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Optimizing the charge profile - considering users' driving profiles

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Abstract

PHEVs are discussed controversially. On the one hand, the evolutionary approach of a hybrid vehicle helps the consumer to adopt to electric driving, using the range extender when driving longer distances. On the other hand, PHEVs have a more complex propulsion system and a potentially low emission impact due to a low electric driving share. These factors, however, strongly depend on the consumers' driving and charging behavior.

Therefore, this paper simulates realistic driving based on the national German travel survey. Firstly, battery profiles are modeled using further information about parking locations, charging scenarios, as well as different battery sizes. Secondly, total costs of different alternative vehicles are calculated and minimized varying the battery size.

According to the simulation, PHEVs are less expensive and thus important for market adoption. High electric driving shares of more than 80% allow fair emission reductions. And for the few longer trips, PHEVs can use the fall-back option of the internal combustion engine. PHEVs thus do not require an oversized battery and are thus more economical. In the early market, PHEVs will be equipped with smaller batteries; and with higher market share, require customization of the battery size for different customer segments and vehicle types.

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1 Introduction

The introduction of electric vehicles (EVs) is a defined policy goal[1], due to benefits such as reducing local emissions, increasing efficiency, and supporting the shift from oil to other energy sources.

A substantial hurdle for consumer adoption is however seen in the limited range of full EVs, requiring the driver to stop for a lengthy recharge[2] after a trip of less than 150 km. To reduce this consumer fear, known as range anxiety[3], there are currently three technologies under discussion: (i) on-route fast charging[4], (ii) swapping depleted batteries as well as (iii) an additional internal combustion engine as "range extender". While fast charging and battery swapping are technically as well as economically challenging, electric cars with a "range extender", known as plug-in hybrids (PHEVs), will be launched shortly by every large OEM.

Despite being technically more complex due to two propulsion systems, PHEVs have advantages from a customer's point of view: (i) With the fall-back option of using an internal combustion engine, consumers can travel longer distances if needed, or don't need to fear getting stranded, when they have forgotten to recharge. (ii) PHEV owners can reach a high electric driving share, charging at home and driving some miles fuel-based, while drivers of full EVs rely on a comparably denser charging infrastructure to cover all their needs. (iii) PHEVs can be designed with smaller batteries which cover the regular trip, avoiding an oversized and costly battery.

The consumer's purchasing decision is driven by technology fit (such as travel range or vehicle size) and costs[5], and in case of electric vehicles should include individual travel pattern and accessibility to recharging infrastructure to assess the applicability of this new technology.

Therefore, this paper uses a detailed German multi-day travel survey to simulate driving behavior and infrastructure access. For each driving profile an op-

1 E.g., Germany aims for one million EVs by 2020, see Bundesregierung (2009).
2 Taking 6 to 8 hours for a full charge at a regular household outlet with 3.7 kW.
3 See Tate et al. (2008).
4 Power connections of more than 100 kW necessary for a 5 min / 50 %-recharge of the battery.
5 As e.g. mentioned in Chéron, Zins (1997) or Högberg (2007).

timal vehicle type was selected considering different charging infrastructure and battery sizes.

2 Background

2.1 Travel behavior

In order to assess the potential of EVs and PHEVs in today's travel behavior, an understanding of the series of trips, the intermediate parking times as well as the charging infrastructure available is important. Normed driving profiles, such as the new European driving cycle (NEDC) or the federal test procedure (FTP 75), focus rather on mileage and do not consider recharging facilities and average parking times. To reflect variations in the daily travel, driving profiles should be recorded over several days.

Most of this data can be typically found in national travel surveys as long as they cover several days, contain detailed information with regard to time and location, and link cars to the reported trips. In Table 1 publicly available international travel surveys are listed and analyzed regarding these requirements.

