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Estimating the PHEV potential in Sweden using GPS derived movement patterns for representative privately driven cars

Lars-Henrik Kullingsjö [1], Sten Karlsson [2]

Energy and Environment, Chalmers University of Technology
Gothenburg, SE-41296, Sweden
[1]larshenr@chalmers.se, [2]sten.karlsson@chalmers.se

Abstract

Plug-in hybrid electric vehicles (PHEVs) can be used to substitute a major share of fossil fuels in car transport by using electricity from the grid. Earlier studies have shown that the battery design and economic viability of the PHEV is highly dependent on the individual car movement pattern and charging options. Here we investigate the battery design, viability and potential for PHEVs in Sweden utilizing a recently available new data set for car movements in which 214 privately driven cars were logged with GPS for 30 days or more. The cars are based in south west of Sweden in a region that is fairly representative for Swedish driving patterns.

On large the study's confirms earlier results from [1] by showing that in a situation where the economic viability of PHEVs is good due to for instance low cost of batteries there will be a wide range in the optimal battery size dependent on the individual movement pattern. For less favourable economic conditions the resulting economic competitiveness of the PHEV and the potential to replace fossil fuels will be much dependent on the possibilities to frequently charge the battery. Improving charging options can thus be an important complement to reducing battery costs for facilitating PHEVs in an introduction phase.

Keywords: battery size, GPS-logging, individual driving pattern, PHEV viability, PHEV potential,

1 Introduction

A plug-in hybrid electric vehicle (PHEV) has the ability to substitute a major share of the fuel normally used in cars by electricity from the grid. This without compromising the range of the vehicle that currently is one of the major weaknesses of the fully electric car, the battery electric vehicle (BEV). Instead the PHEV has a smaller energy battery, large enough to supply energy for a significant share of the driving between recharging, and an internal combustion engine working as a range extender when the battery is emptied and possibly also in parallel to the motor for power delivery.

To become a major alternative to the current fuel-propelled car, it is reasonable that the total economics of the PHEV from a consumer point of view is favourable in comparison to the alternatives. The relatively high costs of energy capacity for the Li-ion batteries, the currently dominating technology, make the economic viability of the PHEV highly dependent on the degree of utilization of the available capacity. Earlier studies has focused much on battery pricing without discussing the marginal battery price and its effect of economical battery design. Optimally, and given everything else unchanged, the cost of marginal battery capacity should be paid for by the lower energy cost achieved by the further substitution of fuel by electricity made possible by the extra capacity. But this substitution is dependent on the specific movement pattern of the individual car as well as the possibility for recharging.

In earlier studies we have explored the potential for PHEV by utilizing different occasionally available data sets for car movement patterns that have been either very limited in scope; 29 cars followed for two weeks [2], or limited to cars from a smaller specific area, a mid-size Swedish town [1]. The studies indicated anyhow that the differences between individual car movement patterns resulted in large variations in the viability for electric propulsion. It has thus been concluded that although the availability of data for car movements are very important for various assessments of electrified vehicles, representative data sets for car movement patterns are rare and need to be gathered [3]. Most other studies assessing electrification of cars have utilized simplified statistics for the driving pattern in the form of statistical distribution of daily driving distances or even only one figure, the average driving daily distance although there are exemptions [4, 5]. To fill this data gap a larger measurement project has been initiated, in which car movement patterns shall be gathered by GPS-logging of around 500 privately driven cars residing within a representative area of Sweden [6].

We here investigate the design, viability and potential for PHEVs in Sweden utilizing the data available so far of 214 individual car movements.

2 Method

A general overview of the method is depicted in in Fig. 1. A model of battery utilization constitutes the centre, which as input uses different charging options, techno economic parameters and individual car movement patterns. The model used in this work is constructed to determine the economically optimal battery design for individual cars. More specifically the result of the optimization is the battery size for each individual car, which minimizes the total cost of ownership of the vehicle due to its individual movement pattern, the available recharging options and the assumed values of exogenous techno-economic parameters. The economic viability of the optimally equipped cars is evaluated by a comparison to a competing alternative in the form of the corresponding HEV, i.e., the PHEV with an energy battery of size zero. The potential for PHEV is then estimated and discussed in terms of the total electric drive fraction, i.e., the possible share of the total driving distance for the whole vehicle fleet, which can be propelled by grid electricity.

