Electrification potential of the car – an estimate from a mid-size Swedish town

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EVS25

Shenzhen, China, Nov 5-9, 2010

Electrification potential of the car –
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Abstract

An electrification of vehicles can contribute to increased energy efficiency and decreased air pollution in urban environments. The high vehicle costs involved, especially for the batteries, means that careful considerations of the options are needed. We have investigated the optimal design and potential for plug-in hybrid electric vehicles (PHEV) under various viability conditions with the help of a data set for individual vehicle movements from a mid-size Swedish town.

In the estimates each car is equipped with a battery cost-optimized in size with respect to the individual car movement pattern and charging options expressed as the minimum break time interval required for considering recharging. The resulting optimal battery sizes are relatively small for lower economic viability, but increase with raised charging options. For high economic competitiveness the optimal sizes are larger, but decrease with better recharging possibilities.

The results point to a PHEV design strategy with a small battery in an introductory phase and then an increased size when the economic competitiveness is further enhanced. Still the resulting optimal battery size is highly dependent on the specific movement pattern of the individual car. It is now urgent for the continued development, planning, and estimates of proliferation and impact of electrified vehicles that further statistical data, today mostly lacking, for the movement patterns of individual vehicles in various regions are assembled and utilized.

Keywords: movement, GPS, charging pattern, battery size, PHEV potential

1   Introduction

An electrification of vehicles can contribute to increased energy efficiency and decreased fossil fuel dependency, as well as the lowering of CO_2 emissions and air pollution in urban environments. Any large-scale deployment of electric vehicles is dependent on vehicle performance, convenience and economic viability from a customer point of view. Due to, among other things, the expensiveness of batteries and driver's range anxiety, plug-in hybrid electric

vehicles (PHEVs) have been suggested as a compromise between cost, performance and range. Still, for any economic viability of PHEVs, the dimensioning of the batteries and the possibilities for recharging are crucial. Using a small data set for car movements, we have highlighted that this viability, assuming charging once a day, may be heavily dependent on the movement patterns of the individual vehicles [1]. With the help of a larger data set for individual vehicle movements from a mid-size Swedish town, we here investigate the possible PHEV design and potential. We estimate the optimal size of the battery and the electric drive fraction for the individual vehicles from their movement patterns and for various assumptions on economic viability and recharging options.

2   Method

Analytical expressions for optimal battery size and electric drive fraction using car movement data with trip distances, times and dates were derived in [1]. We apply these expressions, adding a recharging frequency parameter, to a car movement data set representing 200 cars driving on average 100 days.

2.1   Utilization of the battery in a PHEV

The access to charging posts affects the utilization of the battery. It can be for instance at home, at work or in shopping centers. In the data set used here (see Section 2.3) the specific purpose of the trips are not available, though. If that is the case, this access can be roughly represented by a minimum time interval, T [h], of the stop between two drives when the car is allowed to recharge its battery. Letting the car recharge every time it stops for, say, at least four hours could correspond to the situation when charging posts are accessed both at work and at home whereas a ten hour stop requirement means that the battery probably only will be recharged once a day. We assume that the battery is fully recharged in every break of at least size T.

The car i has a movement pattern over the year described by the frequency $f_i(x,T)$ [yr^{-1}] for the accumulated distance x [km] driven between stops of at least the chosen minimum time length T. We have the annual number of times with distances $\leq d$ [km] driven between the stops

$$F_i(d,T) = \sum_{x=0}^{d} f_i(x,T) \qquad (1)$$

The maximum value of F_i for a given T is then

$$F_i(\infty,T) = \sum_{x=0}^{\infty} f_i(x,T) \qquad (2)$$

(= number of annual driving periods between stops $\geq T$)

(The extreme case $F_i(\infty, 0^+)$ would simply be the number of trips during a year. In the case of daily recharges the maximum value of F_i equals $F_i(\infty) = 365$.) From the individual movement pattern alone it is possible to estimate the extent to which the PHEV can be propelled with electricity from the battery. The PHEVs are assumed to be designed individually with an optimal size of the battery in such a way that the total cost of driving is minimized. A necessary (but not sufficient) requirement for this is that the cost for an extra storage capacity is balanced by the achieved cost savings of the extra driving on electricity instead of fuel. We assume that the cars drive in pure electric mode as long as the state of charge exceeds a minimum value. Although the energy use will vary with driving pattern properties such as speed, aggressiveness, orography and the use of ancillary power, e.g., for air conditioning and lighting, the electric energy used is assumed to be proportional to the distance driven only.