Table 1: Characteristics of different national travel surveys

Survey	Year	Country	Reported period	Detailed Diaries?	Assignment of cars to trips?
Mobilitätspanel[1]	1996-2008	Germany	7 days	Yes	No
Mobilität in Deutschland[2]	2006	Germany	1 day	Yes	Yes
National Travel Survey[3]	2008	Great Britain	7 days	Yes	Yes
Nat. Household Travel Survey[4]	2001	USA	1 day	Yes	Yes
RES Nat. Travel Survey[5]	2005-2006	Sweden	1 day	Yes	No
Mikrozensus Verkehr[6]	2005	Switzerland	1 day	Yes	No

1 See Chlond, Kuhnimhof (2005), MOP (2006), Zumkeller et al. (2010)
2 See Follmer et al. (2003)
3 See UK Department of Transport (2010)
4 See NHTS (2003)
5 See Swedish Institute for Transport and Communications Analysis (SIKA) (2007)
6 See Bundesamt für Statistik (BFS) Schweiz (2007)

Most of the surveys are based on one-day questionnaires, such as „Mobilität in Deutschland". All these surveys show large variations across respondents, but do not reflect day-to-day variations for one driver. Additionally, one-day travel profiles do not include information of multi-day trips or over-night stays. Thus, differences in individual driving behavior are underestimated and one-day surveys represent individual mobility pattern not realistically. For Germany, we concentrated on the "Mobilitätspanel" (MOP) and retroactively aggregated the reported trips on car level. The MOP asks each year approximately 1,000 households in Germany, to report all trips using a travel diary, note the mean of transport as well as further details such as the travel purpose. The survey takes place each year during one week in fall, which is considered to be representative for the annual mobility pattern. With a track record of more than ten years, the MOP can also be used to compare mobility shifts over time and increase the population from approximately 1,000 cars to more than 10,000.

2.2 Infrastructure

Electric vehicles require charging infrastructure to refuel the battery, and in case of PHEVs, regular charging is needed for a high electric driving share. Possible charging infrastructure scenarios range from private outlets, to semi-public (e.g. at the workplace) or public charging stations, as described in Wietschel et al. (2009). These charging spots can have different connection power: the regular household plug provides up to 3.7 kW and with three-phased standards can be increased to roughly 44 kW; higher power connections need to be realized using direct current (DC), which requires higher investments for the charging station. Previous analysis of Kley et al. (2010) showed that roughly 50% of today's vehicle owners can sufficiently charge at home. Higher investments and lower utilization of semi- and public charging infrastructure increase the costs at these charging spots. While e.g. Kalhammer et al. (2007) or Hacker et al. (2009) see a dense public charging infrastructure as one of the key levers for a high market penetration, Kley et al. (2010) showed that a mix of different infrastructures will be dominantly based on private connections with some semi-public and little public charging stations. Likewise, evaluations from pilot tests revealed that public charging points are actually used relatively rarely, but are asked for as back-up solution in case of full EV owners.[6] Moreover, broader investments in this kind of back-up charging infrastructure are in competition with "range extenders" and thus depend on the development of vehicle types in the market.

6 For the pilots in the 1990s see Meier-Eisenmann et al. (2001) or for today's experiences in London and Berlin see Hoffmann (2010).

2.3 Applied car and cost assumptions

Besides travel behavior and different infrastructure access, three types of vehicles have been simulated: a conventional vehicle based on an internal combustion engine (ICE), a PHEV and an EV. The technical and economic parameters taken for simulation can be found in Table 2 and are based on previous works such as Wietschel et al. (2010), Kley, Wietschel (2010), or Kley et al. (2010).

Table 2: Technical and economic parameters for electric vehicles and charging infrastructure

Vehicles Characteristics				ICE	PHEV	EV
Investments	Chassis	[€]	I^V	16,825		
	Tank	[€]	I^{Ta}	125		
	Starter	[€]	I^{St}	300		
	Intern. Combustion Engine, spec.	[€/kW]	I^{ICE}	30		
	Electric Motor, specific	[€/kW]	I^{EM}		27	
	Hybrid Power Train	[€]	I^{Hy}		1500	
Power	ICE	[kW]	P^{ICE}	77	41	
	EV	[kW]	P^{EM}		68	75
Battery	Capacity	[kWh]	κ		1 to 24	30
	System Costs	[€/kWh]	I^B	150 to 750		
Operating Costs	O&M Costs	[€/a]	c^{OM}	300		
	Electricity	[€/kWh]	c_t^E	0.20		
	Fuel	[€/l]	c^F	1.40		
Consumption	Electricity	[kWh/km]	u^E	0.18		
	Charge Efficiency	[%]	ν^{ch}	84%		
	Fuel	[l/km]	u^F	0.06		
Life Time	Maximal Vehicle Mileage	[km]	M	200,000		
	Vehicle	[a]	T^V	12		
	Battery	[a]	T^B	12		
Infrastructure Characteristics				**Private**	**Semi-public**	**Public**
Connection Power		[kW]	P_t^C	3.7	0	0
Infrastructure Costs		[€/kWh]	c_t^I	0.01	0.06	0.24