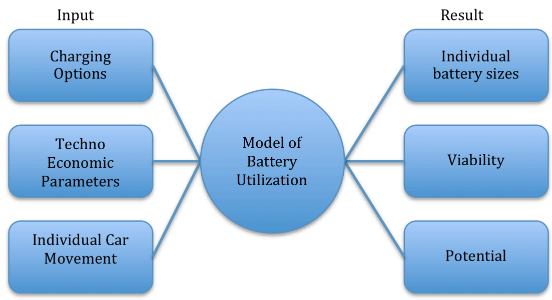

Figure 1: Methodological overview.

The vehicle, the PHEV, is assumed to be a hybrid electric vehicle (HEV), but with an additional energy battery rechargeable from the grid. The energy battery in the vehicle is supposed to be able to deliver the energy and power to propel the vehicle in charge depleting (CD) mode until its useful energy is emptied and the driveline turns into a charge sustaining (CS) hybrid mode. We thus do not consider blended driving mode with both fuel and electricity used for propulsion. Instead we assume that the cars drive in pure electric mode as long as the state of charge exceeds a minimum value. This means that the car has two distinct modes with specific techno-economic properties.

We also assume that each car would keep its movement pattern independent of the battery size and that the driving is representative for the cars' whole economic lifetime.

The economic performance is further affected by the specific techno-economic conditions assumed prevailing. All the vehicles are characterized by the same specific use of electricity e_e and fuel e_f [kWh/km] in the CD and CS mode, respectively. Although the energy use will vary with driving conditions and properties such as speed, driving aggressiveness, orography, load, weather and road conditions, and the use of ancillary power (e.g. air conditioning), the specific energy uses are assumed to be constant and the total energy proportional to the distance driven only. This also implicitly assumes that the cars are of the same size.[1]

Other exogenous parameters influencing the optimal battery size include the utilized share β [kWh (utilized)/kWh (nominal)] of the battery, the marginal battery cost c [\$/kWh (nominal)], the annuity α [yr^{-1}], and the prices p_e and p_f [\$/kWh] of the electricity and fuel, respectively. Other costs are assumed to be equal to all cars and independent of the energy battery size and therefore not influencing the battery optimization.

2.1 Charging options

The possible utilization of the PHEV battery depends 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 need for a long enough time to recharge the battery before the next trip. In the car movement data used, the possibilities of charging are not known, but the lengths of the breaks between trips are. This is therefore used to represent the charging options; it is assumed that the battery is fully recharged in every break of at least size T [h]. In the further analysis we focus on T = 10, 4 and 0.5 hours. Letting the car recharge every time it stops for at least 4 h could correspond to the situation when charging posts are accessed both at work and at home, whereas a 10 h stop requirement means that the battery probably only will be recharged during the night once a day. T = 0.5 h is a rather extreme case assuming access to a fast charging post at every stop of at least this size.

2.2 Economically optimal individual batteries

We define for a car the all-electric range *AER* [km] as the maximum possible distance driven powered exclusively by electricity per charge, and $S_{e,i}$ [km/yr] as the resulting annual distance driven on electricity for a car i. These are determined by the battery size and the specific electric energy use, and $S_{e,i}$ also by the car movement pattern and recharging options.