The all-electric range, *AER* [km], i.e., the maximum possible distance driven on electricity before recharging, depends on the battery size and on the electric energy used per km driven. The annual distance driven on electricity, S_i [km], is the sum of all distances driven over a year between recharging occasions that are less than or equal to the *AER* plus the *AER* multiplied with the number of times the battery is fully discharged:

$$S_i(AER,T) = \sum_{x=0}^{AER} xf_i(x,T) + \qquad (3)$$
$$+AER*\left[F_i(\infty,T) - F_i(AER,T)\right]$$

We define *MRF*, the marginal annual recharging frequency, as the number of times the last battery unit is recharged per year [yr^{-1}]. The MRF_i is equal to the marginal annual distance driven on electricity per *AER*

$$MRF_i(AER,T) = S_i'{}_{AER}(AER,T) = \qquad (4)$$
$$F_i(\infty,T) - F_i(AER,T)$$

See [1] for the derivation of the expression.

2.2 The economics of marginal battery capacity

We now derive an expression for the optimal battery capacity for a given movement pattern. The derivative with respect to range of the annual revenue R_i [\$/yr] is

$$R_i{'}_{AER}(AER,T) = S_i{'}_{AER}(AER,T)(p_f e_f - p_e e_e) \quad (5)$$

where p_f and p_e = prices of fuel and electricity, respectively [\$/kWh], and e_f and e_e = energy use per distance in fuel and electric mode, respectively [kWh/km]. We assume that the battery lasts for the whole service life of the car. The annual marginal cost of the battery [\$/km,yr] is then

$$C'(AER) = \alpha\beta^{-1}C'(B(AER))e_e \quad (6)$$

where α = annuity [yr^{-1}], $\beta = SOC_{max} - SOC_{min}$, the utilized state of charge window [-], and $C'(B)$ = marginal cost [\$/kWh] of battery of size B [kWh]. In the continuation we assume the marginal battery cost is independent of the battery size and equal to c [\$/kWh]. (It can be instructive to compare this assumption to the Toyota Plug-in Prius, which has an add-on grid-charged battery in a modular design. The modules, roughly covering 10 km each, are discharged successively one at a time. The battery can sustain the car in all-electric mode for a cruising speed of around 100 km/h [2].)

Starting from a zero-size battery, it is profitable to expand the battery as long as the annual marginal revenue exceeds the annual marginal cost, i.e., when

$$S_i{'}_{AER}(AER,T)(p_f e_f - p_e e_e) > \alpha\beta^{-1}c e_e \quad (7)$$

Rearranging the inequality, the marginal annual distance driven on electricity per AER is expressed as

$$S_i{'}_{AER}(AER,T) > \frac{\alpha\beta^{-1}c e_e}{(p_f e_f - p_e e_e)} \quad (8)$$

The minimum number of annual recharges for which profitability holds, MRF_{min}, is thus

$$MRF_{min} = \frac{\alpha\beta^{-1}c e_e}{(p_f e_f - p_e e_e)} \quad (9)$$

The economically optimal all-electric range for vehicle i is therefore

$$AER_{i,opt}(T) = AER\big|_{S_i{'}_{AER}(AER,T) = MRF_{min}} \quad (10)$$

The annual net revenue, $NR_i(T)$ [\$/yr], for the PHEV is the difference in yearly fuel and electricity costs, minus the annual cost of the battery. It can also be expressed as the integrated difference, from zero to the optimal battery size, between the marginal recharging frequency and the minimum marginal recharging frequency for which profitability holds, multiplied with the difference in costs per distance for fuel and electricity:

$$NR_i(T) = (p_f e_f - p_e e_e) *$$
$$\int_0^{AER_{i,opt}(T)} [S_i{'}_{AER}(AER,T) - MRF_{min}]\,dAER \quad (11)$$

The PHEV potential can be expressed as the share of cars for which a non-zero battery is the optimum and as the electric drive fraction of the total distance driven by the cars.

It is reasonable that a PHEV has a minimum battery size, or have, compared to an HEV, extra costs for the car above the larger battery, considering the extra costs for charger and increased vehicle complexity, even though it can be argued over the exact limit value. We here include the results only for cars gaining at least 25 \$/yr net revenue, calculated according to Eq. (11). Cars with batteries of very small optimal size will thereby not be included. An upper limit is set to 200 km.

