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Objective functions for plug-in hybrid electric vehicle battery range optimization and possible effects on the vehicle fleet

Lars-Henrik Björnsson*, Sten Karlsson, Frances Sprei

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

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ABSTRACT

This study analyzes how, in a possible electrification of the car fleet through plug-in hybrid electric vehicles (PHEV), the choice of objective function, which potentially reflects different stakeholders' interests, may influence the resulting optimal PHEV battery range, the PHEV share in the vehicle fleet, the fleet total cost of ownership (TCO) savings, and the fleet electric drive fraction under various economic conditions and policy options.

The optimal battery range can differ considerably among objective functions, especially between the objectives of maximizing the number of PHEVs and maximizing driving on electricity. Increased viability of the PHEV, for instance, through lower battery costs, higher running cost savings, or PHEV-promoting subsidies, will strengthen this effect. Therefore, a high share of viable PHEVs in the vehicle fleet does not necessarily result in a high share of electric driving. When designing policies to promote PHEVs, both the short- and long-term policy objectives and their potential effects need to be considered explicitly.

1. Introduction

While a hybrid electric vehicle (HEV) mainly runs on the same fuel as a conventional combustion engine, a plug-in hybrid electric vehicle (PHEV) has the potential to replace most of that fuel with electricity from the grid. Further, the driving-range limitations associated with a pure battery electric vehicle (BEV) do not apply to the PHEV. This makes the PHEV an interesting option for reducing greenhouse gas (GHG) emissions and local air pollutants as well as energy dependence, without sacrificing performance. However, how large fuel reduction that could be expected from PHEVs strongly depends on the battery range and driving and charging patterns (Björnsson and Karlsson, 2015). To maximize fuel reduction, battery capacity should be designed to reach a high share of electric driving. However, maximizing fuel reduction might not be the main objective for all stakeholders when optimizing battery range. Car owners could be more interested in reaching a low total cost of ownership (TCO), while manufacturers might focus on a battery range that suits as many potential buyers as possible. In this study, we analyze how the optimal battery range for the PHEV and the resulting vehicle fleet properties vary with the choice of objective function under various techno-economic conditions and policy options.

* Corresponding author.
E-mail addresses: larshenrik.bjornsson@gmail.com (L.-H. Björnsson), sten.karlsson@chalmers.se (S. Karlsson), fsprei@chalmers.se (F. Sprei).

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1.1. Background

Driven to a large extent by the increasingly stricter regulations on fuel use and CO_2 emissions, (for example CAFE and GHG standards by National Highway Traffic Safety Administration, NHTSA and the U.S. Environmental Protection Agency, EPA[1] and mandatory emission reduction targets in the EU[2]) the on-going trend towards more fuel-efficient cars has led to various degrees of hybridization of the powertrain. Today, what should count as a "conventional" vehicle (CV) is somewhat ambiguous. A wide variety of models up to and including full hybrids are successfully marketed and sold[3], and most cars will soon have at least a stop/start system.

Also, PHEV technology varies. Manufacturers have introduced PHEV models that differ to varying degrees with respect to battery range, electric powertrain, and departure from the manufacturer's non-PHEV models. For example, Toyota's Prius PHEV builds on its original gasoline HEV-only Prius. The body design and fully integrated series/parallel hybrid powertrain are at large the same in the PHEV as in the HEV. The first version of the PHEV had a moderate electricity-only range of 20 km. The new version from late 2016 is offered with an all-electric range of approximately 35 km. The rest of the powertrain is kept intact with moderate electric power.

General Motors' Chevrolet Volt/Opel Ampera is a PHEV with greater electric range, about 85 km (first version about 60 km), with a reasonably small fuel engine as a range extender. The electrical components are therefore necessarily designed for electric drive and for meeting all the power requirements of the vehicle. The vehicle only exists as a PHEV with its own design, which differs from those of all other (hybrid and non-hybrid) vehicles in the GM family.

Thus, depending on the market perception of both how a PHEV should be designed and the requirement on its electric powertrain, as well as of what the alternative conventional/hybrid car looks like, it is possible that the transition from the fuel-efficient conventional/hybrid car to the PHEV may involve a small or a large change of the electric powertrain and its performance. This implies, besides the extra costs for a smaller or larger PHEV battery, a smaller or a larger initial powertrain cost corresponding to the level of technical change. Most studies have focused on the importance of battery cost. We have shown that the powertrain cost also can have a large influence on the viability of the PHEV, especially for short-range PHEVs (Björnsson and Karlsson, 2015). Axsen and Kurani (2013) preformed a survey to compare consumers' stated interest in conventional gasoline, hybrid, blended plug-in hybrid, all-electric plug-in hybrid and pure electric vehicles of varying designs and prices. They found that the low-powered and cheaper, blended PHEV more frequently was chosen than the more expensive all-electric PHEV.

1.1.1. Subsidies

There are today a number of countries and regions with policies in place to enable an earlier introduction of electrified vehicles. While most subsidies for PHEVs and BEVs are indifferent to battery range or capacity, U.S. federal tax credits are a prominent exception, which start at \$2500 for 4 kWh and gradually increase with each additional kWh up to \$7500. The Nissan Leaf and the Chevrolet Volt are both eligible for the full tax credit, while the Toyota Prius PHEV receives \$2500 (IRS, 2013). Additional subsidies exist in some states: e.g., in California, PHEVs are eligible for a rebate of \$1500, while BEVs receive up to \$2500 depending on range (California EPA, 2012)[4]. In Sweden, a BEV qualify for a rebate of \$5000, while a PHEV with emissions below 50 g CO_2/km qualify for a rebate of about \$2500 (Transportstyrelsen, 2017). In France, any vehicle with CO_2-emissions under 20 g CO_2/km receives a rebate of \$6300, which is gradually reduced for higher CO_2 emissions (ACEA, 2015). In the UK, BEVs and PHEVs with CO_2 emissions below 75 g/km are eligible for a grant of up to \$7200 and partitioned in three categories: vehicles with CO_2 emissions below 50 g/km and a zero-emission range of at least either 70 or 10–69 miles, or CO_2 emission between 50 and 75 g/km and a zero-emission range of at least 20 miles (ACEA, 2015). China offers a flat subsidy of about \$5400 (Mock and Yang, 2014).

Besides subsidies, there are several other possibilities to through policies facilitate an earlier introduction of PHEVs. In Sweden for example, PHEVs used as company cars for private driving have a lower fringe benefit tax than conventional cars (Skatteverket, 2017). For vehicle manufacturers, PHEVs are considered low emission vehicles that receive super-credits to meet the corporate average emissions and fuel economy standards in the U.S. and emission reduction targets in Europe (EPA, 2010b; European commission 2015).

1.2. Literature review

A number of studies have analyzed optimal driving ranges for PHEVs (Björnsson and Karlsson, 2015, 2017; Shiau and Michalek, 2011; Shiau et al., 2009, 2010; Smith et al., 2011; Lin, 2012; Özdemir and Hartmann, 2012; Hou et al., 2014; Redelbach et al., 2014; Meinrenken and Lackner, 2014; Kontou et al., 2015). Some have investigated optimality through minimizing TCO (Björnsson and Karlsson, 2015; Smith et al., 2011; Lin, 2012; Hou et al., 2014; Redelbach et al., 2014). Others have compared the tradeoffs between minimizing TCO versus minimizing GHG emissions or fuel use (Shiau and Michalek, 2011; Shiau et al., 2009, 2010; Özdemir and

[1] The EPA has established national GHG emissions standards under the Clean Air Act, and the NHTSA has established Corporate Average Fuel Economy (CAFE) standards under the Energy Policy and Conservation Act. EPA's standards are projected to result in an average industry fleet wide level of 155 g of CO_2 per km (250 g per mile) in model year 2016 (EPA, 2010a). The program was extended for the period 2017 to 2025 with the projection to result in an average industry fleet wide level of 101 g CO_2 per km (163 g per km) in model year 2025 (EPA, 2012).

[2] EU legislation sets mandatory emission reduction targets for new cars, where the target for average emission levels of new cars sold in the EU after 2015 should be under 130 g of CO_2 per km. From 2020 and onwards the target is set at 95 g per km (European Parliament, 2009).

[3] Today 15 million microhybrids are sold yearly; one vehicle battery market forecaster claims 35 million will be sold in 2020 (Pillot, 2016).

[4] Recently, an income cap for high-income users was introduced (Clean Vehicle Rebate Project, 2015).