We define the marginal annual recharging frequency MRF_i [yr^{-1}], as the number of times the marginal battery unit is fully emptied and then recharged per year, which means that MRF_i is also equal to the marginal annual distance driven on electricity per *AER* [1]:

$$MRF_i(AER,T) = S_{e,i}'(AER,T) \qquad (1)$$

With the assumptions made, we get the annual per range marginal revenue R_i' and marginal battery cost C' [\$/km,yr], respectively

$$R_i'(AER,T) = MRF_i(AER,T)(p_f e_f - p_e e_e) \qquad (2)$$

$$C'(AER) = \alpha\beta^{-1}ce_e \qquad (3)$$

The number of marginal annual recharges for which the net revenue is maximized, MRF_{opt}, is the *MRF* for which, on the margin, the revenue equals the cost, or

$$MRF_{opt} = \frac{\alpha\beta^{-1}ce_e}{(p_f e_f - p_e e_e)} \qquad (4)$$

By using the individual car movements we can now make an economic optimization of the size of each car's battery

$$AER_{i,opt} = AER \mid S_{e,i}'(AER,T) = MRF_{opt}$$

2.3 Techno-economic parameters

For each specific MRF_{opt} there is an ambiguity in the corresponding techno-economic parameters, Eq (4), which may affect the economic viability. For making comparison easily possible we base our compilation on a specific set-up of the techno-economic parameters, see Table 1, performed and further discussed in [1]. Generally, with development in technology and with learning and increased scale in industrial production, the MRF_{opt} should decrease, i.e., go from right to left in Table 1. As discussed in [1] the parameters behind MRF_{opt} of 800 yr^{-1} can be thought of as fairly close to today's situation, while MRF_{opt} = 400 yr^{-1} requires a modest development of the parameters, with for instance battery costs predicted for soon after 2012 by [7]. Similarly, MRF_{opt} = 50 yr^{-1} corresponds to a possible future state where considerable development of the crucial parameters has taken place.

[1] Even if our assessment is independent of vehicle size it would be possible to introduce a size dependency by for instance letting e_e and e_f be proportional to vehicle size.

Table 1: Assumed values for techno-economic parameters to give different MRF_{opt} values. Based on [1].

Techno-economic parameter	**Optimal marginal recharging frequency MRF_{opt} [yr^{-1}]**				
	50	**100**	**200**	**400**	**800**
Annuity a [yr^{-1}]	0.15	0.15	0.15	0.15	0.15
SOC window b [-]	0.8	0.75	0.61	0.5	0.5
Marginal battery cost c [$/kWh]	100	160	250	400	800
Energy price $p = p_e = p_f$ [$/kWh]	0.25	0.2	0.17	0.15	0.15
Quota of specific energy uses e_f/e_e [-]	2.5 = 0.375/0.15	2.6 = 0.39/0.15	2.8 = 0.42/0.15	3.0 = 0.45/0.15	3.0 = 0.6/0.2

Some remarks are in place, though. Estimated or stated costs for battery are often given in $/kWh for the battery, i.e. total cost divided by the (nominal) energy capacity. But the specific cost of the current PHEV batteries depends on the capacity for both power and energy. For a given power, the additional cost for energy capacity, that is, what is here represented by the parameter c, can be considerably lower than the specific cost for the whole battery [8, 9, 10]. The marginal cost for battery energy capacity can thus be lower than the stated today's battery specific cost of 600-800 $/kWh ([7, 11] On the other hand, stated costs are often production costs and do not include mark up costs.

The assumed annuity of 0.15 corresponds to a levelized capital cost over a relatively long depreciation period and/or an assumed low rent. In most countries the actual depreciation of cars can be considerably higher in their first few years and then decrease for older cars. For instance, a doubling of the annuity would result in a proportional shift or a doubling of the MRF_{opt}, corresponding to shift one column to the right in Table 1.

The given value for the specific fuel e_f use in the quota for the specific energy uses e_f/e_e is outperformed by currently available HEVs. Assuming a lower quota will translate into a higher MRF_{opt}.

In accordance with [1], a cost of 25 $/yr are added to the PHEV to capture the probable difference in cost going from an HEV to a PHEV. With the assumed annuity this corresponds to an initial investment of 167 $. This can correspond to a long-term cost for an addition of a charger.