2.3 Data

We apply the analysis to a Swedish car movement data set from a mid-size Swedish town, the city of Lund with about 76 000 inhabitants. This car movement data set was created in the years 2000-02 in connection to an evaluation of an in-car intelligent speed adaptation (ISA) system [3-5]. The ISA system engaged an accelerator pedal resistance when the speed limit was about to be exceeded. The engagement was automatic and limited to a certain test area of 27 km^2, roughly the city of Lund, with speed limits of 30, 50 and 70 km/h. Outside the test area a desired speed limit could be set manually by the driver. Drivers of around 4000 randomly chosen vehicles from Lund were contacted in the recruitment process of test vehicles. Just over 200 car drivers were willing to participate in the study and had vehicles that could be equipped with the active accelerator pedal. The study embraced cars, buses and lorries, altogether 284 vehicles, but here we use data only from the 201 cars with a reasonable long recording period.
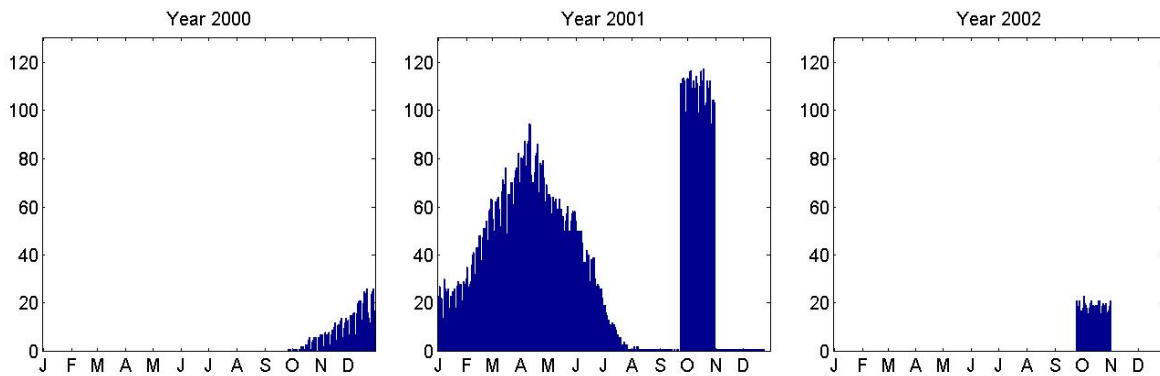
Figure 1: Number of cars with logged drives each day of the years 2000, 2001 and 2002.

The individual car movements were logged for 100 days on average during the periods shown in Fig. 1. The ISA systems were successively installed in the cars during the period November 2000 to May 2001 and were activated at least one month after the installation. The installations had to be done with a few cars per day due to limitations in capacity. The car movements were logged both before the activation and for about one month after. In addition there was a one month logging period in October 2001 to see how the driving behaviors had changed after getting used to the system. The equipment was kept in 16 of the cars for yet another year for a final logging period in October 2002. (The drivers reduced the driving speed directly after the system activation, but then gradually increased it again with time.)
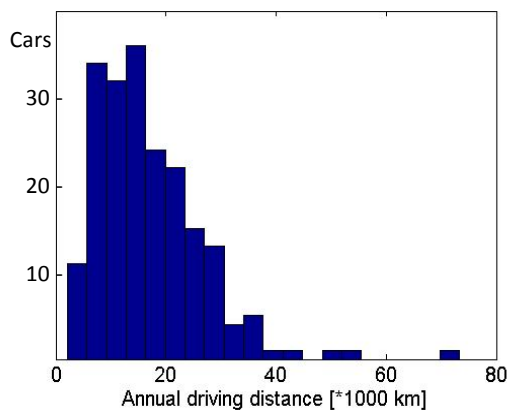

Figure 2: Distribution of extrapolated annual driving distances for the 201 cars.

The logging was done with GPS equipment (global positioning system) giving the position. This was used together with a digital map for the test area to determine the current speed limit. A clock registered the time since the start of a trip, a trip defined by start and stop of the vehicle engine. The actual speed of the car was derived and calibrated from the cars' own speed signal or from a mounted sensor. Integration of the speed data gave the distance driven since the start of each trip. The data is given with a frequency of 5 Hz within the test area and 1 Hz outside that area.

