The effect of PHEV battery range distributions on competitiveness: Implications for design strategy and energy-efficiency policy

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Abstract

Electric vehicles have the potential to contribute to increased energy efficiency. However, competition is fierce among designs, energy carriers, and powertrains; electric vehicles must be economically viable from a consumer point of view. Batteries are still expensive; short of a breakthrough, the energy battery will constitute a considerable share of the vehicle cost for the foreseeable future. Economically efficient battery use is therefore very important. Plug-in hybrid electric vehicles (PHEV) constitute a response to this efficiency requirement. PHEVs rely on a relatively small battery, while still allowing a considerable share of the driving to be powered by electricity.

In previous studies, we investigated optimal battery sizes, from the individual consumer's perspective. In reality, only a limited number of battery sizes will be available. Understanding the relationship between a limited choice of battery sizes and the potential for PHEVs should be of value to car manufacturers, in constructing battery range strategies, as well as to policymakers, in formulating policies for encouraging the introduction of electric vehicles. Here we investigate this relationship by analyzing how various battery range strategies influence PHEV viability, efficiency, and potential. We use a data set on car use from a mid-size Swedish town covering 201 individual cars for 100 days.

The results are presented in terms of the possible loss in net revenue, electrification potential, and energy efficiency for different distributions of battery ranges, which reflect a limited number of optimized sizes and a modular design. We apply our analysis to current conditions and a range of possible future techno-economic and recharging conditions, making it possible to estimate the importance of the different strategies in a variety of future scenarios. For instance, for a single fleet-optimized battery, the estimated loss in average net revenue is up to 30 % of the battery cost, the possible loss in fleet electrification potential is at least up to 10 % of the distance driven, and the potential loss in average vehicle energy efficiency is also around 10 %.

Introduction

Due to the high efficiency of the energy conversion in the electric driveline, electric vehicles have the potential to contribute to increased energy efficiency and decreased fossil fuel dependency in transportation, as well as the reduction of CO_2 emissions and air and noise pollution in urban environments. On the other hand, the electricity generation can entail considerable energy loss, and fossil fuel generating stations emit massive amounts of CO_2. However, studies show that in the long-term, electrification of transportation may be a cost-effective option for meeting stringent climate change targets [Grahn et al 2009, Hedenus et al 2010].

There will in any instance be fierce competition in the car market among different designs, energy carriers, and powertrains. Electric vehicles must be economically viable from a consumer point of view to take on significant market share. Batteries are still expensive; barring a breakthrough, the energy battery will constitute a considerable share of the vehicle cost for the foreseeable future. This will contribute to a higher initial fixed capital cost for the electric vehicle. For this vehicle to be viable, this higher cost must be compensated for by a lower operating cost. The much greater energy conversion efficiency of the electric vehicle can contribute to this lower operating cost, especially in Europe, where vehicular fuel is relatively expensive. At the retail level in Europe, fuel and electricity prices are roughly equal per energy unit, so the electric vehicle's propulsion cost should be much lower than that of its fuel-equivalent. But it is still important to use the battery economically, in order to fully realize this competitive potential. Pure electric vehicles (battery electric vehicles (BEV)) need to carry a large, and therefore relatively expensive, battery to have a range comparable to what is achieved for fuel-driven cars. The actual utilization of this large battery capacity will probably be lower than required for economic competitiveness, which may hamper the acceptance of BEVs. Even for a shorter but reasonable range, if only to overcome driver range anxiety, the battery may be too large and expensive for market acceptance.

Plug-in hybrid electric vehicles (PHEV) offer a response to the range and range anxiety problems. In the PHEV, the electric driveline is supplemented by a (preferably small and cheap) fuel engine. The PHEV is supposed to be more competitive, using only a relatively small, and thus much cheaper, battery while still powering a considerable share of the driving with electricity.

Several studies have investigated PHEV battery size and competitiveness. Often the issue is formulated as an economic choice among battery sizes, expressed as possible ranges on electricity only, for instance 20, 40 or 60 miles, [e.g., EPRI 2001, Bradley and Frank 2009, Shiau et al 2009]. The driving distance to be covered by the assessed vehicles is typically based on statistics for the distributions of average daily driving distances, which can sometimes be extracted from travel statistics (for instance, Karlsson and Ramirez [2007]). National or regional travel survey data are available in many countries. However, in most cases, as in Sweden [SIKA 2007], there is no tracking of the vehicle's travel, only of the individual person's travel, and only for one day. In Western Europe, only a few countries gather information specifically on travel for several days for a given vehicle. For instance, data exist for one week in the UK (and for four weeks for long distance travel), and for five days in France [Karlsson & Wiedemann 2010]. Very few publicly available other data exist on vehicle movement patterns.

In previous studies, we showed that the optimal PHEV battery, from the consumer's perspective, depends considerably on the individual car movement pattern. Using a small data set for car consisting of data from 29 cars tracked by GPS for about two weeks, we highlighted that the economically optimal battery and PHEV prospects may be heavily dependent on the movement patterns of the individual vehicles [Karlsson 2009]. This result was confirmed in a study based on a much larger dataset, with 201 cars from a mid-size Swedish town logged by GPS for around 100 days (Jonson & Karlsson 2010). In that study we investigated the optimal battery dependent on the techno-economic conditions, recharging options, as well as individual movement patterns. The recharging options were simulated by assuming a range of required "breaks" in between trips for recharging. For roughly current techno-economic conditions, the individual battery was non-zero only when assuming that recharging was possible whenever there was a half-hour break between trips. In that case, 26 % of the cars had a non-zero optimal battery with an average range of only 6 km. In a scenario with much more favourable techno-economic conditions (cheaper batteries, etc), almost every car was a PHEV, and the economically optimal battery varied from small to a 200 km range, which was assumed to be the maximum. The average range on electricity was between 61 and 94 km, depending on the recharging options; the better the options the smaller the batteries.