Hartmann, 2012). Meinrenken and Lackner (2014) have, without considering the resulting economic viability, optimized battery range to minimize greenhouse gas emissions over the cars life time. Kontou et al. (2015) instead translated the costs of GHG emissions into monetary terms to find an optimal battery range that minimizes total societal cost during the car's lifetime. The battery range was indirectly optimized in Peterson and Michalek (2013), who analyzed cost effectiveness of subsidizing PHEVs for reducing gasoline consumption and, in Michalek et al. (2011), who assessed the potential for reducing oil consumption and air emissions by introducing HEVs, PHEVs, or BEVs.

What should the purpose be of a policy that promotes PHEVs? Shiau et al. (2009), Michalek et al. (2011), and Kontou et al. (2015) argue that policies should target the introduction of low-range PHEVs since this is found to minimize the TCO, the cost of fuel reduction, and the total societal cost. Redelbach et al. (2014) also suggest that battery ranges today should be rather short if optimized for a low TCO. They also recommend that policies should be designed to decrease the cost of long-range PHEVs to better reduce total GHG emissions from the vehicle fleet. Shiau et al. (2010), Shiau and Michalek (2011) and Meinrenken and Lackner (2014) point out that for the purpose of GHG reduction, the optimal battery range would increase as fossil fuels decrease in power generation.

However, it may not be easy to compare different objective functions. For example, how should we compare the societal gain of increased fuel security to a loss in cumulative cost savings for users? Different stakeholders are also likely to assess the values of the outcomes differently, since they have diverging interests. Most car owners would probably favor a lower TCO, whereas minimizing fuel use benefits society at large through the reduction of GHG emissions and enhancement of energy security. Car manufacturers are perhaps only indirectly interested in the TCO of the drivers and the total distance driven on electricity; they might instead focus on selling more cars. Manufacturers may also want to position their brands in electromobility and establish plans in anticipation of future changes in market conditions and energy/fuel/emissions regulations. For the moment, manufacturers' interest in selling PHEVs might be limited to earning credits related to their corporate emission targets (Bernhart et al., 2015), which might, as discussed by Redelbach et al. (2014), push them to install larger batteries to reduce their average fleet emissions to meet the fleet average vehicle emission standards.

1.3. Our contribution

From previous research, we can see that what should be considered as an optimal battery range seems to be dependent on the chosen objective function for the optimization. There is therefore no clear agreement in what the optimal battery range for a PHEV should be. A number of countries have adopted policies to promote PHEVs. But it is not necessarily clear what the purpose—the objective—is or should be of policies promoting PHEVs nor how the policies may impact the introduction of PHEVs. This study analyzes how the choice of objective function, which potentially represents stakeholders' interests, influences the resulting vehicle fleet in terms of the optimal battery range for the PHEVs, share of PHEVs, TCO-savings, and electric drive fraction. We also assess PHEV promoting subsidies in terms of whether they reduce or increase the resulting differences among the studied objective functions. For simplicity and clarity of argument we analyze a fleet-optimal battery range even though it can be reasonable to assume that different manufacturers will address niches of the market with different battery ranges.

Earlier studies have analyzed multiple objectives (Shiau et al., 2009, 2010), and (Özdemir and Hartmann, 2012). In contrast to these, we:

- Constrain the choice of optimal battery ranges to economically viable PHEVs, to avoid reaching an "optimal" but unrealistic battery range.[5]
- Analyze how the electric powertrain cost influences the results.
- Analyze the maximization of the number of PHEVs in the vehicle fleet, which could be a possible objective both for a manufacturer but also from society's side, for instance, to encourage industrial learning and capacity-building.
- Maximize the share of electric driving instead of minimizing GHG emissions. This since evaluating PHEV technology using today's electricity production system is problematic when the future system (hopefully) will be less GHG intense. Electricity use accounts for a majority of the GHG emissions related to PHEV battery production and use (Michalek et al., 2011). Minimizing GHG emissions thus converges with maximizing electric driving, when emissions from power generation are reduced.
- Use an extensive and representative sample of vehicle driving; the data set contains individual multiday Swedish car movement patterns measured by GPS. This is better than, for instance, travel survey data which often misses day-to-day variations and focuses on people's, rather than cars', travel.

2. Methodology

We compare three different objective functions to find a fleet-optimized PHEV battery range under different techno-economic conditions. The objective functions maximize either the number of PHEVs in the car fleet, $PHEV_{OPT}$; the TCO-savings in the car fleet, TCO_{OPT}; or distance of electric driving of the car fleet, EDF_{OPT}. In each case, drivers are assumed to choose PHEVs when these are economically beneficial given a driver's movement pattern. That is, the driver chooses a PHEV in all cases when the higher investment cost of the PHEV compared to the CV can be offset with the lowered running costs made possible through electric driving. The actual car purchase decision is influenced by a large number of factors beyond the total cost of ownership, such as, household

[5] The longest possible battery range would result in a PHEV with the largest share of electric driving but will most likely be too expensive for most drivers.

income, buyer's car brand preference, available models, access to information, environmental consciousness, interest in new technology. To actually predict how well the PHEVs will perform on the market is therefore difficult based on comparison of the TCO only, and is outside the scope of this study. See for example Al Alawi and Bradley (2013) for a review of HEV, PHEV and BEV market modeling in the US where the most commonly used methods were found to be agent based models, consumer choice models and diffusion rate and time series models. We utilize car movement patterns in terms of trip distance, trip start time and trip stop time from a data set of 432 Swedish vehicles measured with GPS.

2.1. PHEV model

The modeling is based on our previous work in Björnsson and Karlsson (2015). The charged PHEV is assumed to operate in a charge-depleting (CD) mode until the battery is emptied and the vehicle turns into a charge-sustaining (CS) mode. Blended CD mode (used as an energy management strategy in the Toyota Prius PHEV) is not considered. The specific energy use in CD and CS mode, denoted $\boldsymbol{e_e}$ (electricity from grid) and $\boldsymbol{e_f}$ (fuel) [kWh/km], respectively, are assumed to be constant and thus the same for every trip. The effect on energy use of the extra weight from enlargement of the battery with range has been ignored, since this weight increase will make a rather small difference to the vehicles energy demand.[6] The same specific fuel use e_f is assumed for the CV used as comparison, i.e., we assume the comparison CV to be a fuel-efficient HEV; for modeling simplicity, and for not overstating the running cost savings of the PHEV. Increasingly demanding legislation (EPA, 2010a, 2012; European Parliament, 2009; Pillot, 2016) also reduces the differences in energy efficiency and cost of ordinary conventional vehicles and hybrids (from here on we therefore describe the alternative to the PHEV as a HEV). We define the all-electric range AER [km] as the maximum possible distance driven in CD mode. The range properties of the battery are assumed stable throughout the car's economic lifetime.

2.2. Marginal electric distance

How individual drivers utilize the PHEV battery is key to understanding the possibility of offsetting the relatively high investment cost of the PHEV with lower fuel costs. We analyze this by investigating the marginal benefit of battery range in terms of extra kms of electric driving for each individual driver in the data set. It is assumed that the battery is recharged only and fully in every parking period of at least size T.

For vehicle k, the annual electric mileage, $D_{e,k}(AER,T)$ [km/yr], is derived by summing the distances up to the all-electric range AER of all trips between recharging periods of at least length T (Karlsson, 2009; Karlsson and Jonson, 2011). The annual distance driven on fuel is $D_{f,k}$ (AER,T) [km/yr]. The marginal electric distance MED_k [(km$_e$/yr)/km$_{AER}$][7,8] is defined as the derivative of $D_{e,k}$ with respect to the range AER:

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

so that:

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

Fig. 1 shows a MED curve for an illustrative movement pattern where the driver has travelled 20 km or longer 270 times in a year (roughly 5 times per week on average). A marginal battery range increase from 19 to 20 km would result in an extra 270 km of electric distance travelled per year.

2.3. PHEV economics

The difference in the TCO for the PHEV relative to the 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.[9] The extra annual cost C [\$/yr] for the PHEV comprises the annuity α [yr^{-1}] for the initial investment costs I_B and I_P [\$] for the battery capacity and the powertrain, respectively.

$$C = \alpha(I_B + I_P) \tag{3}$$

I_P includes any battery capacity independent investment cost for turning the HEV into a PHEV, such as an on-board charger, increased maximum power of the electric drivetrain, and also the cost for battery power. I_B includes only the cost for the battery's energy capacity. We thus divide the total battery cost into a cost for power and a cost for energy capacity (Santini et al., 2010).