A histogram of the estimated annual driving distances of the cars, extrapolated from daily mean distances for the logging period of each car, is shown in Fig. 2. The average annual driving distance of the cars is 17 000 km, higher than the average annual driving distance of all Swedish cars in 2001, which was 13 000 km. This difference could be due to the actual selection of cars possibly giving an overrepresentation of newer cars with longer annual driving distances. Also older women (> 65 years old) and younger people (< 25 years old) are underrepresented [5], people probably driving less than average.

3   Results

The result from the estimation of optimal battery size, electric drive fraction and net revenue for individual cars are shown in Figs. 3-5, with minimum marginal recharging frequency MRF_{min} equal to 800, 400 and 50 yr^{-1}, respectively. Results are given for three values of the minimum break interval T: 10, 4 and 0.5 hours. A 10-hour minimum interval should correspond reasonably to night charging for the majority of the cases. A break interval of intermediate size means that the charging also can take place when the car is parked at the work place, etc. A fully recharged battery after only half an hour interval means that the charging in most of these cases must be quick charging or fast charging.

MRF_{min} equal to 800 yr^{-1} can be said to be representative for a situation *close to current*

situation. MRF_{min} = 400 yr^{-1} assumes a situation with a modest development of the economic viability, *not far from current situation*, while MRF_{min} = 50 yr^{-1} corresponds to a *future state* with considerable further development from now of crucial parameters. The examples in Table 1 give an indication of the combination of parameter values required to achieve the values of 800, 400 and 50 yr^{-1}, respectively: The annuity is the same in all cases. *In the MRF_{min} = 800 yr^{-1} case*, the assumed battery price is close to current. The cost of battery packages to OEMs for near-future PHEVs can be estimated to 6-800 \$/kWh [6]. The utilized SOC window of β = 0.5 is equal to what was initially planned for Chevrolet Volt. (Finally in 2012 65% was utilized). The exemplified energy price is roughly the current European consumer price for petrol and electricity [7,8]. Hybrid and electric mode energy use of 0.6 and 0.2 kWh/km, respectively, give the assumed efficiency quota of 3. *In the MRF_{min} = 400 yr^{-1} case*, we have exemplified with a battery price reduced to 400 \$/kWh. The necessary development to reach MRF_{min} = 50 yr^{-1}, a further reduction with a factor of 8, is here illustrated with, besides an increased energy price, an increase in β to 0.8, and a further reduced battery price to 100 \$/kWh, which corresponds to USABC long-term goal for EV batteries [9].

The results differ considerably between the MRF_{min} cases. Generally, the better the economic conditions for PHEV, i.e., the smaller the MRF_{min},

the larger the optimal battery, the electric drive fraction and the net revenue.

Table 1: Examples of values for influential parameters for achieving a value of 800 yr^{-1}, 400 yr^{-1} and 50 yr^{-1}, respectively, for the minimum marginal recharging frequency for which profitability holds, MRF_{min}.

Parameter	MRF_{min} [yr^{-1}]		
	800	*400*	*50*
Annuity α [yr^{-1}]	0.15	0.15	0.15
Utilized SOC window β [-]	0.5	0.5	0.8
Marginal battery cost c [\$/kWh]	800	400	100
Energy price $p_e = p_f = p$ [\$/kWh]	0.15	0.15	0.25
Specific energy use quota e_f/e_e [-]	3 = 0.6/0.2	3 = 0.45/0.15	2.5 = 0.375/0.15