2.4 Individual car movements

The analysis is carried out on a dataset recently collected from 214 privately driven cars based in south west of Sweden. The region has a population of about 1.6 million inhabitants and 0.7 million cars, which is about 1/6 of Swedish total population, and car fleet respectively. The region should also be reasonably representative for Swedish driving patterns in terms of driving distances, car ownership and its mixture of larger and smaller towns and rural areas. The region also contains Gothenburg, which is the second-largest town in Sweden. The cars selected for logging were privately driven passenger cars from model year 2002 and newer from Västra Götaland county or Kungsbacka municipality. These where selected randomly from the Swedish vehicle register. Owners to selected cars were then asked to take part of the study. The positive response frequency for participation in the study was around 5% of which most were engaged for the logging. How this low response frequency may have influenced the representativeness of the result has not yet been investigated in detail.

The data collection is divided into several campaigns with logging for up to two months. The first campaign started in June 2010 and the fourth campaign was completed in November 2011. Further data for around 300 cars will be gathered during spring/summer 2012.

The logging is done with commercial equipment containing a GPS unit (global positioning system), which is installed by the car owner. The unit includes a roof-mounted (magnetic holder) antenna and is supplied from the 12V outlet in the car. The logging frequency is 2.5 Hz and the logging includes: timestamp (current and last valid), position (latitude, longitude and altitude), velocity (speed and direction), used satellites (number and identity) and the dilution of precision (pdop, hdop, vdop). The logs are, after possibly intermediately stored on a SD-card, transmitted via GSM network for storage in a database.

The GPS equipment needs some time (mostly roughly 30 seconds) in the beginning of each trip to find satellites and thus to start logging. Data are also missing for other reasons. Methods for trip detection and compensation for missing data from GPS measurement for travel surveys have been discussed and developed [12]. However, because the division in trips in this analysis is not crucial, simplified procedures have been utilized.

The average distance missing in the beginning of the trip is 0.089 km, estimated as the distance (as the crow flies) between the start of the logging of a trip and the end position of the previous trip. For trips where this missing distance is shorter than 2 km it has been added to the total trip distance. Since the corresponding travel time is likely to be short compared to the times needed for charging this is not deducted from the break time between the trips, though.

If the missing distance is longer than 2 km it is handled as a potential gap in data. In that case the function 'directions' from Google maps API is used to get an estimation of the missing trip length (along a road on the map) and travel time from the end of trip A to the start of trip B. The suggested travel time is compared with the actual pause between the trips. If they are of the same size[2] it is assumed that the pause is used to travel the missing trip length. This pause is then not counted as a possibility to charge the battery. If the measured pause and the suggested time needed for travel are not of the same size we do not know for certain if the car was used or not during the remaining pause. A part of this time however is probably a real pause and to be able to use also this trip in our analysis we estimate the length of the pause by creating a randomized pause, weighted with the average length of pauses between the other trips for the same vehicle (trips with gaps excluded). The residual time, that is, the measured pause minus the suggested time for travel minus the randomized pause, is, if positive, deducted from the total period length of the car. The vehicles with a remaining logged driving period of less than 30 days or with more than 5 % of the trips being trips with gaps are removed from the data set. Left in the data set are 214 vehicles, which thus are the vehicles used in the further analysis.

A (perpetual) annual driving for each vehicle is then derived by scaling the remaining logged driving period to one year. Prior to that a randomized pause is added before the first trip to correct for the end point effect. But because we do not know the driving and the pause before the first trip there is an ambiguity in the assumed battery state: we assume that the battery is fully charged when starting the first trip, though.

The logging of the cars are distributed reasonably evenly over the seasons. Some of the cars have therefore a large share of holiday period driving while others have nothing of that sort. The scaling to annual driving involves therefore reasonably some errors, which may tend to overestimate the differences between the cars annual driving, both in the total distance and the specific distribution of trips.