In reality there will be only a limited number of battery sizes available. Knowledge of the relationship between a limited choice of battery sizes and the potential for PHEVs could be used by car manufacturers when choosing battery range strategies and by policymakers when formulating policies to encourage deployment of electric vehicles. Here we investigate this relationship by analyzing how various battery range distribution strategies influence PHEV viability, efficiency, and potential.

When implementing a distribution of battery ranges in a specific PHEV model, manufacturing flexibility, reliability, safety, economics, and marketing, or battery-size exchange options, will need to be taken into account, too. These issues are not dealt with here. All current PHEV models only offer one battery size per model. The battery of the Toyota Prius PHEV is claimed to consist of three modules, though. One is used for power delivery as in an ordinary hybrid electric vehicle (HEV). The other two are utilized for energy storage, with a range of around 11 km each, and are discharged sequentially. Also, some battery manufacturers offer modularly built batteries for electric vehicles [e.g., von Borck et al 2010].

Method

A PHEV can be designed for blended-mode driving in which, for instance, due to power limitations of the electric driveline, the energy comes from both the fuel and the electricity stored in the battery. Or it can be designed to run in a pure electric mode, which means that for a given battery, a larger share of the distance driven is powered by electricity. In this study, we assume the second mode. It can be argued that to fulfil the requirement of acceleration and brake energy recovery, small PHEV batteries will not have high enough specific power. A separation of the electric power and energy delivery (as is done in the Toyota Prius plug-in hybrid mentioned above in the Introduction) can help resolve this dilemma, making a small energy battery more feasible in a PHEV [Burke et al 2010, Ahmadkhanlou et al 2010]. This solution may also enhance the energy battery lifetime by diminishing the dynamic stress, as well as increase the overall energy efficiency of the driveline. In this case also ultracapacitors may be a feasible option for the power supply [Burke et al 2010].

We define the all-electric range (*AER*) as the maximum possible distance driven powered exclusively by electricity. The *AER* is determined by the battery size (*B*) and the utilized share (β) of its nominal capacity, and on the electric energy used per electricity-powered distance driven (e_e), here assumed to be constant:

$$AER = \beta B / e_e \qquad (1)$$

We define the marginal annual recharging frequency (*MRF*) as the number of times the last battery unit is recharged per year. *MRF* is also equal to the number of times that the battery is fully emptied and recharged per year. Recharging of the battery is influenced by the individual car movement pattern and recharging options, as well as battery size. For a given movement pattern and recharging options, we can express *MRF* as a function of battery size expressed as *AER*

$$MRF(AER) = S_e'(AER) = S \bullet EDF'(AER) \qquad (2)$$

S and S_e are the annual distances driven, in total and on electricity, respectively, and *EDF* is the electric drive fraction S_e/S. The prime denotes the derivative.

An economic optimization of the battery can be made based on the individual car movements. In the optimization we include the cost of the battery and the cost of the energy (vehicular fuel or electricity). Other costs are assumed to be independent of battery size. It is profitable to increase the *AER* of a car as long as the extra revenue (savings from running the car on electricity instead of fuel) is larger than the extra cost (of the additional battery unit). The number of marginal annual recharges for which viability is optimized, MRF_{opt}, is the lowest *MRF* of an additional unit of battery that still makes an expansion of the battery economically profitable and implies a cost-minimization of the PHEV. We assume that the battery can be of arbitrary size and that it lasts the (economic) lifetime of the car [Wood et al 2011], which means it can be treated as having an initial fixed capital cost, which is annuitized. MRF_{opt} is then a function of the cost of the battery $C(B)$ and the annuity α, the utilization of the battery capacity, and of the price of fuel (p_f) and electricity (p_e), as well as energy use per distance in fuel- (e_f) and electric-mode (e_e), respectively [Karlsson 2009],

$$MRF_{opt} = \alpha\beta^{-1}C'(B)e_e/(p_f e_f - p_e e_e) \qquad (3)$$

The marginal battery cost $C'(B)$ is assumed to be constant, which means that the battery cost is linear in battery size. The MRF_{opt} will decrease with more favourable-to-PHEV techno-economic conditions: lower annuity or specific battery capacity costs, larger utilization of the nominal capacity, as well as a more favourable relation between fuel and electricity concerning price and specific energy use.

The optimal battery size expressed as the individual *AER* will of course depend on the assumed techno-economic parameters in (3), but also on the individual movement pattern via (2) and the recharging options. Optimality requires

$$AER'_{opt}(EDF) = S \bullet (p_f e_f - p_e e_e)/\alpha\beta^{-1}C'(B)e_e \qquad (4)$$

or by using (1)

$$B'_{opt}(EDF) = S \bullet (p_f e_f - p_e e_e)/\alpha C'(B) \qquad (5)$$

We utilize a car movement data set created in 2000-02 in connection with an evaluation of an intelligent speed adaptation (ISA) system applying a throttle resistance in speed-limited areas [Hjälmdahl et al 2002, Várhelyi et al 2004, LundaISA 2002]. The individual movements of 201 cars from the city of Lund in southern Sweden were logged for around 100 days on average, including an initial period with a non-activated, as well as later on an activated, ISA system. We assume that each car is replaced by a PHEV with the same movement pattern, assumed to be representative for the lifetime of the car.