Assuming I_P to be constant and the specific battery capacity cost i_B [\$/kWh (nominal)] a constant independent of battery range[10],

[6] According to Shiau et al. (2009) 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).

[7] In economics, the marginal cost is defined as the derivate of the total cost with respect to the number of goods. The marginal electric distance, *MED*, is defined analogously. In earlier work, we have used an equivalent variable, the recharging frequency of the marginal battery capacity.

[8] km$_e$, and km$_{AER}$ refer to km of electric driving and km all electric range respectively.

[9] Difference in maintenance costs are commonly assumed negligible in this type of studies, see for example: Shiau et al., 2009, 2010; Lin, 2012; Hutchinson et al., 2014; Bishop et al., 2014; Khan and Kockelman, 2012.

[10] Under this assumption long-range batteries 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 battery power to the powertrain cost would instead make the marginal cost for short-range batteries much too low compared to long-range batteries.

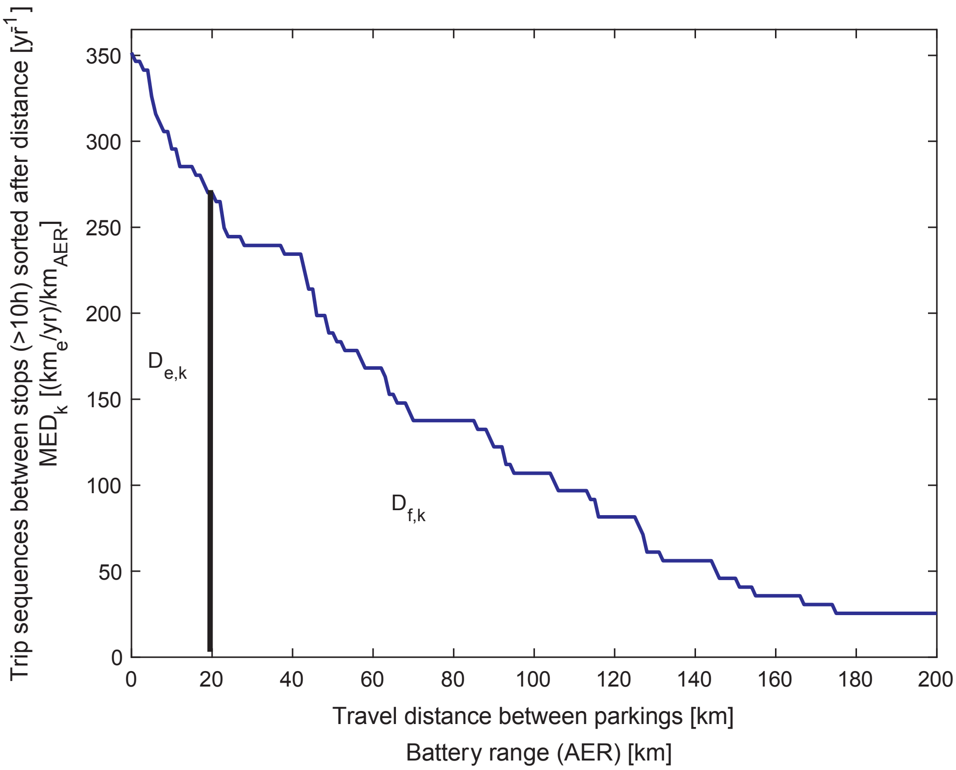

Fig. 1. The curve (blue) gives the number of times per year an example vehicle k has driven a specific distance or longer between stops of duration 10 h or more, where the travel distance can result from a sequence of driving occasions (single trips) with less than 10 h stops in between the trips. It can also be seen as the resulting *MED* for a PHEV with all electric range *AER* fulfilling vehicle k's movement pattern and the battery is assumed fully charged in every stop of duration 10 h or more. The areas $D_{e,k}$ and $D_{f,k}$ are then the PHEV's resulting yearly distance travelled on electricity and fuel, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the annual, per range, marginal cost C' [\$/km/yr], is

$$C' = \alpha\beta^{-1} i_B e_e \tag{4}$$

where β [kWh (utilized)/kWh (nominal)] is the battery depth of discharge[11].

The annual operational cost reduction R_k [\$/yr] is found as the total electric distance multiplied by the specific operational cost savings r [\$/km] of using electricity instead of fuel. With prices p_e and p_f [\$/kWh] for electricity and fuel, we have

$$r = (p_f e_f - p_e e_e) \tag{5}$$

$$R_k = D_{e,k} \cdot r \tag{6}$$

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

$$R_k'(AER,T) = MED_k(AER,T) \cdot r \tag{7}$$

We define MED_{COST} as the *MED* for which, on the margin, the annual operational cost savings equal the annual battery cost.[12] Combining Eqs. (4), (5), and (7) we get

$$MED_{COST} = \frac{C'}{r} = \frac{\alpha\beta^{-1} i_B}{p_f \frac{e_f}{e_e} - p_e} \tag{8}$$

which also is the *MED* that minimizes the total cost of ownership for the individual driver. The owner of a PHEV can offset the higher investment cost C with reduced running costs R_k. The (annual) net TCO-savings S_k [\$/yr] for PHEV k are given as:

$$S_k = R_k - C \tag{9}$$

[11] *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 hybrid energy management.

[12] MED_{COST} is called MED_{OPT} in our earlier paper (Björnsson and Karlsson, 2015).

Table 1
Average household energy prices in Sweden, Germany, and the U.S. in 2011–2015 and the resulting running cost savings per km, assuming powertrain specific energy use $e_e = 0.2$ and $e_f = 0.6$ kWh/km (disregarding any subsidy schemes).

	Sweden	Germany	U.S.
Fuel price, p_f [$/kWh]	0.23	0.22	0.10
Electricity price p_e [$/kWh]	0.23	0.36	0.12
PHEV running cost savings per km, $r = p_f{*}e_f - p_e * e_e$ [$/km]	0.092	0.060	0.036

2.4. Objective functions

As mentioned above, the driver k is assumed, regardless of objective function, to choose a PHEV when, and only when, it is economically beneficial to do so, that is, when $S_k \geq 0$. Let $1_{S_k(AER,T)>0}$ be an indicator function defined as

$$1_{S_k(AER,T)>0} = \begin{cases} 1, S_k(AER,T) > 0 \\ 0, S_k(AER,T) \leqslant 0 \end{cases} \tag{10}$$

That is $1_{S_k(AER,T)>0}$ equals one if the net TCO-savings for household k are positive and zero otherwise. The three objective functions analyzed in this paper can now be formulated.

Maximization of the total number of PHEVs in the vehicle fleet:

$$PHEV_{OPT}(\mathrm{T}) = \max_{AER} \sum_k 1_{S_k(AER,T)>0} \tag{11}$$

Maximization of the total cost of ownership savings:

$$\mathrm{TCO}_{OPT}(\mathrm{T}) = \max_{AER} \sum_k 1_{S_k(AER,T)>0} \cdot S_k(AER,T) \tag{12}$$

Maximization of fleet electric driving:

$$EDF_{OPT}(\mathrm{T}) = \max_{AER} \sum_k 1_{S_k(AER,T)>0} \cdot D_{e,k}(AER,T) \tag{13}$$

In the case of $\mathrm{PHEV_{OPT}}$ there are situations when two or more battery ranges result in the maximum (and same) number of PHEVs in the fleet. The shortest battery range will then be chosen because of its lower investment cost.

2.5. Techno-economic conditions determining the MED_{COST}

It is assumed that the battery is recharged only and fully in every parking period of at least size $T = 10$ h. In reality the charging frequency depends on the drivers' charging habits (Smart et al., 2014; Tal et al., 2014), but our results serve to show the potential battery utilization. Recharging during all stops of 10 h or more simulates night-time charging for most drivers.

We have in this work assumed an annuity of 15%, which for example could correspond to a payback time for the extra PHEV battery and equipment of 8 years at a 5% discount rate. Or it could correspond to a situation where the car is sold after 3 years for a resale value of 55% of the original purchase price.

It is difficult to give an exact figure for the level of battery cost that best represents today's situation. Price estimates (including markup costs) from current PHEV models (2015) span from $669 down to $271 per kWh (EPA, 2016). The price has been projected to decrease to 200 $/kWh "in the near future" (Nykvist and Nilsson, 2015). By internalizing the cost for battery power capacity under the I_P, the specific cost for battery capacity, i_B, can be assumed independent of battery capacity and lower than the total battery costs above.

