on the movement patterns and have intentionally excluded the information contained in the registered detailed second by second driving, which reflects, for instance, variation in average speed, driving aggressiveness, topography, etc., and which possibly reflects different specific energy (kW h/km) use. These effects are discussed under Section 2.4 and are shown to be of smaller importance for our analysis.

The study is limited to a comparison of the PHEV and its HEV/efficient CV alternative. With inexpensive batteries (i.e., at the low MED_{opt} end), which entail large optimal PHEV batteries, an alternative could also be the pure battery electric vehicle (BEV). With inexpensive batteries, the BEV range could viably be so large that it only very seldom would be a limitation for most cars. Also, in industrialized nations, many cars (in Sweden around half of the car fleet) belong to many-car households. Choosing which car to drive depending on the expected trip distance on each specific occasion could easily circumvent the BEV range limitation in many cases.

We have found that a large share of the movement patterns with earliest viability and the movement patterns that resulted in the highest savings belonged to commuters. Commuters reach higher yearly mileage on average than non-commuters, their movement patterns also commonly include two longer parking periods per day and are thus suitable for more charging. Their movement patterns commonly have a large number of trips of the same distance. All these conditions are important for a high utilization of the optimal battery and high savings. This highlights commuters as an important group for the PHEV market, both in the long term and as potential early adopters.

Today, all marketed PHEV models are available with one battery size only (even though sizes do differ between models). As one would expect, the optimal battery size of an individual PHEV increases as the marginal battery cost decreases, which suggests that marketed batteries should increase in size over time as battery cost decreases. But new viable PHEVs with small optimal batteries are also added. For the vehicle fleet, the range of optimal battery sizes thus increases. The results suggest that both buyers of PHEVs and society at large would benefit (in terms of increased savings and increased fuel substitution, respectively) from more battery sizes to choose from on the market, even if fully custom-sized batteries may not be feasible. For instance, commuters' possibility to fully reap the potential savings from improved charging options at work depends on the availability of suitable battery sizes. A modular battery system could be one way forward.

The results also show that the battery-capacity-independent fixed investment cost (I_F) substantially affects the cars' economic viability. This impacts the time and pace of the introduction, the long-term market penetration, and the corresponding potential for fuel substitution for PHEVs. Currently, a challenge for cars with a small battery is the available maximum power, which may not be sufficient to enable a pure electric CD-mode for most real driving. In a blended CD-mode, the energy efficiency gains are smaller. But low maximum power may also mean a lower transition cost I_F. A reasonable transition from an HEV to a PHEV could be, with increased PHEV battery range, a gradual increase of the maximum electric power and thus the I_F, and therefore in parallel a gradual increase of the CD-mode energy efficiency.[19] However, this transition will depend on the market's perception, what car manufactures will offer and how different customers perceive and value various properties of different drivelines.[20] If policies to support the uptake

[19] When modeling the future cost of batteries of different chemistries and sizes, [52] argue (contrary to their earlier analysis in [45]) that optimal battery for HEVs and possibly small PHEV batteries may be designed to have less available power than larger PHEV batteries.

[20] This can be illustrated with two PHEVs, which represent two extremes in the current market. The Toyota Prius PHEV fully builds on the Prius HEV, but the battery has been exchanged for a small PHEV battery with an electricity-only range of a moderate 20 km, while the rest of the driveline is kept intact. The General Motors' Chevrolet Volt/Opel Ampera has a range on electricity of around 60 km. It is a power-split PHEV with an electric motor as powerful as a fully battery electric vehicle and with a reasonably small fuel engine as range extender. The electrical components are necessarily designed for electric drive only and for meeting all the performance requirements on the driveline. The difference in electric driveline between the two models also leads to large differences in energy use and emissions of regulated pollutants depending on the driving conditions [53].

of electrified vehicles are present, the transition will also depend on the specific incentives put forward and how these influence the viability and valuation of various designs [54].