Further assumptions include, that PHEVs drive electrically as long as the battery state of charge (SOC) is above 20% of its nominal capacity and switch to the internal combustion engine when the battery capacity reaches this threshold. Furthermore, an upper battery limit of 80% SOC was assumed in light of higher battery degradation and lower charging efficiencies in these boundary areas. This results in an operating area for the battery of 60%. The given numbers include all taxes such as value-added tax or fuel tax. For total cost of ownership calculations an interest rate (i) of 3% has been assumed. In this paper, battery ageing costs have been excluded but are generally integrated in the model.

3 Simulation

3.1 Deriving the driving and parking profiles

Based on the reported start and end times as well as the trip length, driving profiles can be generated for each individual. At the end point of each trip, the type of parking location (at home, at work, …) is determined from the trip purpose. In case of several reporting individuals, driving profiles are aggregated on vehicle level. The resulting driving and parking profiles are broken down in intervals of 15 minutes and have a total length of seven days. Driving profiles are given in kilometers driven per interval, and parking profiles are codified by type of parking location.

3.2 Cost-optimal battery profiles

Based on the above described profiles and further assumptions about the charging infrastructure available, the parking profiles can be converted into available connection power, and secondly, battery usage and charging can be simulated. The resulting battery profile describes the state of charge of the battery. For a regular EV operation, the boundary restrictions of the lower and upper battery limit must not be violated.

With multiple time-variant parameters such as electricity price, or different power connections, the optimal battery profile can only be derived solving a minimization problem. Given parameters in this minimization problem include the travelled distance in each interval (d_t in km), specific electricity consumption (u^E), electricity prices (c_t^E), costs for using the charging infrastructure (c_t^I), the charge efficiency (ν^c), and the available battery capacity (κ). Additionally, the available connection power in each parking location (P_t^C) was assigned by applying different infrastructure scenarios. The battery state of charge (s_t in %) is simulated with the charging load (l_t in kWh) as decision variable in each interval, describing the consumer's search for a cost-optimal charging strategy. For PHEVs, a further term needs to be added to the optimization problem, allowing to consume gasoline (f_t in kWh) if the battery is depleted. Herewith the optimization problem can be described[7]:

$$\mathcal{X} = \min_{l_t} \underbrace{\sum_{t\in\tau_1} (c_t^E + c_t^I) l_t}_{\text{Charging Costs}} + \underbrace{\sum_{t\in\tau_2} c^F \frac{u^F}{u^E} f_t}_{\text{Fuel Costs}}$$

With $\tau_1 = \begin{cases} t, & P_t^C > 0 \\ 0, & else \end{cases} \wedge \; \tau_2 = \begin{cases} t, & d_t > 0 \\ 0, & else \end{cases}$ and subject to:

(1) $s_t = s_{t-1} - \frac{d_t u^E}{\kappa} + \frac{l_t v^c}{\kappa}$ $\quad \forall t = 1 \dots T$

(2) $0 \le l_t \le P_t^C \Delta t$ $\quad \forall t = 0 \dots T$

(3) $0.2 = \underline{s} \le s_t \le \overline{s} = 0.8$ $\quad \forall t = 0 \dots T$

(4) $s_0 = s_T = \overline{s}$

(5) $f_t = \begin{cases} 0, & s_{t-1} - \frac{d_t u^E}{\kappa} > 0.2 \\ d_t u^E - \kappa(s_{t-1} - \underline{s}), & else \end{cases}$ $\quad \forall t = 0 \dots T$

With 672 time intervals a formal solution of this problem is quite complex. An easier approach is the simulation of possible states of charge in a forward operation, determining the optimal solution in the last time step and retrieving the optimal charging strategy in a backward operation.