The running costs and thus the running cost savings of the vehicles depend on the energy prices. In our base case, we use the average household energy prices in Sweden in 2011–2015, Table 1. However, household energy prices vary considerably among countries and regions. To indicate how energy prices on different markets affect the MED_{COST}, the corresponding prices for Germany and the U.S., together with the resulting running cost savings per km, r, are presented in Table 1 (IEA, 2011–2015).

Earlier economic assessments have generally varied energy cost, battery cost, annuity, etc., separately. However, the MED_{COST} parameter makes it possible to evaluate a continuum of scenarios without defining an exact level of the specific battery capacity cost, battery depth of discharge, annuity, etc., because there are several possible combinations of techno-economic parameters for each specific value of MED_{COST}, Eq. (8). Fig. 2 exemplifies how country-specific running cost savings can affect the MED_{COST} (assuming powertrain specific energy use $e_e = 0.2$ and $e_f = 0.6$ kWh/km, annuity $\alpha = 0.15$, and SOC window $\beta = 0.7$). The MED_{COST} is presented as a function of battery cost in Fig. 2. Because of lower running cost savings, a German and an American PHEV owner need to drive 1.5 and 2.6 times as many electric km per year, respectively, to reach the same annual savings as a Swedish driver.[13] This result

[13] If the Swedish driver faces a MED_{COST} of 200 [($\mathrm{km_e}$/yr)/$\mathrm{km_{AER}}$], the German and American drivers would then face a MED_{COST} of 300 and 520 [($\mathrm{km_e}$/yr)/$\mathrm{km_{AER}}$], respectively. A MED_{COST} of 200 [($\mathrm{km_e}$/yr)/$\mathrm{km_{AER}}$] roughly corresponds to a situation where the marginal battery unit needs to be utilized 4 times a week to be able to result in enough savings to offset the corresponding cost for marginal battery range while the German and American driver need to fully utilize their batteries about 6 and 10 times a week, respectively.

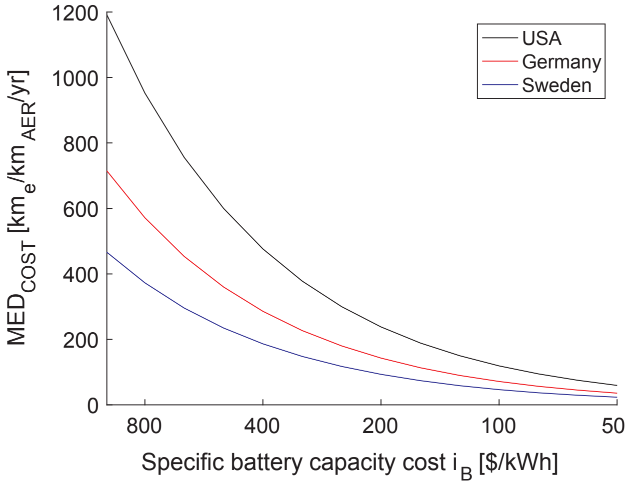

Fig. 2. Marginal electric distance needed to offset a marginal increase of battery range for Swedish, German, and American energy prices as function of the battery price. Assuming powertrain specific energy use $e_e = 0.2$ and $e_f = 0.6$ kWh/km, annuity $\alpha = 0.15$, and SOC window $\beta = 0.7$.

is based on the average energy price, but differences can be substantial within a country or, for example, between night and day electricity price.

In real driving situations, the specific energy use varies with driving conditions, and properties such as speed, driving aggressiveness, load, road conditions, and the use of auxiliary power (e.g., air conditioning). In our previous paper, we have however shown that the individual difference in specific energy use is of small importance for the MED_{COST}-level of the individual car (Björnsson and Karlsson, 2015). We also want to point out that our objective is not to calculate an exact number for the optimal battery range but rather to understand the dynamics and the influence of different objectives and conditions.

2.6. Extra powertrain cost I_P

As mentioned above, the extra powertrain cost (I_P) will be dependent of how the transition to PHEVs develops. We consider two I_P values: $500 (Low-$I_P$) and $3500 (High-$I_P$). Low-$I_P$ corresponds to "Prius-like" conditions, in which the difference in powertrain cost between the PHEV and a competing HEV is the smallest, equal to the cost of a charger and extra cabling. High-I_P can be seen as a "Volt-like" case, in which larger investments are made to increase the power of the electric powertrain. The purchase price premiums were estimated for a Toyota Prius PHEV and Chevrolet Volt by Hutchinson et al. (2014) using data and markup costs from ORNL (2010) and Brooker et al. (2010). These cases are only meant to illustrate the difference in powertrain cost and for simplicity, the same specific energy use has been assumed in both cases. The first version of the Toyota Prius PHEV could only go all electric under limited power. It thus required blended mode driving in for example steep ascents and in all speeds above 100 km/h. Such a PHEV could then in practice result in considerably lower share of electric driving than a comparable PHEV designed for electric driving in all power needs (Redelbach et al., 2014). The new Prius PHEV version, Prius Prime, can however handle somewhat higher power outtakes; it can for example manage to go all electric up to 130 km/h. The focus of our analysis was however not to perform a complete assessment of the differences between a "Prius-like" and a "Volt-like" powertrain design but to assess if and how the powertrain cost affects the individual driver's possibilities to reach economic viability with a PHEV. If blended mode were to be implemented in our model, a short-ranged PHEV in a Low-I_P case would use relatively more electricity in the later parts of the trip and occasionally also reach a lower battery utilization. The power capacity limitation of the battery would be small for high energy capacity cases.

Offsetting an I_P of $3500 with a 15% annuity requires about 5700 and 14,600 km of electric annual driving under Swedish and American energy prices, respectively, Table 1. A high I_P will thus downwards restrict the span of viable battery ranges since the possible electric kilometers per year is in practice limited by the number of recharging occasions and the yearly mileage of the individual driver.

2.7. Swedish car movement data

The aim of the Swedish car movement data project was to gather and analyze a larger amount of data on the characteristics and distribution of individual movements for privately driven cars in Sweden by measurement with GPS equipment. We use this data set to estimate fuel and electricity use and economic viability for hypothetical PHEVs with different possible electric range options. The data set includes GPS-logged movements of 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 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 reasonably representative of Sweden in terms of movement patterns, car ownership, and mix of larger and smaller towns and rural areas. The measurements, with logging up to 3 months, are distributed fairly 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. For additional information about the Swedish car movement data project, see Karlsson (2013).

For this study we use a selection of 432 vehicles with good movement data quality for at least one month each (58 days, on average). We utilize the data on the trip level only: trip distance, trip start time, and trip stop time. The annual driving for each vehicle is obtained by scaling the logged driving period to one year. The measured movement patterns are assumed to be representative of the car's economic lifetime and to be unaffected by the switch to a PHEV.

3. Results

Optimal battery ranges and resulting share of PHEVs, TCO-savings and EDF for the vehicle fleet are estimated for the studied objective functions under two levels of extra powertrain cost (I_P) and a range of techno-economic scenarios (MED_{COST}-levels). We then assess how different PHEV-promoting subsidies and the level of running cost savings affect the results.

3.1. Objectives and the resulting PHEV fleet composition

Fig. 3a shows the optimal battery ranges for the three studied objective functions as a function of the MED_{COST} when assuming a low extra powertrain cost of $500 (Low-$I_P$). Fig. 3b, c and d show the resulting share of PHEVs in the vehicle fleet; average cost savings per PHEV; and share of electric driving respectively. For Swedish running costs conditions (r = 0.092 from Table 1) and Low-I_P case, the first viable PHEVs enter the market around MED_{COST} = 400 [(km$_e$/yr)/km$_{AER}$], with rather short battery ranges regardless of the objective function, see Fig. 3. The differences in optimal battery range are relatively small at high MED_{COST} levels but increase with a gradual lowering of the MED_{COST}. The resulting share of PHEVs in the fleet, average cost savings, and potential electric drive fraction for the fleet are, as expected, largest for their respective objective functions. The case of $PHEV_{OPT}$ stands out from the other