In the MRF_{min} = 800 yr^{-1} case, for most of the cars the optimal is no battery at all. Only in the fast charging option case (T = 0.5 h) one fourth of the cars are optimally PHEVs, and then the battery is a small one, with a range mostly less than 20 km. The driving share on electricity is between 0.1 and 0.5 and in most cases much below 50%.
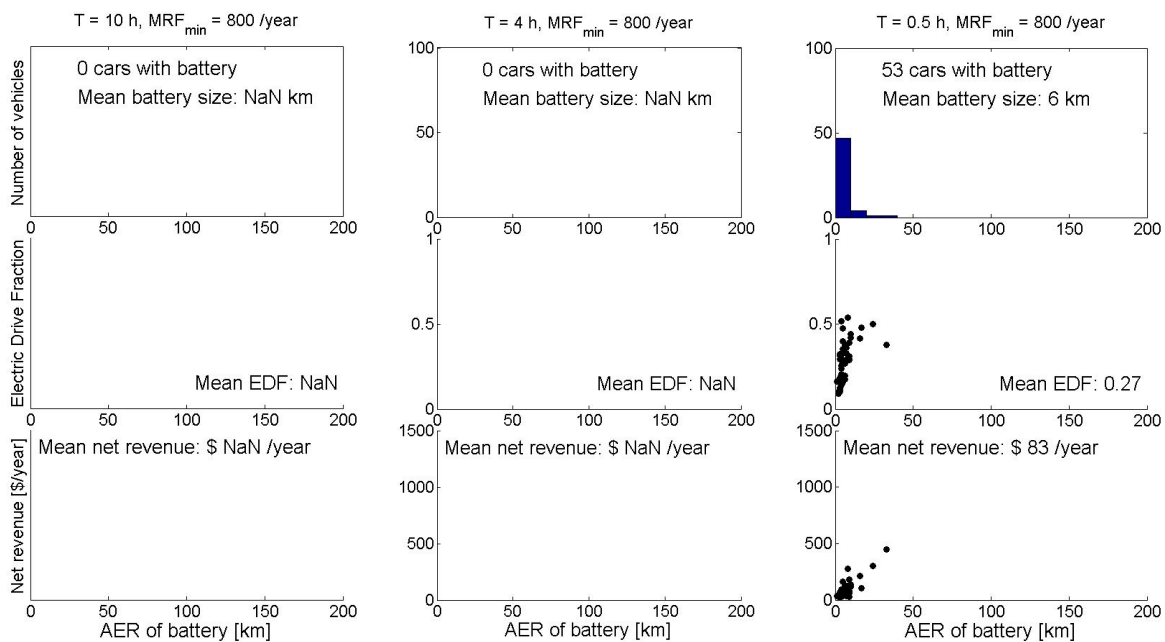