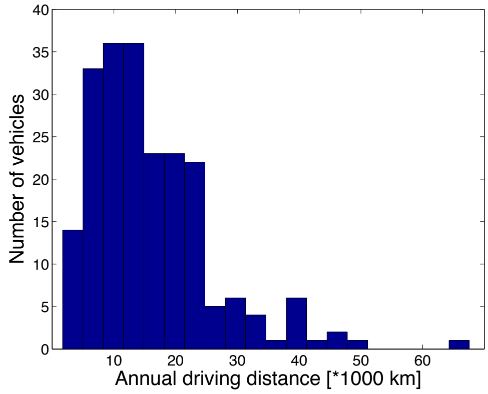

Figure 2: Extrapolated annual driving distances for the 214 cars.

Fig. 2 shows the distribution of the derived annual driving distances. The average annual distance is 15 951 km, which is somewhat lower than the average annual driving distance of about 16 800 km in 2008 for Swedish cars ≤ 9 years old, a figure also including non-privately driven cars, though [13].

3 Result

Fig. 3 gives the fleet average number of pauses longer than break time *T* for different *T*. This thus shows the number of rechargings per day for different break time *T* in our analysis. We can note that if recharging only when pauses are 10 hours or longer will imply charging only around 0.7 times a day in average. Many cars do not drive every day, which holds the figure down.

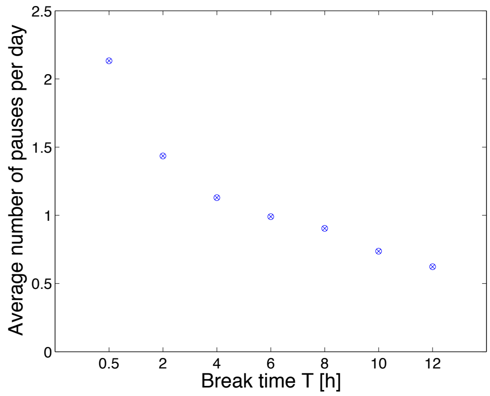

Figure 3: Fleet average number of pauses per day longer than break time *T*.

[2] We assume the trips to be of the same size if the difference between the measured pause and the estimated travel time for the missing trip length is less than 0.5 h.

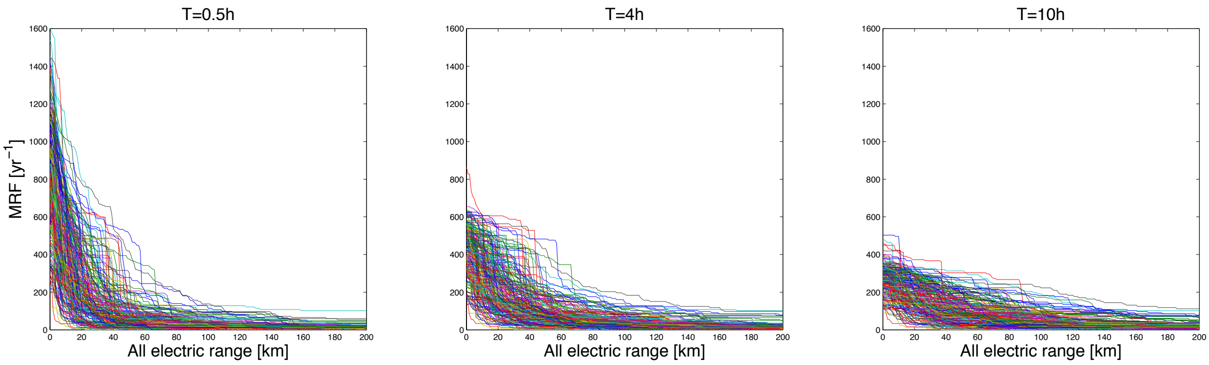

Figure 4: The individual marginal annual recharging frequency (*MRF*) as function of the all electric range (*AER*) and required break time *T* for recharging the battery for the 214 cars.

Other may actually not have a long enough pause each day due to the distribution of their driving over the day. Increasing the recharging options to pauses of 4 hours or longer will give roughly 50 % more rechargings. Recharging for every half an hour pause will further double the recharging occasions to just over twice a day.