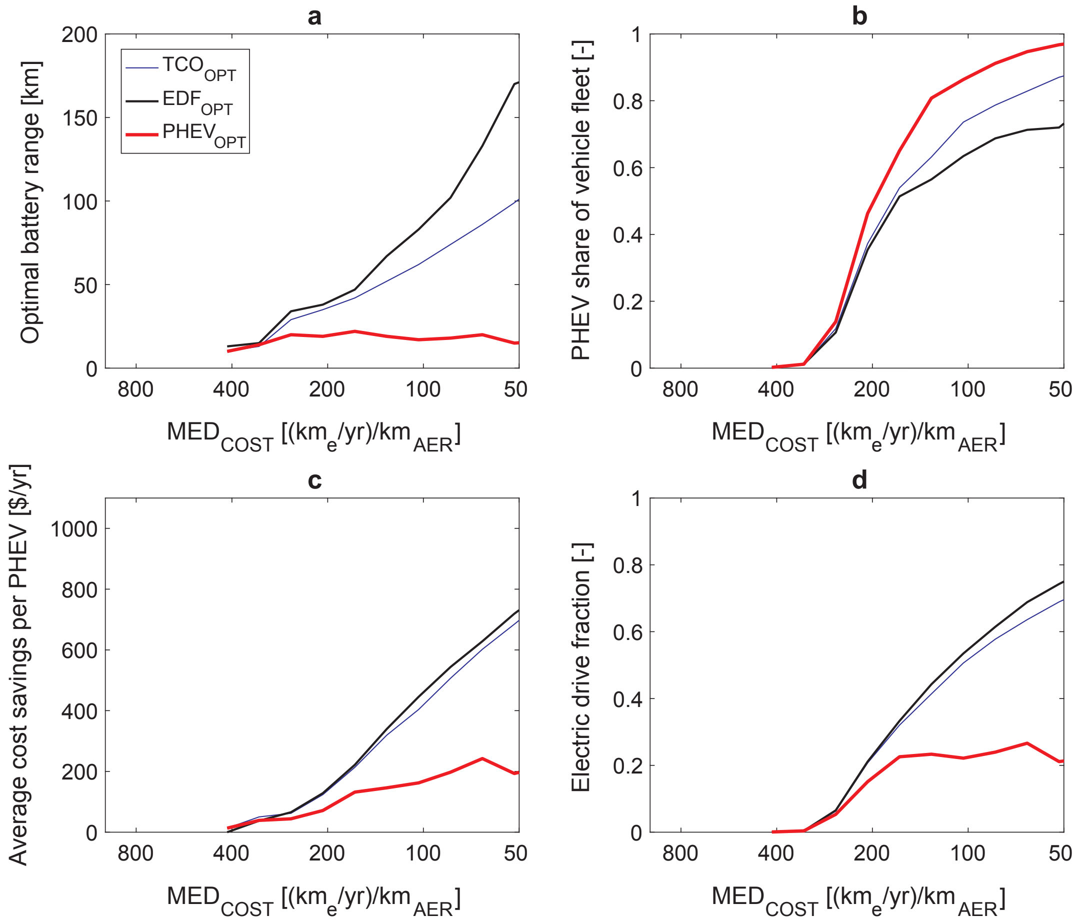

Fig. 3. For the studied car fleet under three different objective functions, (a) the optimal battery range; (b) the PHEV share of fleet; (c) the cost savings per PHEV; and (d) the share of electric driving, all as a function of MED_{COST}, for Low-I_P ($500).

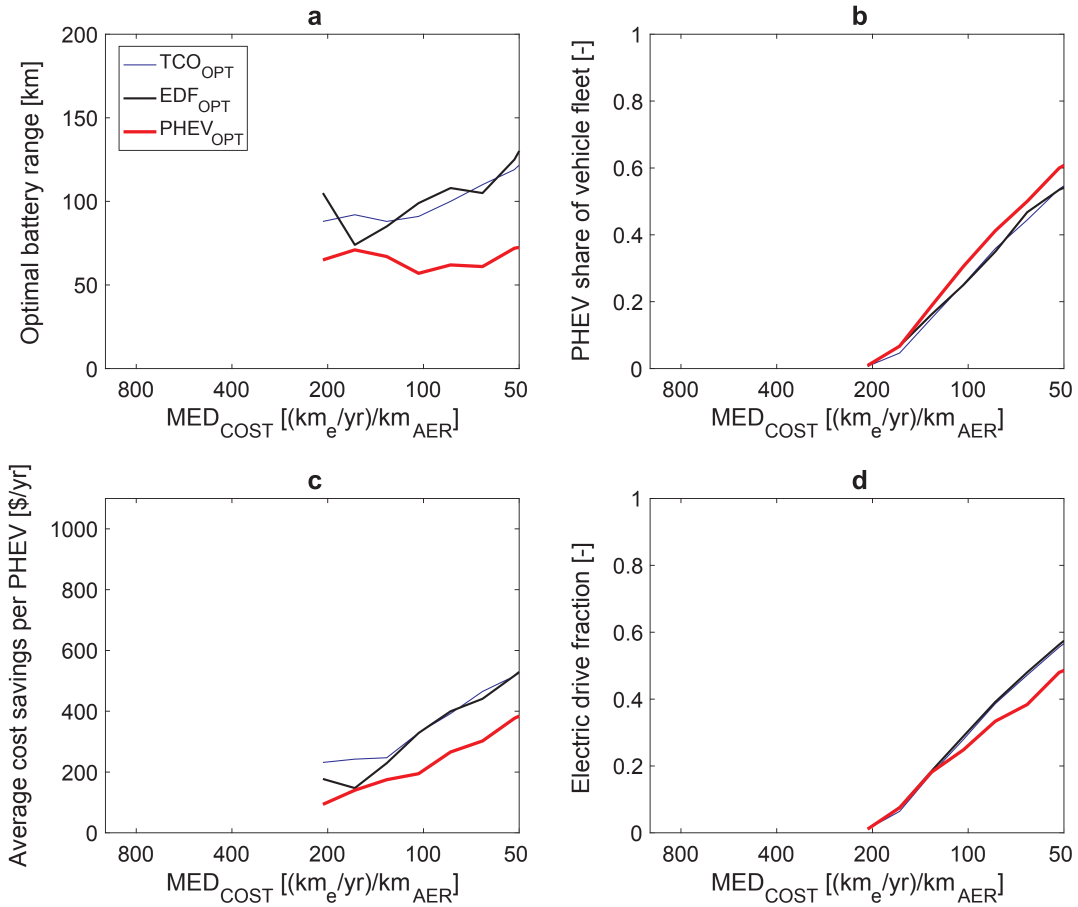

Fig. 4. For the studied car fleet under three different objective functions, (a) the optimal battery range; (b) the PHEV share of fleet; (c) the cost savings per PHEV; and (d) the share of electric driving, all as a function of MED_{COST}, for High-I_P ($3500).

two by its overall lower battery range, lower electric drive fraction, and lower level of cost savings for the car owner. The differences between EDF_{OPT} and TCO_{OPT} are in general smaller, especially for TCO-savings and electric drive fraction.

Fig. 4 gives the corresponding results for the Swedish High-I_P case (r = 0.092, I_P = $3500). The introduction of viable PHEVs is postponed until MED_{COST} = 200 [(km$_e$/yr)/km$_{AER}$], and the optimal battery ranges are longer in order to be able to accumulate enough savings to offset the higher I_P. The differences in optimal battery range among the three objectives are smaller than in the Low-I_P case, but $PHEV_{OPT}$ still stands out with shortest range. The smaller difference in optimal battery range results in a smaller spread in share of PHEVs, TCO-savings, and fleet EDF among the three objective functions. Compared to the Low-I_P case, the share of PHEVs in the car fleet and the TCO-savings per PHEV are reduced under all three objectives because of the higher extra powertrain investment cost. The reduction in fleet electric drive fraction is not as large since the fewer PHEVs have larger batteries compared to the Low-I_P case.[14]

3.2. Influence of subsidies

3.2.1. Flat subsidy

A high I_P can be alleviated by, for example, a fixed (battery-capacity-independent) subsidy, to facilitate an earlier introduction of PHEVs. A purchase rebate of $3000 would turn the High-I_P case into the Low-I_P shown in Fig. 3. Although the subsidy doesn't affect the individual driver's optimal battery range, it will allow many drivers with a shorter optimal battery range to reach viability (since a much lower cost to offset the extra powertrain cost is needed). Thus, it will make fleet optimal battery ranges to go down for all objective functions, and lead to more viable PHEVs, higher TCO-savings, and a larger electric drive fraction. But it will also imply larger differences in optimal battery range, share of PHEVs, TCO-savings and EDF for the vehicle fleet.