Figure 3: Optimal battery size and the corresponding electric drive fraction and net revenue of cars when MRF_{min} = 800 yr^{-1} and the cars can charge at 10, 4 and 0.5 hrs breaks, respectively.
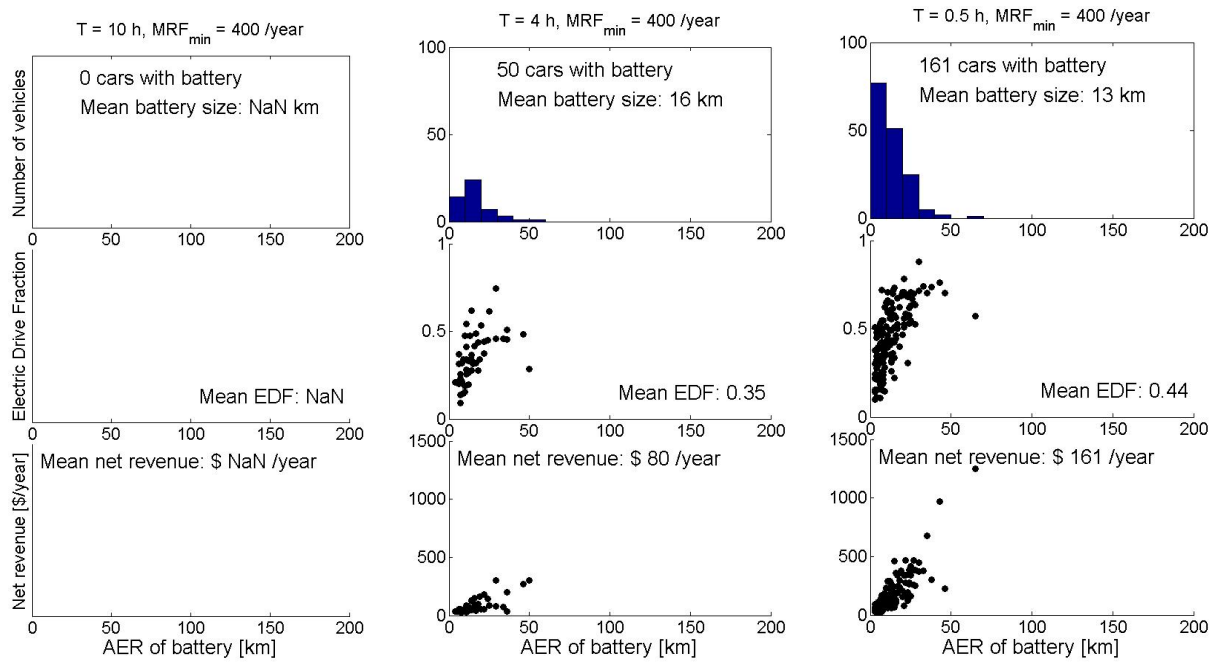
Figure 4: Optimal battery size and the corresponding electric drive fraction and net revenue of cars when $MRF_{min} = 400$ yr^{-1} and the cars can charge at 10, 4 and 0.5 hrs breaks, respectively.
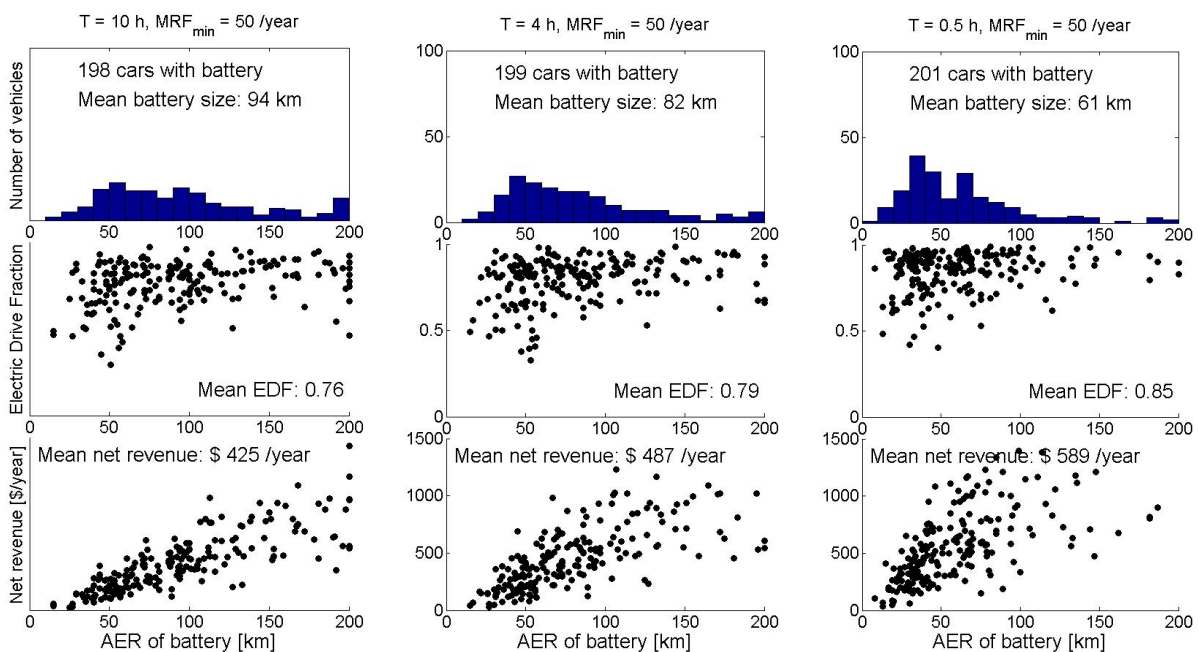

Figure 5: Optimal battery size and the corresponding electric drive fraction and net revenue of cars when $MRF_{min} = 50$ yr^{-1} and the cars can charge at 10, 4 and 0.5 hrs breaks, respectively.
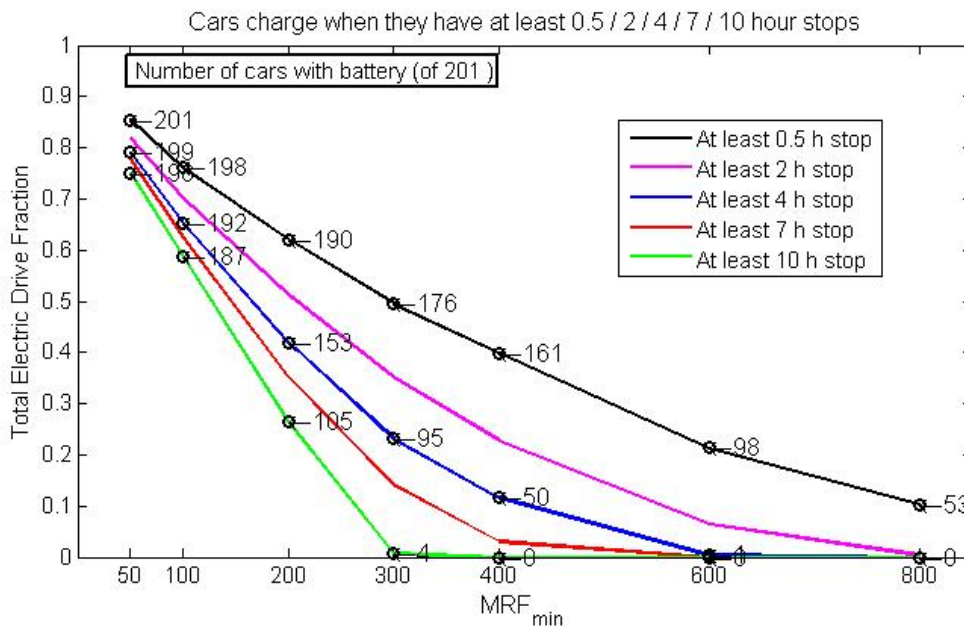
Figure 6: Total fleet electric drive fraction and number of PHEVs of the total fleet of 201 cars in the maximum potential scenario as a function of the viability parameter MRF_{min} and a range of different minimum break intervals T between 0.5 and 10 hrs.