If the vehicle in the last time interval is driving or parked at a location without charging facilities, condition (4) can be relaxed to $s_0 = \overline{s}$, not requiring a fully charged battery in s_T. The missed charging costs $(\overline{s} - s_T)\left(c_T^E + \min\left\{\{c_t^I | \forall t = 0 \dots T\} \setminus 0\right\}\right)$ should then however be added to $\mathcal{X}$ for comparability reasons.

3.3 Total cost and the optimal vehicle

The total annual costs ($\mathrm{TCO}_{\mathrm{annual}}$ in €) for a vehicle is the sum of the annuities of capital (a_{capex}) and operating expenditure (a_{opex}), which are calculated as following:

$$a_{\mathrm{capex}} = [I^V + I^{Ta} + I^{St} + I^{ICE} P^{ICE} + I^{EM} P^{EM} + I^{Hy}] \frac{(1+i)^{T^{V'}} i}{(1+i)^{T^{V'}} - 1} + I^B \kappa \frac{(1+i)^{T^{B'}} i}{(1+i)^{T^{B'}} - 1}$$

$$a_{\mathrm{opex}} = [c^{OM} + 52\mathcal{X}]$$

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7 Please find further definitions of variables in Table 2.

A vehicle can be operated for the maximal lifetime or until it reaches the maximum mileage. The battery needs to be replaced when it stops working beforehand. This results in the adapted lifetimes of $T^{V'} = \min\left\{T^V; \frac{M}{52\sum_{\forall t} d_t}\right\}$ and $T^{B'} = \min\left\{T^B; T^{V'}\right\}$. Residual values for the vehicle or the battery after their lifetime have not been considered.

A more tangible interpretation of the total costs are mileage-based costs which can be calculated as $\mathrm{TCO}_{100\mathrm{km}} = 100\frac{\mathrm{TCO}_{\mathrm{annual}}}{52\sum_{\forall t} d_t}$. In order to select the best car technology for each single driving profile, an EV and PHEVs with different battery capacities have been simulated and optimized regarding their operating expenditure. Together with an ICE, with $a_{\mathrm{opex}} = c^{OM} + 52\, c^F u^F \sum_{\forall t} d_t$, the best car was selected based on the comparison of total costs.

4 Results

The simulation selects for each driving profile a cost-optimal vehicle, providing detail e.g. on the electric driving share, the selected battery-size or in comparison among profiles gives indication on which segments will pick a PHEV or EV first.