If the subsidy is greater than I_P, this can result in the situation depicted in Fig. 5, which shows a case in which PHEVs with a battery range of 10 km or more are eligible for a fixed subsidy of $3000 in the Low-$I_P$ case and $6000 in the High-$I_P$ case. This lets

[14] For a MED_{COST} of 100 [$\frac{km_e/yr}{km_{AER}}$] or lower, the EDF is actually higher for $PHEV_{OPT}$ compared to the Low-I_P case.

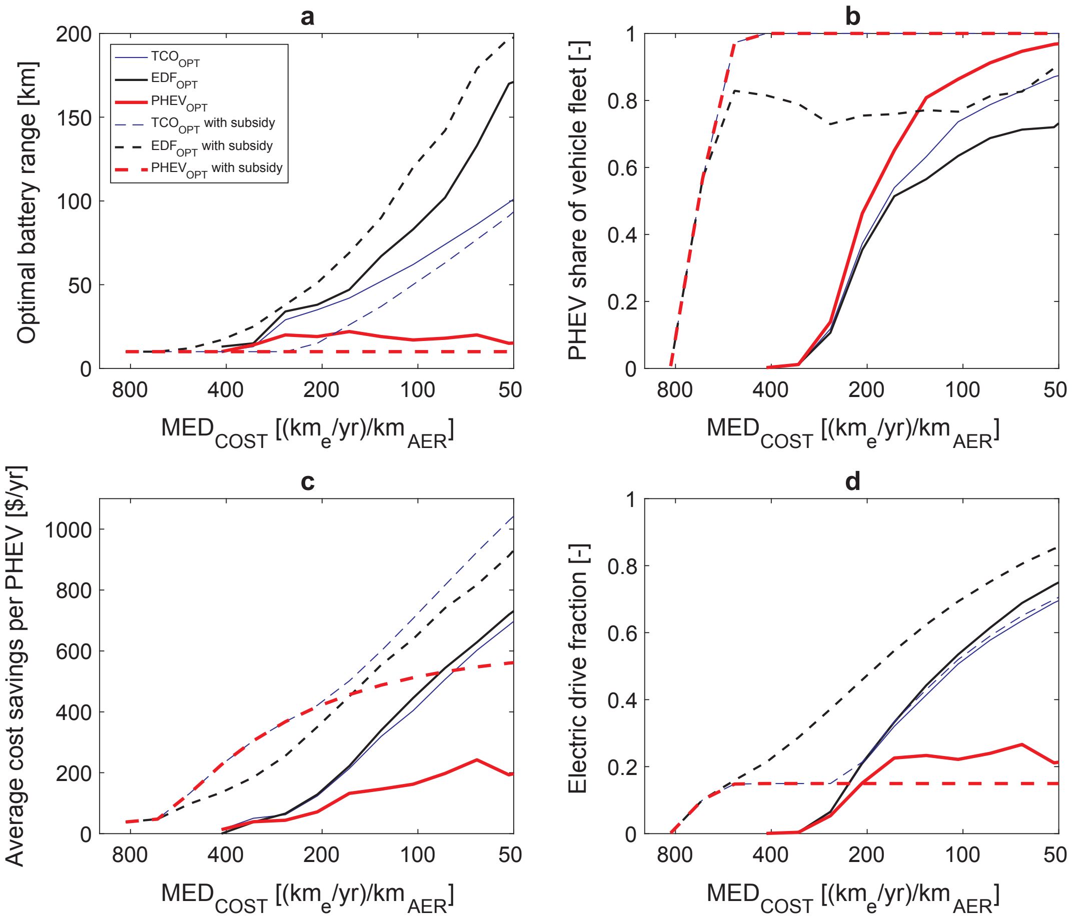

Fig. 5. For the studied car fleet under three different objective functions, the (a) the optimal battery range; (b) the PHEV share of fleet; (c) the cost savings per PHEV; and (d) the share of electric driving, all as a function of the MED_{COST}, for Low-I_P ($500, solid lines) and a flat subsidy of $3000 (dashed lines).

PHEVs to be introduced at an MED_{COST} of 800 [(km$_e$/yr)/km$_{AER}$], and all car owners benefit economically from buying a PHEV already at an MED_{COST} = 400 [(km$_e$/yr)/km$_{AER}$]. The difference in optimal battery range is large and again EDF_{opt} results in the largest battery range and $PHEV_{opt}$ in the shortest. At high MED_{COST} levels the optimal range for TCO_{opt} is close to that of $PHEV_{opt}$ (instead of being close to the EDF_{opt} as in Fig. 3). The fleet electric drive fraction increases compared to no-subsidy until $MED_{COST} \approx 200$ [(km$_e$/yr)/km$_{AER}$], below which the EDF increase is limited compared to the unsubsidized case. In the EDF_{OPT} case, the battery range increases with lower MED_{COST}, and the electric drive fraction follows. All cars are not PHEVs though; the higher EDF results from long-range batteries in fewer cars. In the $PHEV_{OPT}$ case there is a risk that a subsidy in this situation could increase the number of PHEVs in the fleet without increasing the fleet EDF, and it could even have a negative effect on the fleet EDF when optimizing for the number of PHEVs.[15,16]

3.2.2. Subsidy proportional to battery capacity

A subsidy proportional to battery capacity could effectively act as a lowering of the cost for marginal battery range C'. As seen in Eq. (8), MED_{COST} is proportional to the marginal battery cost and a subsidy corresponding to halving the cost for marginal battery capacity could thus move MED_{COST} from say 800 to 400 [(km$_e$/yr)/km$_{AER}$]. Such a policy simply corresponds to a shift towards the right in Figs. 3 and 4, along each objective function's trajectories. In the Low-I_P case, this increases the differences between the studied objective functions in optimal battery range and the resulting share of PHEV, TCO-savings and EDF in the vehicle fleet. In the

[15] The battery range in the $PHEV_{OPT}$ case will be determined by the minimum battery range required to receive a subsidy. A minimum battery range of 21 km would secure at least a similar battery range as in the Low-I_P case and no subsidy. A strategy to at least fend off a negative result can thus be to demand a minimum limit on battery range to be eligible of a subsidy.

[16] In the $PHEV_{OPT}$ case, a span of battery ranges all result in 100% PHEVs. A company aiming to sell as many PHEVs as possible, could try to design the battery to have a range within this span that also minimizes the TCO for the individual driver. The $PHEV_{OPT}$ would then collapse to the TCO_{OPT} curve in Fig. 5. However, a higher investment cost and longer payback time could be used to argue against a focus on the longer battery ranges in the span. A possible strategy for the producer would then be to go for the minimum battery range that still allows for a subsidy, to minimize the upfront investment cost and to shorten the payback time for the buyer. The battery range for $PHEV_{OPT}$ would then stay at a minimum.