Fig. 4 shows the resulting marginal annual recharging frequency *MRF* as function of the battery size expressed as the *AER* [km] of the battery. There is a large variety between different cars depending on their individual movement patterns regardless of charging option. The individual $MRF_i(AER)$ falls steeply when the specific 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 driving between home and work. Another feature seen especially in the figure for $T = 0.5$ h is that the driving often includes a lot of short distance trips (giving rise to high *MRF* for low *AER*).

In general better charging opportunities (shorter *T*) leads to more recharging occasions and thus that the driving is divided into shorter distances between recharging. This results in a higher *MRF* for smaller batteries, as well as lower *MRF* for larger *AER*.

The result of the vehicle/battery design is presented in Fig. 5-6 showing the distribution of the battery sizes, and the number and shares of PHEVs in the car fleet. The result is given for minimum annual recharging frequency MRF_{opt} = 50, 100, 200, 400 and 800 yr^{-1}, minimum break time T = 10, 4 and 0.5 hours, respectively. The result differs widely with the MRF_{opt}.

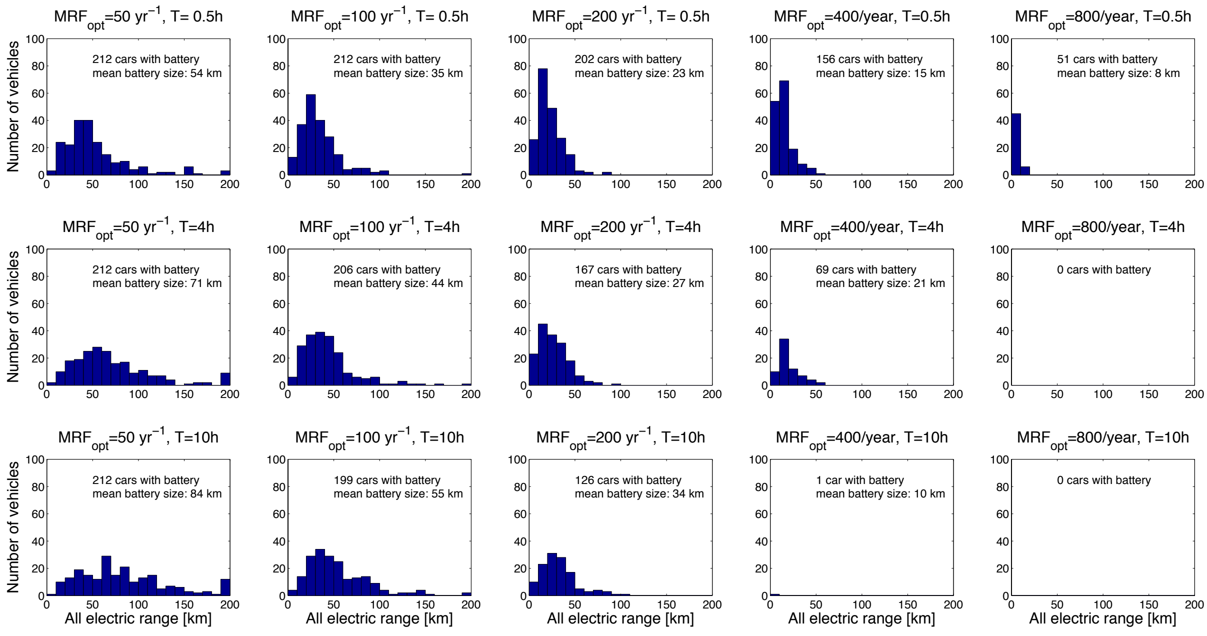

Figure 5: Distribution of battery size (km *AER*) for individually optimized vehicles. From right to left: increasing economic viability, i.e. decreasing MRF_{opt}. From bottom to top: better recharging options, i.e. shorter minimum break time *T* for recharging.

In general, the better the battery economics for PHEV, i.e., the smaller the MRF_{opt}, the more cars with batteries and the larger the batteries. Small MRF_{opt} also means that the optimal battery varies considerably in size. For MRF_{opt} =50 yr^{-1}, although almost all of the cars have an energy battery, the optimal size varies from almost zero to 200 km, the upper limit set in the calculations. The larger the MRF_{opt}, are the more concentrated are the optimal sizes in a small range.