Figure 1: Selected vehicles by type

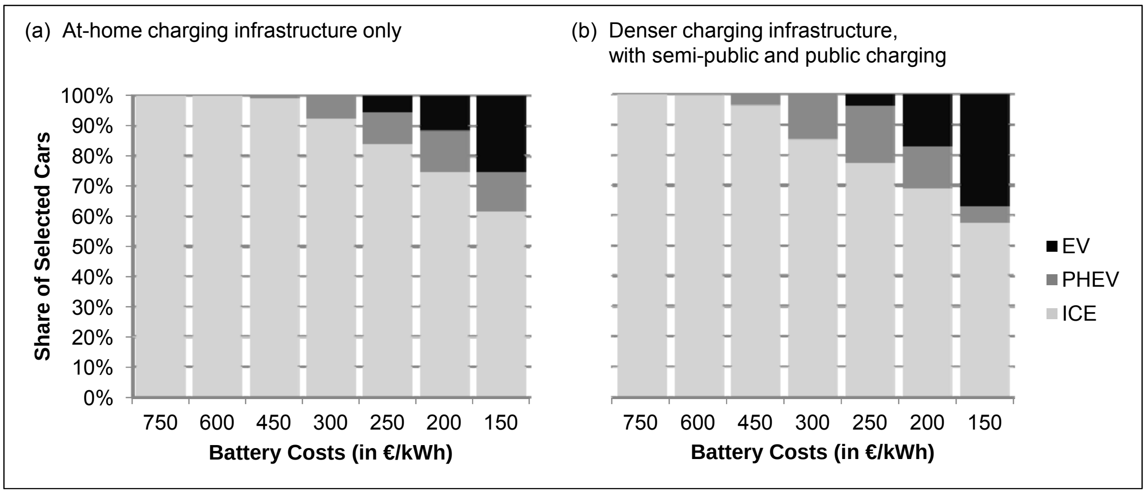
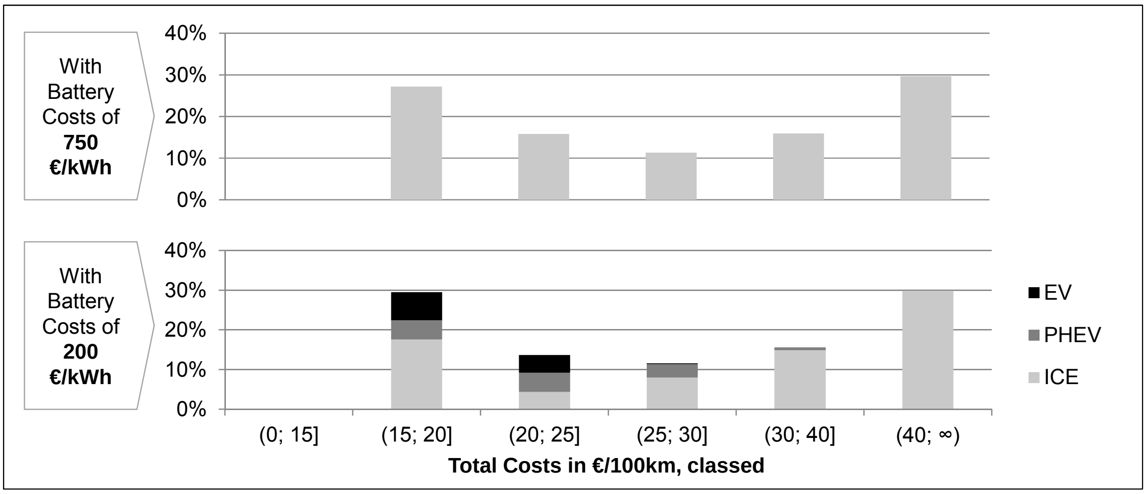


Figure 1 shows the market share of PHEV and EVs selected in relation to different battery sizes. Here PHEVs enter the market at battery costs of round about 450 €/kWh and dominate the electric vehicle market up to 250 €/kWh. With lower battery costs, full EVs can also gain significant market share, however, with ICEs still holding a lion share of new registrations. In the meantime, PHEVs are an important market enabler for electric driving, not only because of costs, but also due to the "range extender" assuring to reach the destination without getting stranded. A denser charging infrastructure with access in semi-public and public locations has limited effect on this outcome, and shows even fewer EVs until battery costs will drop to 200 €/kWh, as depicted in part (b) of Figure 1.

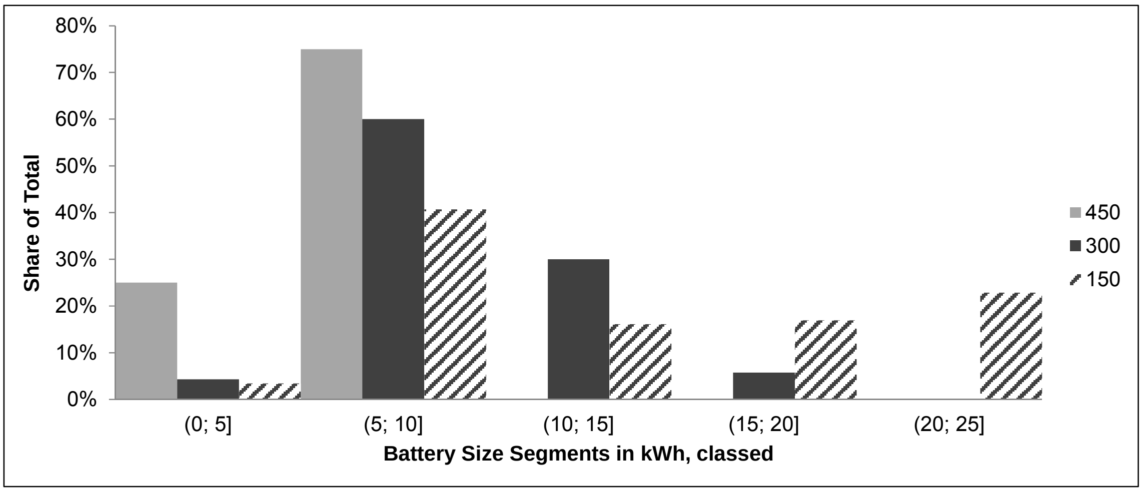
Interestingly, **PHEVs show high electric driving shares of 85-90%** when selected as optimal vehicle in all infrastructure and battery price scenarios. This is mainly due to the fact that **PHEVs and EVs need to be utilized comparatively higher than ICEs with annual mileages above 17,000 km**. Figure 2 shows the distribution of total costs per 100 km for two different battery price scenarios.