We estimate, as a function of MRF_{opt}, the influence of different battery range strategies on the viability, energy efficiency, and transport electrification potential. The *viability* is estimated as the economic competitiveness in the form of the net revenue of a PHEV compared to the corresponding car without an energy battery, the hybrid electric vehicle (HEV). The net revenue is defined as the revenue from lower energy costs minus the cost of the energy battery. If PHEVs are available, it is reasonable to assume that the corresponding HEVs are available, too. The competition with a conventional (non-hybrid) car is not investigated. Today a conventional car is also not well-defined when a range of cars with different degrees of hybridization are available on the market. The *electrification potential* is here estimated, for the total vehicle fleet, as the share of the distance driven on electricity (*EDF*) realized when the most cost-efficient vehicle type and design are used under the assumed techno-economic prerequisites. The *energy efficiency* is calculated as the achieved average specific energy use for the vehicle fleet when the electrification potential is realized.

The different battery range strategies investigated are

- individually optimal batteries, reference case (IB)
- 1, 2, or 3 fleet-optimized batteries, respectively (1B, 2B, 3B)
- 23, 64, or 23 and 64 km battery, respectively (P, V, PV)
- modular 23 km batteries (MP)

The IB strategy, in which the batteries are separately optimized against the individual movement patterns, is used as the reference case and is further elaborated in Jonson and Karlsson [2010]. In strategy 1B one battery, which is cost-optimized against all movement patterns, is applied. Strategies 2B and 3B have two and three similarly optimized batteries, respectively. The Toyota Prius PHEV with a range of 23 km and the Chevrolet Volt with an initially claimed range of up to 64 km (40 miles)[1] are coming to market. We use these battery sizes separately (strategies P and V, respectively) or combined (strategy PV), that is either/or, such that the optimal one is chosen for the individual car based on its unique movement pattern. A modular battery strategy is applied in the last strategy (MP), in which batteries with modules of 23 km range are optimally applied to the car movement patterns.

We determine, as a function of the viability parameter MRF_{opt}, the battery size of the individual PHEV dependent on strategy. The optimal battery can also be zero, which means the optimal (cost-minimized) car is an HEV. The optimal battery sizes will depend not only on the assumed MRF_{opt} but also on the recharging options in the form of access to charging posts at workplaces, in public parking areas, and in private garages. When simulating the variations in state of charge, the access to charging posts is represented by a minimum time length T of the stop between two trips for the car to possibly recharge its battery[2]. The battery is fully charged at every possible recharge occasion, i.e., at breaks equal to or longer than T. This means that charging is assumed available wherever and whenever this break occurs, and in case of recharging also at short breaks, the availability of fast charging is assumed to be able to always fully

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[1] The range varies with the conditions, but is now stated as 35 miles (56 km), referring to an estimate by the US EPA [http://www.chevrolet.com/volt/ Accessed Feb 25 2011]

[2] This means that all the functions in (2), and the left-hand sides of (4) and (5), also depend on the parameter T.

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Table 1. Assumed parameter values for MRF_{opt} = 50, 100, 200, 400, 800 yr^{-1}, respectively. Based on Jonson and Karlsson [2010].

Parameter	MRF_{opt} [yr^{-1}]				
	50	**100**	**200**	**400**	**800**
Annuity α [-]	0.15	0.15	0.15	0.15	0.15
Depth of discharge β [-]	0.8	0.75	0.61	0.5	0.5
Marginal battery cost $C'(B)$ [$/kWh]	100	160	250	400	800
Energy price $p_e = p_f = p$ [$/kWh]	0.25	0.2	0.17	0.15	0.15
Specific energy use quota 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

charge the battery within the allotted time. It also assumes that the driver actually utilizes all recharging options.

MRF_{opt} equal to 800 yr^{-1} can be said to be representative of a situation *close to the current situation*. MRF_{opt} = 400 yr^{-1} assumes a situation with a modest development of economic viability, *not far from current situation*, while MRF_{opt} = 50 yr^{-1} corresponds to a possible *future state,* at a time when a considerable further development of crucial parameters has occurred. The examples in Table 1 give an indication of the combination of parameter values required to achieve the different values between 800 and 50 yr^{-1}, respectively: The annuity is the same in all cases. *In the* MRF_{opt} *= 800* yr^{-1} *case*, the assumed battery price is close to current. The cost of battery packages to car manufacturers of near-future PHEVs can be estimated at $6-800/kWh[3]. The state of charge (SOC) window, 0.5, is equal to that currently applied in the Chevrolet Volt. The energy price is roughly the current European consumer price for petrol and electricity. Hybrid and electric mode energy use of 0.6 and 0.2 kWh/km, respectively, give the assumed efficiency quota, 3. *In the* MRF_{opt} *= 400* yr^{-1} *case*, we assume a battery price of $400/kWh, a price somewhat below the estimated current price, but predicted for soon after 2012 by Deutsche Bank [2010]. The necessary development to achieve the lowest value of MRF_{opt} *= 50* yr^{-1}, a further reduction by a factor 8, is here illustrated by – besides an increased energy price – a further reduced battery price, to $100/kWh and an increased SOC window, to 0.8, which correspond to US Advanced Battery Consortium (USABC) long-term goal for EV batteries.

Results

OPTIMAL INDIVIDUAL BATTERIES

In reference case IB, the batteries are individually optimized [Jonson and Karlsson 2010]. Figure 1 gives the estimated optimal battery sizes for minimum annual recharging frequency MRF_{opt} equal to 800, 400 and 50 yr^{-1}, respectively. Results are given for three values of the minimum break time *T*, 10, 4 and 0.5 hours. A 10-hour minimum break time should correspond reasonably to overnight charging in the majority of cases. A break time of intermediate length means that charging can take place when the car is parked at the work place, etc. A fully recharged battery after only a half-hour break assumes that many of these charge instances allow for fast charging.