5. Conclusion

The viability of PHEVs in Sweden was assessed utilizing representative data on car movement patterns for 432 passenger cars in private use logged with GPS for 30 days or more. A simple parameterization was used to analyze the requirements on hypothetical PHEV counterparts to the vehicles in the data set performing the same individual movements, under a large range of techno-economic conditions.

Good opportunities for charging and regularity in distance traveled between rechargings increase the potential for battery-powered driving and, along with a high annual mileage, enhance the viability of the PHEV. Therefore, commuters are likely to be dominating among the first drivers for whom the PHEV will be cost-effective. Making charging infrastructure available at work places would enhance the opportunity for this group of early adopters, as we show that charging while at work is comparable at the initial stage to halving the marginal battery costs for the average consumer.

Acknowledgments

This analysis was done within the Chalmers Energy Initiative and the Swedish car movements measurement project financed by The Swedish Energy Agency, The Göteborg Energy Research Foundation, Consat, Lindholmen Science Park, Telenor, and Vattenfall, which is greatly acknowledged.

Appendix A. List of variables

α (yr^{-1})	THE annuity of the initial PHEV investment
AER_k (km)	The all-electric range of the modeled PHEV for car k
$\mathrm{AER}_{\mathrm{k,opt}}$ (km)	The optimal all-electric range for car k
β (kW h (utilized)/kW h (nominal))[a]	The battery depth of discharge
BC_k (yr^{-1})	The battery cycles for car k. Defined as the total yearly energy flow through the battery divided by the usable energy capacity[b]
C_k ($/yr)	The (extra) annual costs for PHEV k comprising the annuitized cost for the battery investment $I_{B,k}$ ($) and the battery-capacity-independent fixed investment I_F ($)
C' ($/km,yr)	The marginal fixed cost for increasing battery capacity
$C_{B,k}$ ($/yr)	The annuitized cost for battery-capacity-investment for car k
$D_{e,k}$ (km/yr)	The annual distance driven on electricity for car k
$D^{I}_{e,k}$ (km/yr)	The annual electric distance, which operational cost savings offset the cost for the battery-capacity-investment for car k
$D^{II}_{e,k}$ (km/yr)	The annual electric distance proportional to the annual battery savings $S_{B,k}$
e_e (kW h/km)	The specific electric energy use per km for the model PHEV
e_f (kW h/km)	The specific fuel energy use per km for the model PHEV
$I_{B,k}$ ($)	The initial investment cost for the additional battery capacity for car k
I_F ($)	The fixed battery-capacity-independent cost of turning an HEV into a PHEV
MED_k $\left[\frac{\text{km (electric driving)/yr}}{\text{km (range)}} = \text{yr}^{-1}\right]$	The extra annual electric distance made possible by an additional unit of battery range for car k. Defined as the derivative of $D_{e,k}$ with respect to the range AER_k
MED_{opt} $\left[\frac{\text{km (electric driving)/yr}}{\text{km (range)}} = \text{yr}^{-1}\right]$	The specific value of the marginal electric distance MED for which the total cost of ownership is minimized. Also the minimum electric distance needed to offset the cost for a marginal battery range increase
p_e ($/kW h)	Price for electricity
p_f ($/kW h)	Price for fuel
r ($/km)	The specific operational cost savings from using electricity instead of fuel
R_k ($/yr)	The annual operational cost reduction for driving PHEV instead of HEV for car k
R_k' ($/km,yr)	The annual per range marginal operational cost reduction for car k
T (h)	The minimum lengths of parking periods between trips used for charging
S_k ($/yr)	The (annual) total cost of ownership savings for PHEV k
$S_{B,k}$ ($/yr)	The annual battery savings, the cost reduction for car k made available through the remaining electric distance $D^{II}_{e,k}$ (km/yr)

[a] *Utilized capacity* refers to the capacity corresponding to the maximum grid electricity stored. Outside this range in state-of-charge, part of the nominal capacity can be used for the hybrid energy management.

[b] Usable energy capacity is here defined as the nominal energy capacity times the depth of discharge used for grid electricity storage.