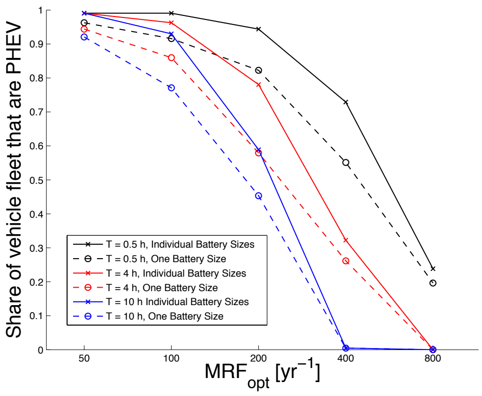

Figure 6: Share of car fleet being PHEVs (of 214 cars) as a function of the viability parameter MRF_{opt} and charging options. For individually optimal battery sizes (solid lines) and one-size battery (dashed lines).

For increased recharging options, i.e., lower T, the number of viable PHEV cars increases. The sizes of the batteries generally tend to decrease though, except for the smallest batteries or zero-sized batteries, when the optimal car turns from HEV to PHEV. However, the average battery size is generally decreasing, especially at low MRF_{opt}. At MRF_{opt} = 50 yr^{-1}, when T changes from 10 to 0.5 h, the average battery shrinks in size with about a third from 84 to 54 km *AER*.

The competitiveness of PHEV increases thus with both the lowering of the MRF_{opt}, and increased recharging options. For MRF_{opt} = 800 yr^{-1} it is only for the most extreme recharging option, T = 0.5, that any PHEV is competitive. For recharging only in pauses of at least 10 hour the MRF_{opt} need to be as low as 200 to achieve any considerable share of PHEVs.

For very good economic conditions for PHEVs, here represented by MRF_{opt} =100 yr^{-1} or lower, almost all cars have batteries regardless of charging option. For MRF_{opt} = 200 and 400 yr^{-1} the viability is largely depending on the charging option; for MRF_{opt} = 400 yr^{-1}, for instance, ranging from close to 0 % up to 70 % of the cars. Thus for the PHEV competitiveness, the different charging options are most important in the transition from low to high viability of the battery economics.

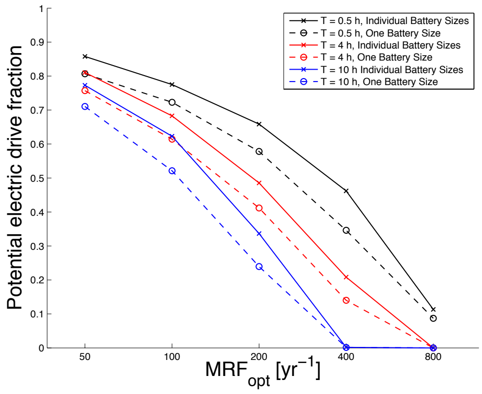

Figure 7: Potential electric drive fraction for the car fleet as function of the viability parameter MRF_{opt} and charging options. For individually optimal battery sizes (solid lines) and one-size battery (dashed lines).

Fig. 7 shows the resulting overall potential for PHEV to substitute fossil fuel with electricity for the vehicle fleet. For the less PHEV favourable conditions at high values of MRF_{opt}, similar to the number of competitive PHEVs, shown in fig 6, the electric drive fraction is very dependent of charging options as well as the specific battery economics. Generally the achieved fossil fuel substitution, i.e., the electric drive fraction, is smaller than the share of vehicles that are PHEVs, though. For instance, the share of PHEVs at MRF_{opt} = 200yr^{-1} and T = 10 h is around 60% while the electric drive fraction is only just over 30%.

This also means that, compared to the number of PHEVs, the electric drive fraction is more sensitive to charging condition and battery economics also at very favourable economic conditions; even at MRF_{opt} = 50 or 100 yr^{-1}, the EDF increases considerably for better recharging options and/or further improvements in battery economics.