In *the MRF_{min} = 400 yr^{-1} case*, the number of cars that optimally are PHEVs is very sensitive to recharging options and varies between 0 (for T = 10 h) and almost 80% (for T = 0.5 h). The optimal battery is generally still relatively small, with an average (usable) size of around 15 km. For the PHEVs the *EDF* is between 0.1 and 0.5 (for T = 4 h) to 0.75 (for T = 0.5 h). In most cases it is still below 50%. Although generally the *EDF* increases with the battery size, for the same battery size it varies considerably between the cars depending on the specific movement pattern of the vehicle.

In the most viable case, *the MRF_{min} = 50 yr^{-1} case*, the optimal battery is non-zero for almost all cars and is distributed over a considerable range, between 10 and 200 km (the maximum allowed value), with a concentration between 30 and 100 km. The share of driving on electricity is high, for most cars above 0.6 and with an average of close to 80%. For optimal batteries below 60 km the *EDF* can be as low as 30%, though. The annual net revenue has an average value of around 450 $. The spread in net revenue is considerable for the same-sized batteries, and is also dependent on the vehicle movement pattern.

For more recharging possibilities, i.e., lower T, the *EDF* and the net revenue increases. The individual optimal battery follows another pattern, though; with increased charging options, at low viability (Fig. 3) the optimal battery gets larger.

(The average battery still gets smaller due to the addition of PHEVs with small batteries when T decreases, Fig. 3.) At high viability (Fig. 4) the optimal battery size decreases with better recharging options (smaller T). At low viability, increased charging options may increase the utilization of the capacity of a battery making it profitable to increase its size and for more cars electric propulsion turns profitable. On the other hand, at high viability more charging occasions means the already comparably large battery will probably be fully charged less often, which means less capacity is optimally needed.

The net revenue is as mentioned the difference in total cost between a car without a battery and the one with an optimal battery. Generally it tends to increase with optimal battery range, Fig. 3, and as already noted with increasing recharging options (decreasing T). The net revenue can be considerable in comparison to for instance the assumed battery cost. At T = 0.5 h the average net revenue is about 10 $/km,yr. For an electric mode specific energy use of 0.2 kWh/km this corresponds to 50 $/kWh,yr, or about 330 $/kWh for an annuity of 0.15 yr^{-1}.

Fig. 6 shows the resulting fleet electric drive fraction for the whole vehicle fleet as a function of MRF_{min} and a range of different minimum break intervals T. For charging possible only once in a day (i.e., roughly corresponding to the 10 hrs break interval curve), with the prerequisites

assumed here, the MRF_{min} must be less than or equal to 365 yr^{-1}, i.e., recharged once a day the year round, before a PHEV even should be considered. (Fig. 5 only gives the data for MRF_{min} at 300 yr^{-1} and 400 yr^{-1}, though.) For an MRF_{min} of 200 yr^{-1}, more than 50% of the cars have a cost minimum with a non-zero battery. Still the fleet *EDF* is only around 25%. At a very low MRF_{min} of 50 yr^{-1}, i.e., good economic viability, the fleet *EDF* is around 80%, and this is more or less independent on the recharging possibilities. For a situation where only half an hour break is all that is needed for fully recharging whatever the battery status and car position, the fleet *EDF* is slightly more than 0.3 at MRF_{min} equal to 500 yr^{-1} and roughly 0.85 at a MRF_{min} of 50 yr^{-1}.