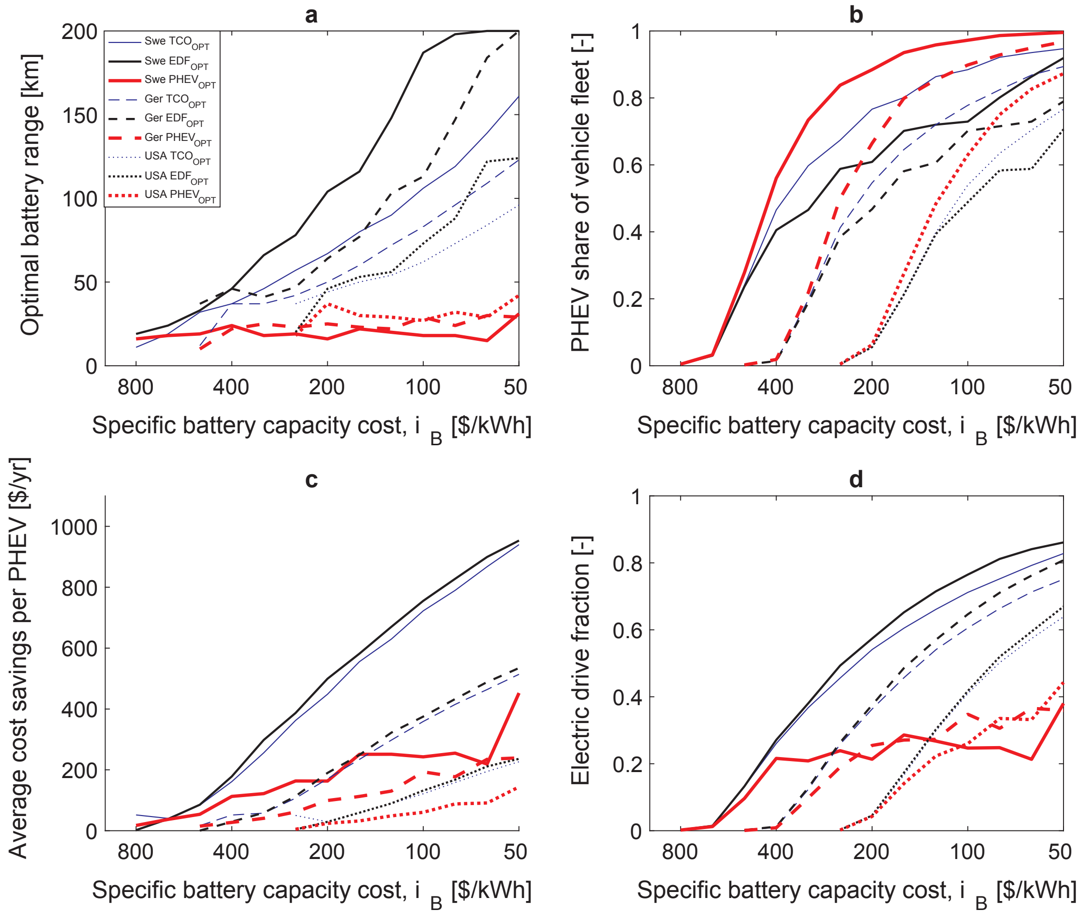

Fig. 6. For the studied car fleet under three different objective functions, (a) the optimal battery range; (b) the PHEV share of the fleet; (c) the cost savings per PHEV; and (d) the share of electric driving, all as a function of the specific battery capacity cost, i_B, for Swedish (solid lines), German (dashed), and U.S. (dotted) energy prices, for Low-I_P ($500), powertrain specific energy use e_e = 0.2 and e_f = 0.6 kWh/km, annuity α = 0.15, and SOC window β = 0.7.

High-I_P case the difference in optimal battery range increases somewhat between the objective functions but without any larger differences in the fleet's number of viable PHEVs, TCO-savings, or EDF. This since a fairly large electric distance is still needed to offset the high extra powertrain cost, thus reducing the possibilities for larger variation between the objective functions.

3.3. *Influence of running cost savings*

Running cost savings can, as seen in Table 1, differ substantially among countries because of differences in electricity and fuel taxes, electricity production methods, and more. Figs. 6 and 7 present the optimal battery ranges of the Swedish car movement data for the Low-I_P and High-I_P cases, respectively, with three examples of country-specific running cost savings r. Since the MED_{COST}-level is dependent on the running cost savings, the results are here plotted against the specific cost for battery capacity, i_b [$/kWh], to better illustrate the differences among the countries.

The resulting differences in optimal battery range among the objectives are smaller in the German and American cases. This leads to smaller differences in PHEVs' share of the fleet, TCO-savings, and fleet EDF. The effect is primarily due to the lower viability resulting from the higher MED_{COST} and the reduced possibility to offset $I_{P,}$ making the span of viable battery ranges smaller and the number of drivers that reach viability for a PHEV fewer.

Drivers in regions that face high running cost savings r can offset the extra powertrain cost I_P with fewer kilometers of electric driving and can thus afford a higher I_P.

4 Summary and discussion

This study has assessed how the choice of objective function—potentially reflecting different stakeholders' interests—and the PHEV incentive design, influences, at the fleet level, the resulting optimal PHEV battery range, share of PHEVs, TCO-savings, and the electric drive fraction.

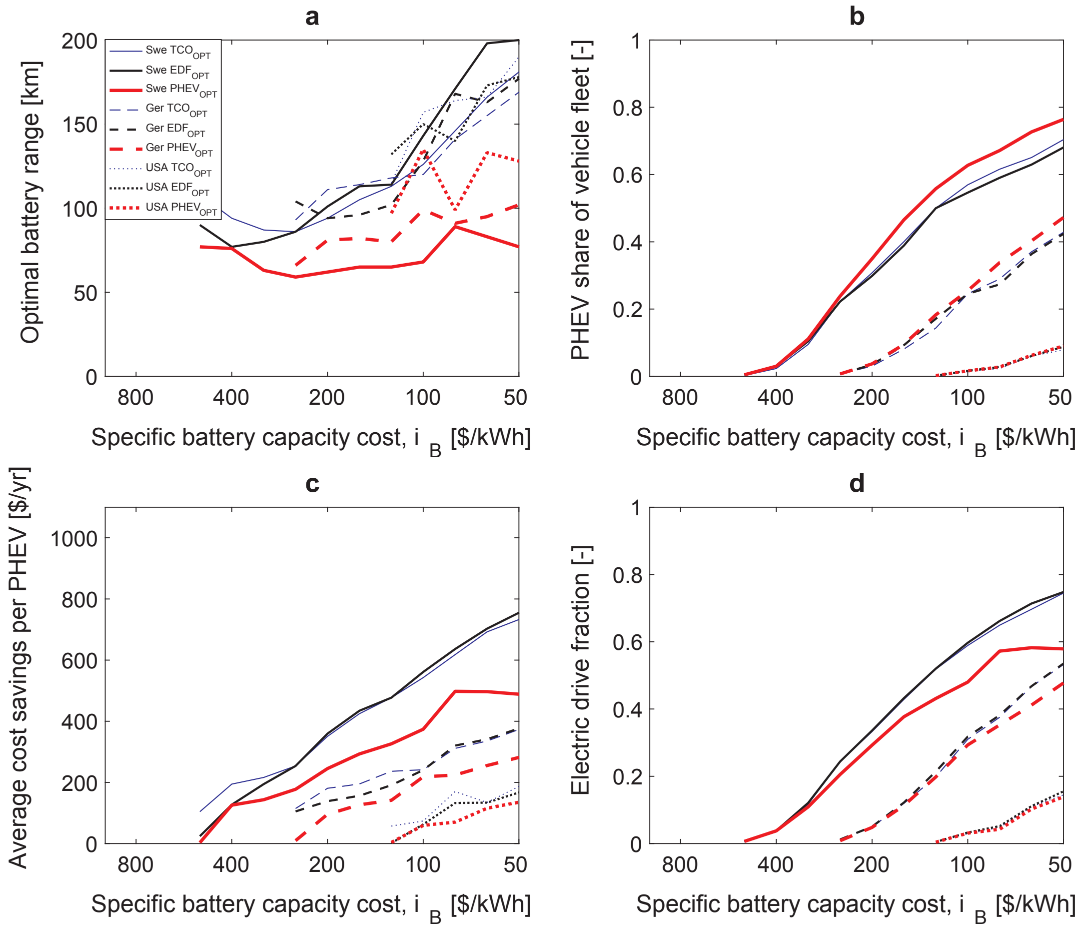

Fig. 7. For the studied car fleet under three different objective functions, (a) the optimal battery range; (b) the PHEV share of the fleet; (c) the cost savings per PHEV; (d) the share of electric driving, all as a function of the specific battery capacity cost i_B, for Swedish (solid lines), German (dashed), and U.S. (dotted) energy prices, for High-I_P (=\$3500), specific energy use $e_e = 0.2$ and $e_f = 0.6$ kWh/km, annuity $\alpha = 0.15$, and SOC window $\beta = 0.7$.

4.1. Economic viability

It is mainly through electric driving with low running cost that a PHEV driver can reach economic viability. Thus, when the PHEV is expensive to buy and/or drive (high extra powertrain cost and/or high MED_{COST}), the drivers that anyhow reach economic viability must have driven long distances on electricity. This situation is however not favorable from any of the three objective functions' point of view; few drivers will afford a PHEV, for those who do the level of TCO-savings will be low, and the fleet EDF will be small. By subsidizing the PHEV, it is possible to enable more drivers to reach economic viability. But this also means that the electric distance needed to reach viability is lowered, which results in a larger variation in electric distance among the viable PHEVs, and, as we have seen, in a larger difference in optimal battery ranges between the studied objective functions. It is for example not certain that a large share of PHEVs in the vehicle fleet will lead to a high share of electric driving (as could be seen in Figs. 3 and 5).