For most of the movement patterns, the PHEV battery does not pay for itself at a high MRF_{opt}; the HEV, i.e., a car with no energy battery, is the most economic vehicle. When a non-zero battery is optimal, it is in most cases relatively small. In a situation with high economic viability of batteries i.e., a low MRF_{opt}, there will be a large range of optimal individual battery sizes dependent on the individual car movement patterns. The average size of the optimal non-zero battery, also given in Figure 1, is roughly inversely proportional to the MRF_{opt} and decreases with decreasing minimum break time *T*.

The average net revenue for PHEVs compared to their HEV counterparts increases with lower MRF_{opt} and better recharging possibilities given as minimum break time *T* for considering recharging (see Table 2). (Cost of enhanced charging infrastructure is not included in the net revenue estimates.)

Table 2 also shows the average cost for the individually optimised batteries. The battery cost is between 170 and 340 $/yr; it thus only varies by a factor 2, over a large range of values for MRF_{opt} and *T*. Better techno-economic conditions in the form of a lower MRF_{opt} is to a large extent transferred into larger optimal batteries.

BATTERY RANGE DISTRIBUTION STRATEGIES

Economic viability

When not using an individually optimized battery, the net revenue will be lower, either because the battery is not large enough so that further gains in energy costs outpace the extra cost for the battery if increasing its size, or vice versa for a too large battery (see Figure 2). The maximum net revenue corresponds to the optimal battery. The specific profile for the net revenue when departing from the optimum depends on the individual movement pattern. For the most favourable conditions with low values of both MRF_{opt} and *T*, Figure 2a, the net revenue stays positive (i.e., it is economically compatible with the non-battery alternative, the HEV) for a large range in battery size, between zero and 300 km *AER,* or even more. For less competitive conditions with a larger MRF_{opt} and/or larger *T*, the revenue falls, the battery range with positive net revenue shrinks or even disappears, and the individual optimal battery size decreases, possibly to zero.

Figure 3 gives the average net revenues for the assessed different battery strategies as well as for the reference case IB. (“Average” here refers to the average for all 201 cars, not only for those with a positive net revenue. For those cars with no or negative net revenue, the net revenue is set to zero.) For the strategies 1B, 2B, and 3B, the losses in net revenue (relative to the assumed reference level, case IB) generally increase with

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[3] Current costs for actual battery packages are not publicly available, but the figure given here is supported by claims by for instance GM [http://www.treehugger.com/files/2009/03/gm-fights-back-chevy-volt-plug-in-hybrid-battery-cost.php Accessed Feb 25 2011]

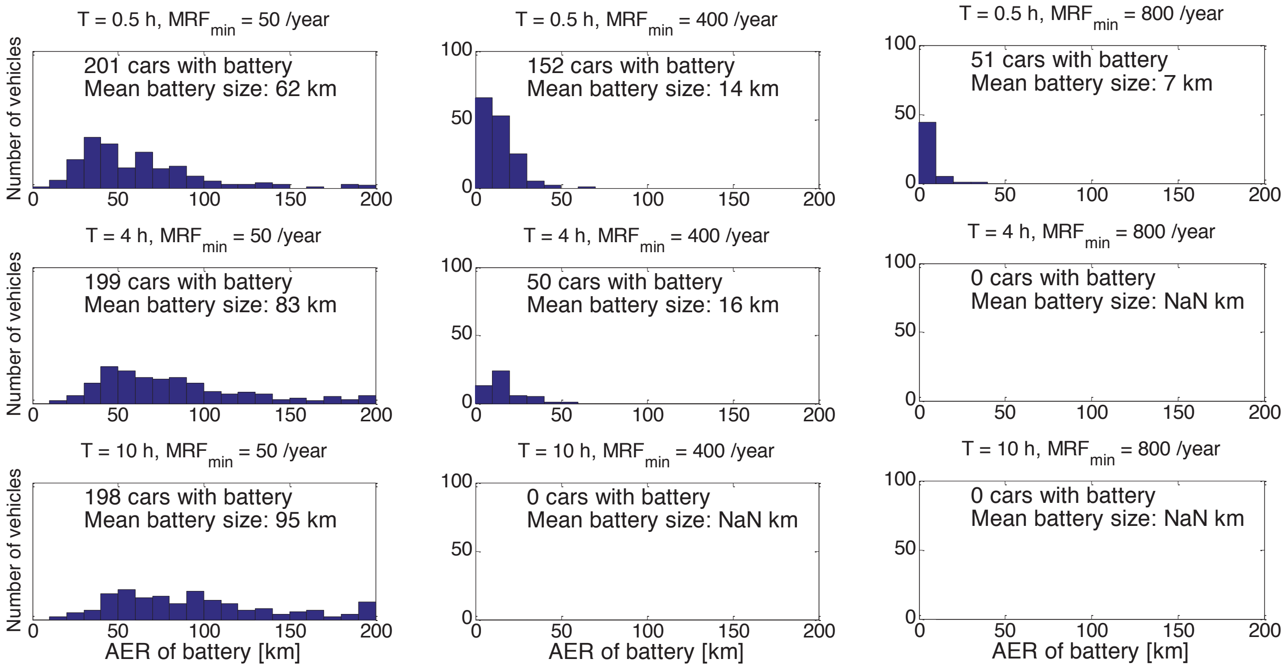


Figure 1. Optimal battery size. Distribution of battery sizes (km AER) for individually optimized vehicles (case IB). From right to left: Increasing viability, i.e., decreasing MRF_{opt}. From bottom to top: Better recharging options, i.e., shorter minimum break time T for recharging.

Table 2. Average net revenue [$/yr] and average battery cost [$/yr] for PHEVs compared to their HEV counterparts.