Figure 2: Distribution of total cost by type of selected vehicles



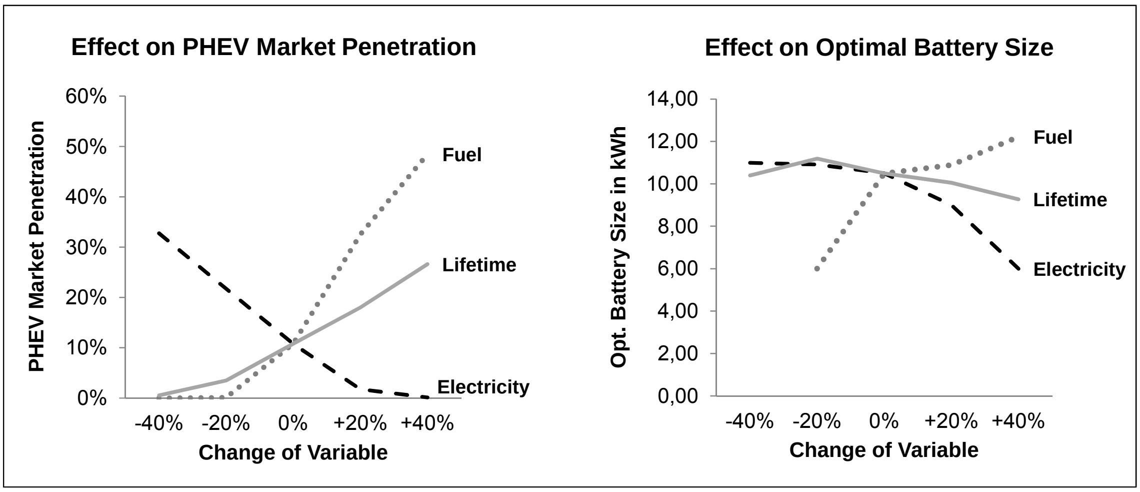
With different battery costs, the optimal PHEV battery size varies. While the first PHEVs are equipped with smaller batteries of no more than 10 kWh, battery capacity will get more diverse with dropping battery costs.

Figure 3: Distribution of optimal battery size for different battery cost levels



As depicted in Figure 3, optimal PHEVs in a battery cost scenario of 150 €/kWh use battery capacities from 5 to 25 kWh almost equally. This **requires OEMs to think about customization strategies** for the same car with different battery sizes. The results particularly regarding the selected car type and **market share are highly sensitive to the external input factors** such as fuel or electricity prices, as shown in Figure 4. Especially fuel and electricity costs are subject to different tax regimes and a key driver of cost-based customer adoption, so that in a scenario based on untaxed numbers no PHEV or EV was selected for any battery price.

Figure 4: Sensitivity of the parameter: lifetime, fuel and electricity price at 250 €/kWh



5 Summary and conclusions

The simulation of mobility profiles provides a better understanding of the economics, of the rational choice of alternative car types and the utilization of these cars. Findings include the importance of PHEVs as market enabler, or that these well utilized cars allow electric driving shares of above 80%. PHEVs will be equipped with small batteries in the beginning and require customization with higher market share. High sensitivities however, require further detailed analysis including e.g. different infrastructure scenarios as well as technical aspects such as battery degradation.

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