References

[1] Wu X, Dong J, Lin Z. Cost analysis of plug-in hybrid electric vehicles using GPS-based longitudinal travel data. Energy Policy 2014;68:206–17. http://dx.doi.org/10.1016/j.enpol.2013.12.054.

[2] Michalek J, Chester M, Jaramillo P, Samaras C, Shiau C-S, Lave L. Valuation of plug-in vehicle life cycle air emissions and oil displacement benefits. PNAS 2011. http://dx.doi.org/10.1073/pnas.1104473108.

[3] Karabasoglu O, Michalek J. Influence of driving patterns on lifecycle cost and emissions of hybrid and plug-in electric vehicle powertrains. Energy policy 2013;2013. http://dx.doi.org/10.1016/j.enpol.2013.03.047.

[4] Peterson S, Michalek J. Cost-effectiveness of plug-in hybrid electric vehicle battery capacity and charging infrastructure investment for reducing US gasoline consumption. Energy policy 2012;2012. http://dx.doi.org/10.1016/j.enpol.2012.09.059.

[5] Le Duigou A, Guan Y, Amalric Y. On the competitiveness of electric driving in France. Impact of driving patterns. Renew Sustain Energy Rev 2014. http://dx.doi.org/10.1016/j.rser.2014.04.056.

[6] Neubauer J, Brooker A, Wood E. Sensitivity of plug-in hybrid electric vehicle economics to drive patterns, electric range, energy management, and charge strategies. J Power Sources 2012;2012. http://dx.doi.org/10.1016/j.jpowsour.2012.07.055.

[7] Gonder J, Simpson A. Measuring and reporting fuel economy of plug-in hybrid electric vehicles. NREL/CP-540-40377. <http://www.nrel.gov/docs/fy07osti/40377.pdf>; 2006.

[8] Electric Power Research Institute. Comparing the benefits and impacts of hybrid electric vehicle options. Palo Alto [CA]: Electric Power Research Institute; 2001.

[9] Electric Power Research Institute. Comparing the benefits and impacts of hybrid electric vehicle options for compact sedan and sport utility vehicles. Palo Alto [CA]: Electric Power Research Institute; 2002.

[10] Electric Power Research Institute. Advanced batteries for electric drive vehicles a technology and cost-effectiveness assessment for battery electric vehicles, power assist hybrid electric vehicles and plug-in hybrid electric vehicles. Palo Alto [CA]: Electric Power Research Institute; 2004.

[11] Simpson A. Cost-benefit analysis of plug-in hybrid electric vehicle technology. In: 22nd International battery, hybrid and fuel cell electric vehicle symposium and exposition (EVS-22). Yokohama (Japan): National Renewable Energy Lab; 2006.

[12] United States Department of Energy (DOE). Annual energy outlook 2009 with projection to 2030. Washington [DC]: U.S. Energy Information Administration; 2009.

[13] Shiau C-S, Michalek J. Global optimization of plug-in hybrid vehicle design and allocation to minimize life cycle greenhouse gas emissions. J Mech Des 2011. http://dx.doi.org/10.1115/1.4004538.

[14] Lin Z, Greene D. Assessing energy impact of plug-in hybrid electric vehicles: significance of daily distance variation over time and among drivers. Transp Res Rec 2011;2287:37–43. http://dx.doi.org/10.3141/2252-13.

[15] Kelly J, MacDonald J, Keoleian G. Time-dependent plug-in hybrid electric vehicle charging based on national driving patterns and demographics. Appl Energy 2012;94:395–405.

[16] Al-Alawi B, Bradley T. Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles. Appl Energy 2013;103:488–506. http://dx.doi.org/10.1016/j.apenergy.2012.10.009. ISSN 0306-2619.

[17] Kihm A, Trommer S. The new car market for electric vehicles and the potential for fuel substitution. Energy Policy 2014. http://dx.doi.org/10.1016/j.enpol.2014.05.021.