For estimating the effect of introducing individual batteries, in Fig. 6 and 7, are also shown the resulting PHEV share and electrification of driving for a case with only one battery optimized in size for the whole vehicle fleet. The effect of individual batteries ranges from a few per cent points up to around 10 per cent points larger electric drive fraction and up to 20 per cent points larger share of PHEVs.

At low EDF this effect can correspond to a considerable part of the total contribution. For instance, for MRF_{opt} = 200 yr^{-1} and T = 10 h the change from a one-size-for-all battery to individual ones leads to about 25 % less distance driven on electricity. For the individual car owner with a specific driving pattern, the effects can of course be considerably larger and be the difference that makes an HEV or a PHEV the competitive vehicle.

4 Discussion

The general results achieved in this study are consistent with result presented in [1], which utilized movements of cars coming from a mid-sized Swedish town only. Both studies show that in a situation where the economics of batteries is very favourable, there will be a wide range of optimal battery sizes dependent on the individual car movement pattern. For intermediate economics the resulting economic viability of the PHEV and the potential to replace transportation fuels will be much dependent on the possibilities to charge the battery. For facilitating electric propulsion by the adoption of PHEVs, improving charging options may therefore be of importance.
We have in the analysis assumed a constant marginal cost for the energy capacity independent of size and therefore indirectly also a constant battery power equal for all PHEV and the HEV we compare to. For small PHEV batteries as well as the HEV battery this may in reality not be true.
When modelling the future cost of batteries of different chemistries and sizes [14] argue (contrary to their earlier analysis in [9]) that optimal battery for HEVs and possibly small PHEV batteries may be designed to have less available power than larger PHEV batteries. The consequence of such a design is that the marginal cost for increasing energy capacity is larger for smaller batteries, when the power will increase in parallel to the energy capacity, than for larger ones with constant power. Also, this tendency is strengthened by the possibility that battery packs, when made larger, need to increase the number of cells implying even higher marginal costs, while large batteries may stay constant in number of cells and thus keep the marginal production costs down as size increases. Assuming higher marginal costs for smaller than for larger batteries will reinforce the conclusion made here that, especially for low MRF_{opt}, the optimal individual battery size varies over a large range; small batteries tend to be even smaller and large ones larger. Generally the HEV also gets more competitive with PHEVs, resulting in possibly somewhat fewer cars with a non-zero optimal battery.
The viability of the PHEV is in this work analysed through a comparison with the HEV only. A more thorough comparison also with conventional vehicles, possibly with various degree of hybridization, for various movement patterns is of importance to better understand the economic viability and potential of the PHEVs. Whatever the outcome of such a comparison, a good competitiveness in many cases of the PHEV with the full HEV, as illustrated here if the battery costs comes down further, means that the HEV is not per se easier to introduce to the market on large before introducing the PHEV. The initial investment of an HEV might be too large to actually compete with conventional vehicles on a large scale and the additional PHEV energy battery might then be the difference that makes the whole investment economically sound.

5 Conclusion

This study further confirms earlier results that the large variation in utilization of battery capacity, stemming from great differences in individual movement patterns, results in large differences in economic feasibility for different battery sizes. This suggests that a 'one-size fits all' approach would not be the most economically sound solution for the individual car. Manufactures of PHEVs and policy makers need to consider the individual utilization of battery capacity when designing PHEVs or suggesting measures for facilitating their adoption.

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Authors

M.Sc. Lars-Henrik Kullingsjö
Lars-Henrik Kullingsjö achieved a M. Sc. in Industrial Ecology in 2011 and is currently doing a PhD in System analytical modelling and assessment of design, viability and potential of plug-in hybrids at the Department of Energy and Environment, Chalmers University of Technology, Sweden.

Dr. Sten Karlsson
Sten Karlsson received a PhD in 1990 and is senior lecturer at the Department of Energy and Environment, Chalmers University of Technology, Sweden. His current research is focusing on energy efficiency and technology assessment, especially concerning private cars and the electrification of vehicles.