Minimum break time *T*	Average net revenue [$/yr] ; Average battery cost [$/yr]				
	MRF_{opt} = 50 yr^{-1}	MRF_{opt} = 100 yr^{-1}	MRF_{opt} = 200 yr^{-1}	MRF_{opt} = 400 yr^{-1}	MRF_{opt} = 800 yr^{-1}
0.5 hrs	641 ; 174	435 ; 192	259 ; 206	157 ; 252	92 ; 336
4 hrs	539 ; 233	317 ; 245	157 ; 240	77 ; 288	–
10 hrs	473 ; 267	241 ; 283	79 ; 289	–	–

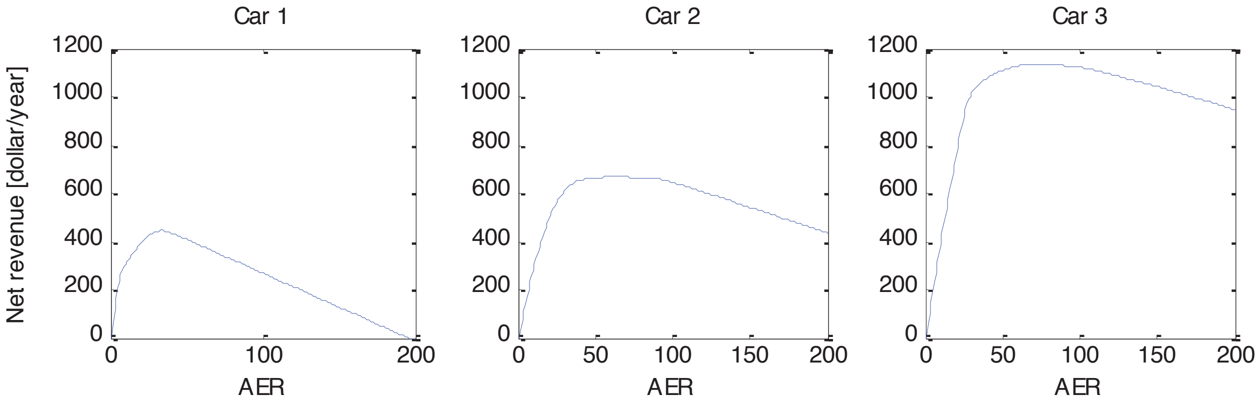
lower MRF_{opt}. Lower MRF_{opt} corresponds to a larger size range in the individually optimized batteries and therefore generally implies less of a fit when using a limited number of optimized batteries. The losses for a one-size battery (1B) is, on average, up to around $55/car annually. This can be compared to the average cost of the battery also given in Table 2. The average net revenue loss is up to 30 % of the battery cost for a low MRF_{opt} and therefore a large optimal battery range. The net revenue loss (of course) decreases with increased number of batteries. For three optimum batteries (3B) the losses are around 1/4 compared to 1B, and thus up to 5-7 % of the average battery cost. The battery size in 1B is always larger than the average in the reference case IB. The distance between the different sizes of the batteries in 3B tend to be a factor 2.

The fixed battery sizes (P and V) are each best adapted to a specific value of MRF_{opt}, around 250 and 50-100, respectively. The Prius-sized battery is better adapted to the total fleet than the Volt-sized battery for values of MRF_{opt} larger than around 100. With availability of both batteries simultaneously (strategy PV), the average revenue losses are of course less than in either the P or V strategy. The PV combination adds very little when MRF_{opt} is close to the optima for P or V. A modular design with modules of 23 km (*AER*) entails a considerable loss at high $MRF_{opt,}$ for which even the chosen module size is too large compared to most of the individually optimal batteries. For the same reason, PV performs worse than any of 1B, 2B or 3B for large MRF_{opt} and worse than 3B down to around 100 for MRF_{opt}.

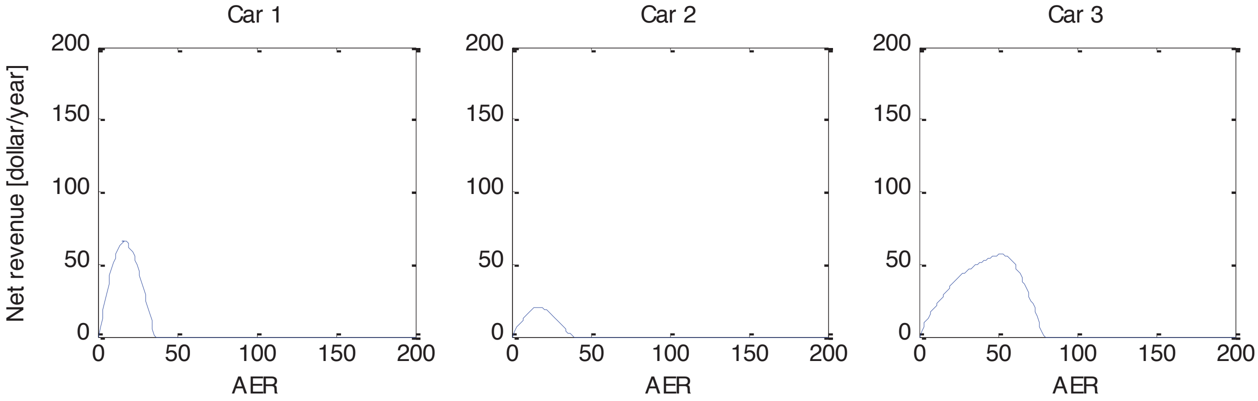
Impact on PHEV electrification potential and energy efficiency gains

Figure 4 shows for the reference case IB with individually optimized batteries, the resulting electrification potential, the total electric drive fraction for the whole vehicle fleet as a function of MRF_{opt} and a range of different minimum break times *T*. For charging possible only once in a day (i.e., roughly corresponding to the 10-hour break time curve), with the assumptions made here, the MRF_{opt} must be less than or equal to 365 yr^{-1}, i.e. recharged once a day year round, before a PHEV even should be considered. For an MRF_{opt} of 200 yr^{-1}, more than 50 % of the cars have a cost minimum with a non-zero battery. Still the total *EDF* is only around 25 %. At a very low MRF_{opt} of 50 yr^{-1}, i.e., good economic viability, the total *EDF* is around 80 %, a value less dependent on recharging possibilities. For a situation where a half-hour break is all that is needed to fully recharge regardless of battery status and car location, the total *EDF* is slightly more than 0.1 at MRF_{opt} equal to 800 yr^{-1}, 0.4 at 400, and almost 0.9 at an MRF_{opt} of 50 yr^{-1}.