[18] Bishop J, Martin N, Boies A. Cost-effectiveness of alternative powertrains for reduced energy use and CO_2 emissions in passenger vehicles. Appl Energy 2014;124:44–61.

[19] Redelbach M, Özdemir ED, Friedrich HE. Optimizing battery sizes of plug-in hybrid and extended range electric vehicles for different user types. Energy policy 2014;2014. http://dx.doi.org/10.1016/j.enpol.2014.05.052.

[20] Karlsson S, Wiedemann T. G4V: impact and possibilities of a mass introduction of electrified vehicles on the electricity networks in Europe. In: Proceedings of EVS25, Shenzhen, China; November 5–9, 2010.

[21] Elango V, Guensler R, Ogle J. Day-to-day travel variability in the commute Atlanta study. Transp Res Rec 2014:39–49. http://dx.doi.org/10.3141/2014-06.

[22] Pas E, Sundar S. Intrapersonal variability in daily urban travel behavior: some additional evidence. Transportation (Netherlands) 1995;22:135–50. http://dx.doi.org/10.1007/BF01099436.

[23] Pendyala R, Pas E. Multi-day and multi-period data for travel demand analysis and modeling. In: TRB transportation research circular EC008: Transportation; 2000.

[24] Karlsson S, Jonson E. The importance of car movement data for determining design, viability and potential of PHEVs. In: Proceedings of international mobility advanced forum (IAMF) Geneva March 8–9, 2011.

[25] Puget SoundRegionalCouncil. Traffic choices study. Technical report. <⟨http://www.psrc.org/assets/37/summaryreport.pdf>; 2008 [accessed 01.07.14].

[26] Khan M, Kockelman K. Predicting the market potential of plug-in electric vehicles using multiday GPS data. Energy Policy 2012;46:225–33.

[27] Schoenfelder S, Li H, Guensler R, Ogle J, Axhausen K. Analysis of commute Atlanta instrumented vehicles GPS data: destination choice behavior and activity spaces. Arbeitsberichte Verkehrsund Raumplanung, 303, IVT, ETH, Zürich; 2005. http://dx.doi.org/10.3929/ethz-a-005226366.

[28] Pearre N, Kempton W, Guensler R, Elango V. Electric vehicles: how much range is required for a day's driving? Transp Res Part C: Emerging Technol 2011;19(6):1171–84. http://dx.doi.org/10.1016/j.trc.2010.12.010.

[29] Santini D, Zhou Y, Elango V, Xu Y, Guensler R. Daytime charging-what is the hierarchy of opportunities and customer needs? – A case study based on Atlanta commute data. In: TRB 93rd annual meeting compendium of papers; 2014.

[30] http://auto21.uwinnipeg.ca/index.html.

[31] Ashtari A, Bibeau E, Shahidinejad S. Using large driving record samples and a stochastic approach for real-world driving cycle construction: Winnipeg driving cycle. Transp Sci 2014;48(2):170–83. http://dx.doi.org/10.1287/trsc.1120.0447.

[32] Smith R, Shahidinejad S, Blair D, Bibeau E. Characterization of urban commuter driving profiles to optimize battery size in light-duty plug-in electric vehicles. Transp Res Part D 2011;16:218–24. http://dx.doi.org/10.1016/j.trd.2010.09.001.

[33] Smith R, Morison M, Capelle D, Christie C, Blair D. GPS-based optimization of plug-in hybrid electric vehicles' power demands in a cold weather city. Transp Res Part D 2011;16:614–8. http://dx.doi.org/10.1016/j.trd.2011.08.008.

[34] Paffumi E, De Gennaro M, Scholz H, Martini G. Assessment of the potentiality of electric vehicles and charging strategies to meet urban mobility requirements. Transp A: Transp Sci 2014. http://dx.doi.org/10.1080/23249935.2014.913732.

[35] De Gennaro M, Paffumi E, Scholz H, Martini G. GIS-driven analysis of e-mobility in urban areas: an assessment of the impact on the electric energy distribution grid. Appl Energy 2014;124:94–116.