For intermediate MRF_{min} between 200 and 400 yr^{-1}, the recharging possibilities are decisive. Going from a *T* of 10 to 0.5 hour increases the fleet *EDF* by more than 40 percentage points. At $MRF_{min} = 300$ yr^{-1} it increases from almost zero to 50%. The PHEV share of the vehicle fleet increases with more than 40% with a maximum of 85% at around $MRF_{min} = 300$ yr^{-1}. To fully compensate for these increased recharging options not coming off, a lowering of the MRF_{min} with at least a factor of 2 would be necessary, i.e., for instance, a halving of the battery price. At very low or very high MRF_{min} the recharging possibilities are less important.

In summary the results of the study show that in a situation with high economic viability of batteries there will be a large range of optimal battery sizes. With intermediate economic viability the possibilities for charging make a major difference for the electric drive fraction. Increasing charging potential could be just as important for the economic viability of PHEVs as lowering battery costs. With today's conditions only very few driving patterns can economically motivate PHEVs.

4   Discussion

Different methods for estimating the movement patterns of cars give different information. The method applied for the data set used here with car movement pattern determined from GPS gives no explicit purpose of the individual trips. Indirectly though, this could be derived to a certain degree of confidence by an (effort-intensive) analysis and categorization of all the stop positions for the trips. This could be of importance for any evaluation of possible influence of enhanced charging opportunities in connection to, for instance, workplaces and shopping centers. Often, in National Travel Surveys the purpose with each trip is categorized into trips for going to work, leisure activities, visits, shopping etc. On the other hand, the specific locations for the stops are in most cases not collected.

The result can suggest a design strategy for the introduction of PHEVs. As already noted, for high values of MRF_{min} a small battery is optimal and the optimal size increases with increased economic viability i.e., a lowering of the MRF_{min}. A development towards lower costs of the battery and increased possibilities for utilization of the full capacity of the battery without compromising the battery lifetime points to a strategy where in the introduction a small battery is utilized and then as the cost comes down the battery size successively increases. Also, when this happens, the variation in optimal battery size within the vehicle fleet depending on the specific movement patterns suggests individually adapted batteries. In that case modular battery systems may be preferable.

5   Conclusion

We have shown that individual car movement patterns are vital for a successful assessment of the profitability of PHEVs and the potential market in the form of fleet EDF for the vehicles.

We conclude that it is now urgent for the continued development, planning, and estimates of proliferation and impact of electrified vehicles that further statistical data, today mostly lacking, for the movement patterns of individual vehicles in various regions are assembled and utilized.

Acknowledgment

References

[1] S. Karlsson, *Optimal size of PHEV batteries from a consumer perspective – estimation using car movement data and implications for data*

harvesting. WEVA Journal, Vol 3. (2009), (ISSN 2032-6653) http://www.wevaonline.net/.

[2] http://www.toyota.com/esq/pdf/PHVPriusProgram Overview.pdf, accessed on July 2, 2010.

[3] *LundaISA Sammanfattning av ISA-projektet i Lund*. (LundISA Summary of the ISA project in Lund) Publication 2002:94, Swedish Road Administration, Borlänge, Sweden, 2002. (in Swedish)

[4] M. Hjälmdahl, S. Almqvist, and A. Várhelyi, *Speed regulation by in-car active accelerator pedal – effects on speed and speed distribution*. IATSS Research, 26(2) (2002), p. 60–67.

[5] A. Várhelyi, M. Hjälmdahl, C. Hydén, and M. Draskóczy, *Effects of an active accelerator pedal on driver behaviour and traffic safety after long-term use in urban areas*, Accident Analysis and Prevention 36 (2004), p. 729–737.

[6] Treehugger, http://www.treehugger.com/files/2009/03/gm-fights-back-chevy-volt-plug-in-hybrid-battery-cost.php, accessed on 2010-08-19.

[7] Energy Information Administration, http://www.eia.doe.gov/emeu/international/gas1.html, accessed on 2009-04-15.

[8] Eurostat, http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-QA-08-023/EN/KS-QA-08-023-EN.PDF, accessed on 2009-04-15.

[9] USABC, http://www.uscar.org/guest/view_team.php?teams_id=11, accessed on 2010-08-19.

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