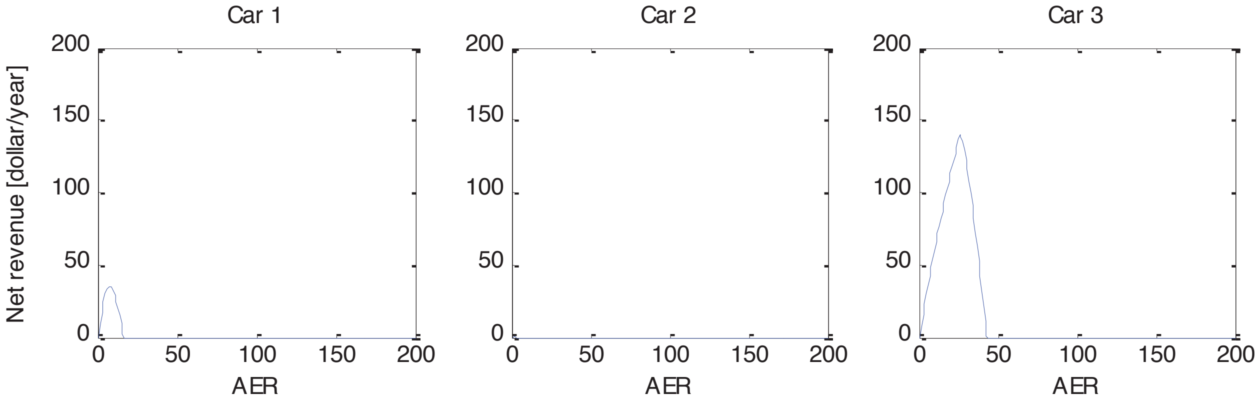
At very low or very high MRF_{opt} the recharging possibilities are less important. For intermediate MRF_{opt} between 200 and



a) $MRF_{\mathrm{opt}} = 50$, $T = 0.5$ hrs



b) $MRF_{\mathrm{opt}} = 200$, $T = 10$ hrs



c) $MRF_{\mathrm{opt}} = 400$, $T = 4$ hrs

Figure 2. Individual net revenues. Illustrative examples of individual net revenues [\$/yr] as a function of battery size given as AER [km] for three cars at MFR_{opt} and T equal to a) 50 and 0.5 hrs, b) 200 and 10 hrs, and c) 400 and 4 hrs, respectively.

400 yr^{-1}, the recharging possibilities are decisive and can make a major difference for the electric drive fraction. Going from a T of 10 to 0.5 hour increases the potential fleet *EDF* by more than 40 percentage points. At $MRF_{\mathrm{opt}} = 300\ \mathrm{yr}^{-1}$ it increases from almost zero to 50 %. The PHEV share of the vehicle fleet increases by more than 40 % with a maximum of 85 % at around $MRF_{\mathrm{opt}} = 300\ \mathrm{yr}^{-1}$. To fully compensate for these increased recharging options should they not be realized, a lowering of the MRF_{opt} by at least a factor 2 would be necessary, for instance, by halving the battery price.

The potential enhancement in fleet energy efficiency, taken as the reduction in energy use per distance driven Δe [kWh/km] measured at the car level (from "tank to wheel" ("TTW")) is directly proportional to the total *EDF* multiplied by the difference in specific energy use in the electric and fuel mode

$$\Delta e = EDF \bullet (e_f - e_e) \qquad (6)$$

Figure 5 depicts the potential change in fleet specific energy use in the reference case IB. The gains can be seen relative to the non-battery alternative, the corresponding HEV. The specific energy use is potentially more than halved for the most favourable situation.

Figure 6a shows the loss in total *EDF* for the one-optimal-battery strategy 1B compared to the reference case IB. The loss