[36] De Gennaro M, Paffumi E, Scholz H, Martini G. Analysis and assessment of the electrification of urban road transportation based on real-life mobility data. In: 27th Electric vehicles symposium, Barcelona (Spain); 2013.

[37] http://www.theevproject.com/index.php.

[38] Smart J, Bradley T, Salisbury S. Actual versus estimated utility factor of a large set of privately owned Chevrolet volts. SAE world congress 2014. http://dx.doi.org/10.4271/2014-01-1803.

[39] Karlsson S. The Swedish car movement data project: final report. PRT report 2013:1, Chalmers University of Technology, Gothenburg. <http://publications.lib.chalmers. se/records/fulltext/187380/local_187380.pdf>; 2013.

[40] Karlsson S, Kullingsjö L-H. GPS measurement of Swedish car movements for assessment of possible electrification. In: Proceedings of EVS27 symposium, Barcelona, Spain. <http://publications.lib.chalmers.se/records/fulltext/184575/local_184575.pdf>; 2013.

[41] Karlsson S. Optimal size of PHEV batteries from a consumer perspective – estimation using car movement data and implications for data harvesting. WEVA World Electric Vehicle J 2009;3. http://www.evs24.org/wevajournal/weva.html.

[42] Deutsche Bank. The end of the oil age 2011 and beyond: a reality check. <http://bioage.typepad.com/files/1223fm-05.pdf>; 2010.

[43] Element energy limited. Cost and performance of EV batteries – final report for the committee on climate change 21/03/2012. <http://www.element-energy.co.uk/wordpress/wp-content/uploads/2012/06/CCC-battery-cost_-Element-Energy-report_March2012_Finalbis.pdf>; 2012.

[44] Graham R, et al. Comparing the benefits and impacts of hybrid electric vehicle options, report 1000349. Palo Alto, USA: Electric Power Research Institute. 2001.

[45] Nelson P, Santini D, Barnes J. Factors determining the manufacturing costs of lithium-ion batteries for PHEVs. In: Proceedings to EVS24 stavanger, Norway. <http://www.transportation.anl.gov/pdfs/B/624.PDF>; 2009.

[46] Vijayagopal R, Maloney P, Kwon J, Rousseau A. Maximizing net present value of a series PHEV by optimizing battery size and vehicle control parameters. SAE paper 2010-01-2310. http://dx.doi.org/10.4271/2010-01-2310; 2010.

[47] Gopalakrishnan D, van Essen H, Kampman B, Grünig M. Impacts of electric vehicles – deliverable 2 assessment of electric vehicle and battery technology. Delft, CE Delft. <http://ec.europa.eu/clima/policies/transport/vehicles/docs/d2_en.pdf>; 2011.

[48] Shiau C-S, Samaras C, Hauffe R, Michalek J. Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles. Energy Policy 2009;37:2653–63.

[49] Laurikko J, Granström R, Haakana A. Realistic estimates of EV range based on extensive laboratory and field tests in Nordic climate conditions. In: Proceedings of EVS27 symposium, Barcelona, Spain; 2013.

[50] US department of energy. <www.fueleconomy.com>; 2014 [accessed 27.11.14].

[51] Transport Analysis. Körsträckor 2008 (driving distances 2008). Published 2011-04-18; 2011.

[52] Santini D, Gallagher K, Nelson P. Modeling of manufacturing mosts of lithium-ion batteries for HEVs, PHEVs, and EVs. In: Proceedings to EVS25, Shenzhen, China; 2010.

[53] Duarte G, Lopes R, Gonçalves G, Farias T. Energy and environmental characterization of operational modes of plug-in vehicles. In: Proceedings of EVS27 symposium, Barcelona, Spain; 2013.

[54] Kullingsjö L-H, Karlsson S, Sprei F. Conflicting interests in defining an 'optimal' battery size when introducing the PHEV? In: Proceedings of EVS27 symposium, Barcelona, Spain. <http://publications.lib.chalmers.se/records/fulltext/184577/local_184577.pdf>; 2013.