4.2. Subsidies

The way that subsidies are designed affects the resulting optimal battery range, for the studied objectives, differently. In the Low-I_P case, the *battery-range-dependent subsidy*, led to an increasing difference between the studied objective functions in optimal battery range, and in resulting share of PHEVs, TCO-savings, and EDF in the vehicle fleet, while the corresponding changes were relatively small in the High-I_P case. In both cases, though, the TCO_{opt} followed the EDF_{opt} in terms of TCO-savings and EDF. This since the cost-optimal battery range for the individual driver increases with the subsidy (a battery-range-dependent subsidy effectively lowers the MED_{COST} level, which determines the cost-optimal battery range for individual driver, see Eq. (8)).

A *flat subsidy* leads to larger differences in optimal battery range, share of PHEVs, TCO-savings and EDF, between the studied objective functions in both the Low-I_P and High-I_P case. It does not however impact the cost-optimal battery range for the individual driver. In a situation with high battery costs the driver must have a high level of battery utilization to economically justify a battery investment. The optimal battery ranges are in this situation in general small, which explains why the TCO_{opt} follows the $PHEV_{opt}$ in case of a large subsidy (Fig. 5). This suggests that the increase in EDF from a flat subsidy can be expected to be limited even if the battery range were optimal for maximizing TCO-savings.

Besides subsidies, there are several policies which can affect a PHEV purchase decision. The results of this study are therefore not meant as an assessment of the effects of the particular PHEV subsidy schemes in place in for example Sweden and USA.

4.3. Running cost savings

Sufficiently high and stable future running cost savings facilitate a PHEV introduction. In a short-term perspective, it may be difficult to introduce policies that achieve large changes in a country's energy prices. In the long term, it is likely that energy pricing needs to favor electricity use in order for a country to reach a larger share of PHEVs (or BEVs for that matter) without subsidies or stricter emission regulation.

When running cost savings are small, it will be relatively more expensive to reach viability through subsidies. Other policies not directly affecting the TCO of the PHEV, e.g., corporate emission targets, could therefore be of greater importance in countries and regions with low running cost savings.

In Germany, the support for renewable power production as part of the Energiewende[17] is to a large extent financed by a price increase on electricity for private households. Such a support scheme, which hits the running cost savings, can in effect act as a barrier to the introduction of electrified vehicles.

Volatile market energy prices can quickly change the preconditions for the PHEV's economic viability. We used a five-year average (2011–2015) energy price to illustrate the differences among Sweden, Germany, and the U.S. Using only the 2015 average, the PHEV savings per km electric driving r would change to 0.06, 0.022, 0.018 \$/km for Swedish, German and American drivers, respectively (compare Table 1). Thus, in 2015, American PHEV drivers needed about twice as many yearly electric kms to offset the fixed costs compared to the 2011–2015 average, and German drivers faced almost as low running cost savings as the Americans. The American running cost savings in 2015 correspond to only 30% of the Swedish savings, down from an average of 40% for the period 2011–2015.

4.4. Method

For reasons of clarity/transparency the chosen PHEV model is deliberately simplistic while still capturing the main characteristics that affect the share of electric driving and the total cost of ownership for the individual driver. For example, we analyze a fleet-optimal battery range even though it can be reasonable to assume that different manufacturers will address niches of the market with different battery ranges. The results should therefore not be seen as an attempt to foresee what battery ranges will be offered in the future.

Furthermore, the actual car purchase decision is influenced by a large number of factors beyond the total cost of ownership, such as household income, buyer's car brand preference, available models, access to information, environmental consciousness, and interest in new technology. To actually predict how well the PHEVs will perform on the market is therefore difficult based on comparison of the TCO only, and is therefore outside the scope of this paper.

The competing car was here assumed to be a full hybrid, but in reality, the transition towards PHEVs may take off from a range of different vehicles, which in turn to some extent will be market specific.[18] Comparing the PHEV to mild hybrids or conventional cars could justify a higher I_P than in our examples but also higher running cost savings. The extra investment cost for an HEV compared to a mild hybrid can be estimated to about \$2500 (Hutchinson et al., 2014), or roughly the difference between the Low-I_P and High-I_P case. However, the running cost savings from driving a PHEV compared to the competing car would increase in both CD and CS mode, which could offset the extra investment cost. Increasingly demanding legislation also reduces the differences in energy efficiency between conventional vehicles and hybrids.

Charging was assumed to take place at home only, or actually when $T = 10$ h. The second most common long-term time parking is in general at work. Charging at work can for commuters be as valuable as a halving of the battery price of the PHEV (Björnsson and Karlsson, 2015). This since the battery range could be halved while retaining almost the same share of electric driving. Workplace charging can therefore affect the optimal battery range when maximizing the total cost of ownership savings or the number of PHEVs in the vehicle fleet. Increased battery utilization through workplace charging would also increase the EDF of short-ranged PHEVs, which then possibly would reduce the large differences in EDF between long- and short-ranged PHEVs seen in our results. On the other hand, we have assumed that PHEV owners always charge when possible. Results from a survey of Californian drivers suggest that a shorter battery range can make the driver less likely to charge the PHEV (Tal et al., 2014). Such an effect would further increase the already seen differences in EDF between PHEVs with long and short battery ranges. According to the survey, workplace charging is today relatively uncommon in California and only occurs during 15 and 11% of the commutes of Chevrolet Volt and Toyota Prius owners, respectively.

[17] The transition towards an energy system dominated by renewable energy, energy efficiency, and sustainable development.
[18] In 2013, HEVs reached about 1.4% and 6% of new car sales in Europe and the U.S., respectively (ICCT, 2014).

4.5. Comparing our results with earlier studies

Contrary to Shiau et al. (2009), Michalek et al. (2011) and Kontou et al. (2015), our results do not support the idea that battery ranges in general should be short-range to minimize total cost of ownership for the driver. If only considering the cost for battery enlargement, short-range batteries do reach higher battery utilization, but to be able to offset I_P, the battery cannot be too small.

Michalek et al. (2011) and Kontou et al. (2015) study the economic implications when every driver in an assumed vehicle fleet has to drive either a PHEV20 or a PHEV60 (km). Individual drivers face diminishing returns from battery range investments and a setup where every driver is forced to drive a PHEV (unlike our model where drivers who do not benefit economically from driving a PHEV are assumed to drive a HEV) will therefore almost inevitably result in a better economic situation for the shorter battery range, if there are drivers who do not benefit from the long-range PHEV. With such assumptions, it is not possible to find a result where a smaller group of PHEV drivers with large battery capacity could reach higher total TCO-savings than a larger group of PHEV drivers with short-range batteries.[19]

The short-term policy objective may differ from the medium- and long-term objective, due to changes in technology and societal prerequisites over time. For instance, initially, if the carbon intensity of the electricity production is high, the policy could be tailored to support short-range PHEVs (as suggested by Shiau et al. (2009), Michalek et al. (2011), and Kontou et al. (2015)), facilitating the build-up of industrial capacity. Later, when more low-carbon renewable electricity is available, the objective could turn to support longer battery ranges to maximize electric driving, facilitating climate mitigation (as indicated by Shiau et al. (2010), Shiau and Michalek (2011), Meinrenken and Lackner (2014), and Redelbach et al. (2014)). In the short term, the support could possibly vary among regions, where countries with carbon-intense electricity production could focus on low-range PHEVs while countries with lower carbon intensity could instead favor long-range PHEVs.

5. Conclusions

The optimal battery range can differ considerably among objective functions, especially between the objectives of maximizing the number of PHEVs and maximizing driving on electricity. Increased viability of the PHEV, for instance, through lower battery costs, higher running cost savings, or PHEV-promoting subsidies, will strengthen this effect. Therefore, a high share of viable PHEVs in the vehicle fleet does not necessarily result in a high share of electric driving. When designing policies to promote PHEVs, both the short- and long-term policy objectives and their potential effects need to be considered explicitly.

Current differences in household energy prices between countries result in large differences in running cost savings and in turn in optimal battery ranges and economic viability of driving a PHEV. Besides pointing out countries and regions with high running cost savings as possible forerunners for the technology, the results also suggest that the level of running cost savings should be considered in the choice and design of PHEV policies.

Acknowledgments

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[19] Shiau et al. (2009) modeled PHEVs on a drive cycle and vary the assumed distance travelled between charging (0–100 miles). They assume the same average yearly mileage for the vehicle, regardless of distance between charging, which will result in lower recharging frequency the longer the distance between charging (Shiau and Michalek, 2011). A perfectly matched short-range battery will thus by model design reach a higher utilization rate (have a higher MED). This is problematic since PHEVs of any battery range need high utilization of their marginal battery capacity to reach economic viability (Björnsson and Karlsson, 2015).

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