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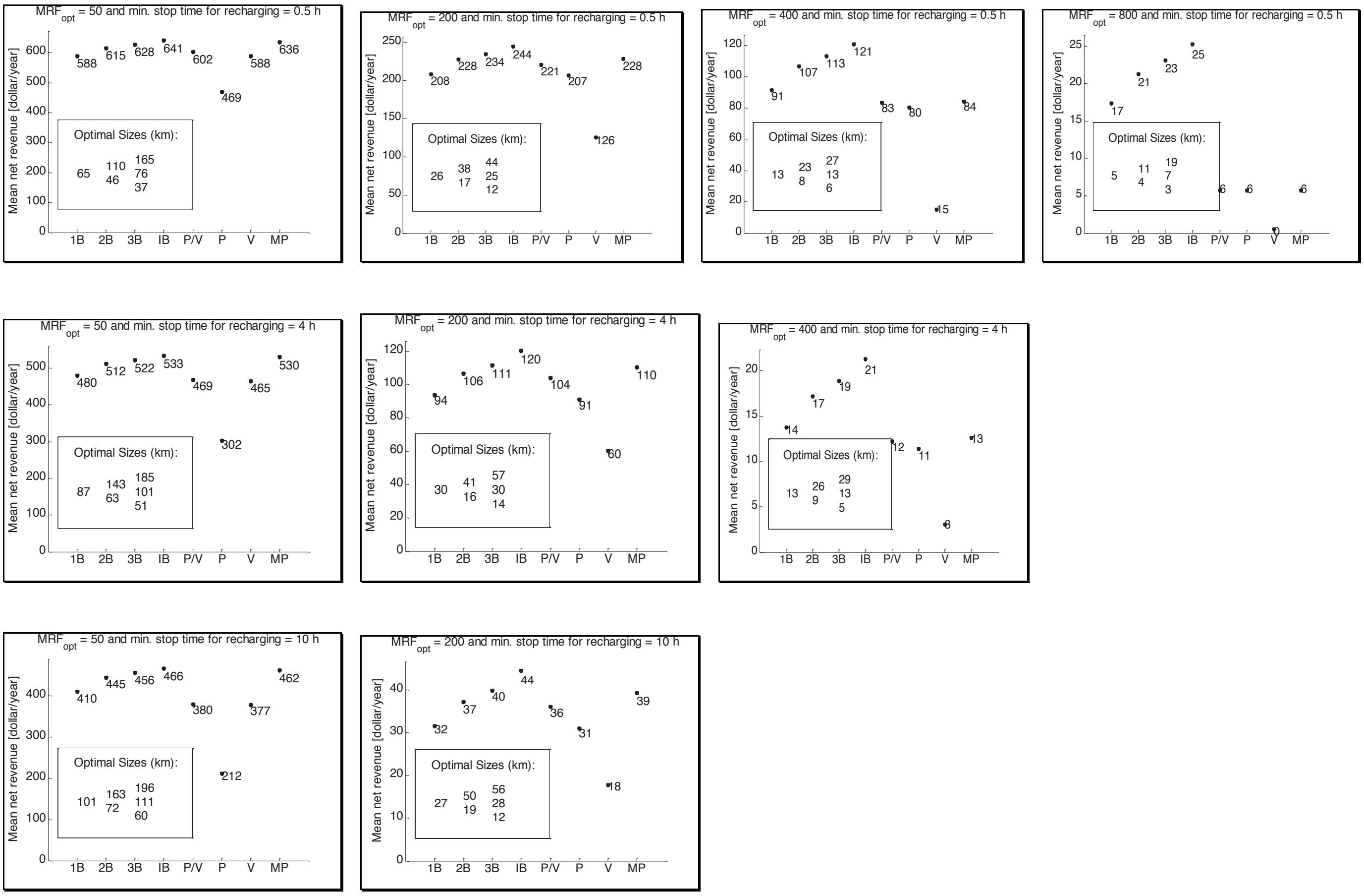

Figure 3. Net revenues for different battery range distribution strategies. From right to left: Average net revenues achieved in the different range strategies, for increasing viability, i.e., decreasing MRF_{opt}. From bottom to top: Better recharging options, expressed as shorter minimum break time T for recharging. Insert: optimal battery sizes expressed as AER [km] for strategies 1B, 2B and 3B, respectively. IB is the reference case with individually optimized batteries.

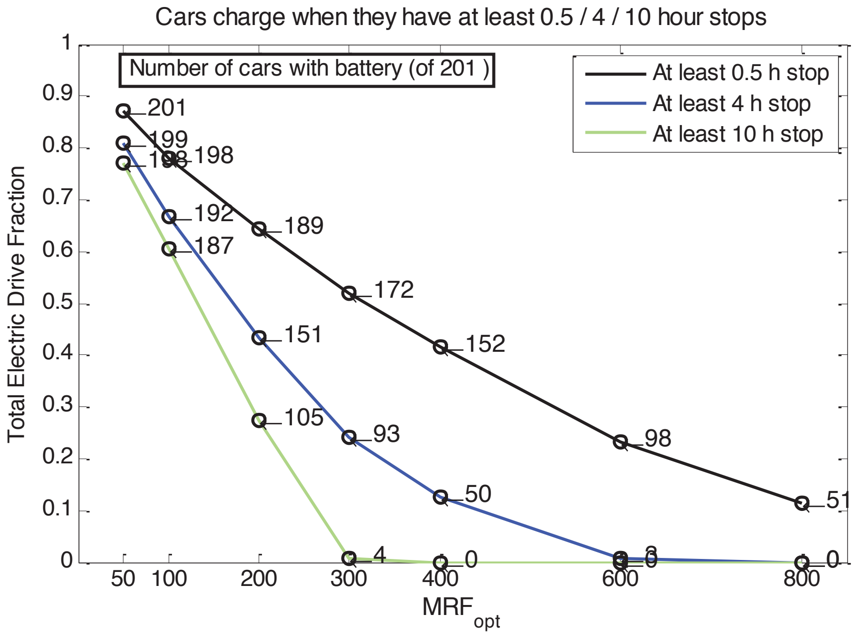

Figure 4. Potential car electrification. Total electric drive fraction and number of PHEVs (of the total fleet of 201 cars in the reference case IB (with individually optimized batteries)) as a function of the viability parameter MRF_{opt} and minimum break times T equal to 0.5, 4 and 10 hrs, respectively.

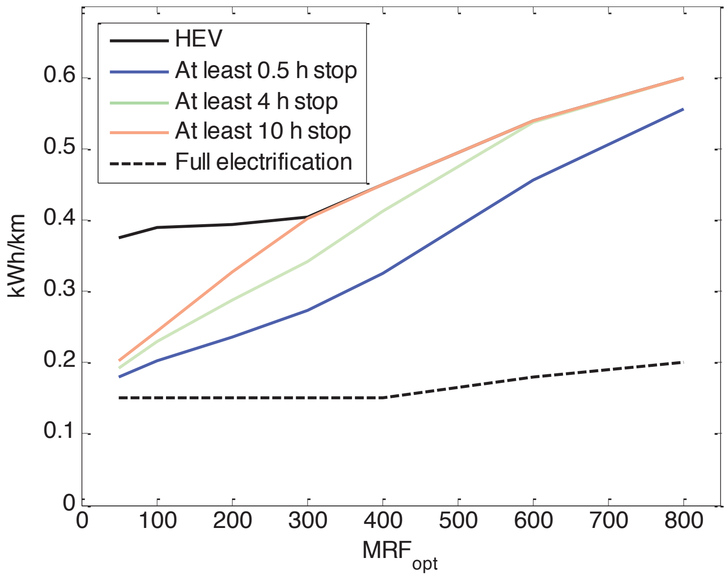

Figure 5. Potential energy efficiency enhancement. The specific energy use [kWh/km] for the total fleet in the reference case IB as a function of the viability parameter MRFopt and different minimum break times T. For comparison data are also given for no electrification (HEV) as well for full electrification, i.e., 100% electric propulsion.

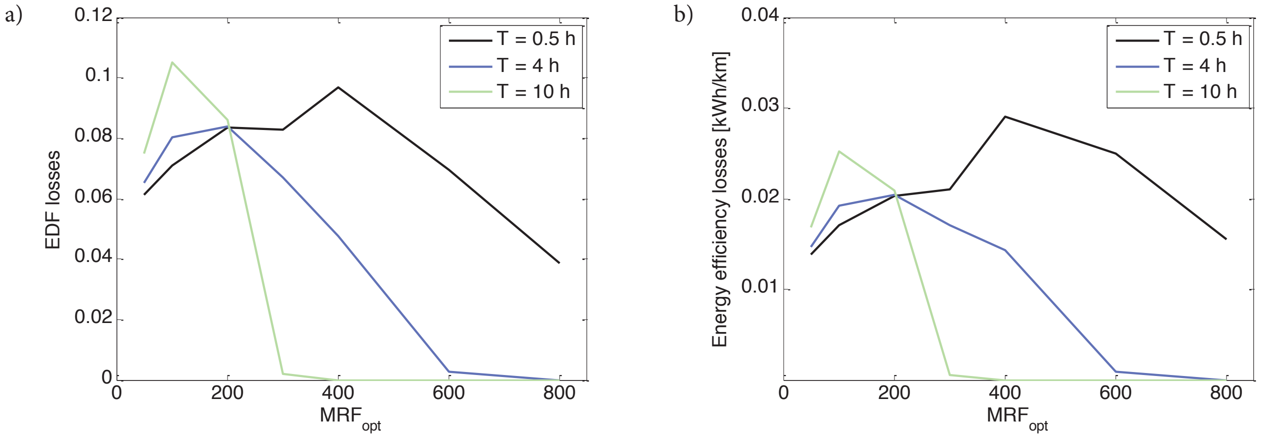

Figure 6. Loss in total EDF and energy efficiency. The loss for the one-optimized-battery strategy (1B) relative to individually optimized batteries (the reference case IB). a) Loss in total EDF, b) Loss in specific energy use.

is between 0.05 and 0.1 for a total potential *EDF* larger than around 0.15. Figure 6b gives the corresponding loss in average specific energy use. The loss is between 0.015 and 0.03 kWh/km for a total potential *EDF* larger than 0.15. The 0.03 kWh/km value corresponds to about 10 % of the potential energy efficiency, given in Figure 5.

Discussion and Conclusions

This study focuses on the impact of battery range distribution on the competitiveness of PHEVs, when considering the variation in movement patterns between individual cars. At specified techno-economic conditions, a small number of selected battery sizes can be enough. The conditions can change rapidly, though. For instance, the price of batteries for electric vehicles is expected to decrease fast. The sizes of the batteries need to change accordingly. This can work in favour of a modular battery system. It can then start with relatively few batteries of small sizes but gradually be expanded by adding extra modules and thus increase both the number of different sizes and the maximum size.

Policies aiming at rapid deployment of electric vehicles and increased vehicle energy efficiency could lower the marginal cost of extra battery capacity by tailoring subsidies based on battery size or, more specifically, on achieved all-electric range, rather than prescribing a one-subsidy-fits-all. This would also favour light and efficient vehicles and batteries that make the best use of their nominal capacity. The result also implies that, especially in an introductory phase with still a relatively high specific cost of the battery, there is a high sensitivity of the economic viability of PHEVs to the recharging options. Policies aiming at enhanced recharging also at workplaces and other frequently visited places as a complement to charging at home could also be efficient in facilitating a rapid deployment.

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Glossary

AER	All-Electric Range: total distance that a PHEV can operate on electricity from the (totally charged) battery from the beginning of a driving profile till the engine turns on (Markel and Simpson 2006). In blended operation the engine and the battery-motor combination work together at the same time.
BEV	Battery Electric Vehicle: vehicle that is powered by electricity entirely
SOC	State Of Charge: the current energy content as a fraction of the total energy capacity of a battery
EDF	Electric Driving Fraction: fraction of the annual driving distance driven on electricity
HEV	Hybrid Electric Vehicle: vehicles, whose drive train includes an engine and a battery-motor combination. In these vehicles some of the energy from braking is saved as electrical energy in the battery and then the battery-motor combination can provide power, this is typically called regenerative braking. This configuration avoids low efficiency engine operation like idling and low load.
MRF	We define the marginal annual recharging frequency (*MRF*) as the number of times the last battery unit is recharged per year
PHEV	Plug-in Hybrid Electric Vehicle: a HEV with capability to charge a larger battery from the grid

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