Empirical Fuel Consumption and CO_2 Emissions of Plug-In Hybrid Electric Vehicles

Patrick Plötz,[1] Simon Árpád Funke,[1] and Patrick Jochem[2]

[1]*Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe, Germany*
[2]*Institute for Industrial Production (IIP), Chair of Energy Economics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany*

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Summary

Plug-in hybrid electric vehicles (PHEVs) combine electric and conventional propulsion. Official fuel consumption values of PHEVs are based on standardized driving cycles, which show a growing discrepancy with real-world fuel consumption. However, no comprehensive empirical results on PHEV fuel consumption are available, and the discrepancy between driving cycle and empirical fuel consumption has been conjectured to be large for PHEV. Here, we analyze real-world fuel consumption data from 2,005 individual PHEVs of five PHEV models and observe large variations in individual fuel consumption with deviation from test-cycle values in the range of 2% to 120% for PHEV model averages. Deviations are larger for short-ranged PHEVs. Among others, range and vehicle power are influencing factors for PHEV model fuel consumption with average direct carbon dioxide (CO_2) emissions decreasing by 2% to 3% per additional kilometer (km) of electric range. Additional simulations show that PHEVs recharged from renewable electricity can noteworthily reduce well-to-wheel CO_2 emissions of passenger cars, but electric ranges should not exceed 200 to 300 km since battery production is CO_2-intense. Our findings indicate that regulations should (1) be based on real-world fuel consumption measurements for PHEV, (2) take into account charging behavior and annual mileages, and (3) incentivize long-ranged PHEV.

Introduction

Transport is responsible for a major share of global carbon dioxide (CO_2) emissions, and the global passenger car fleet, which is responsible for the most emissions within the transport sector, is projected to double until 2050 (Sims et al. 2014). Electrification of road transport by plug-in electric vehicles is seen as a main measure to cut CO_2 emissions in the transport sector (Jochem et al. 2015; Meinrenken and Lackner 2015). However, their emissions reduction potential strongly depends on their actual usage, all electric range (AER), and the underlying electricity generation (Hawkins et al. 2012a, 2012b; Messagie et al. 2010; Lane 2006; Lin 2014).

Plug-in hybrid electric vehicles (PHEVs) combine an electric drive train with a conventional one (Bradley and Frank 2009). This hybrid drive train is in contrast to battery electric vehicles (BEVs) on one hand and conventional vehicles (internal combustion engine vehicles; ICEVs) on the other hand. Assessing fuel consumption of PHEVs is challenging since PHEVs can use both electricity and conventional fuel for propulsion

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Address correspondence to: Patrick Plötz, Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Straße 48, 76139 Karlsruhe, Germany. *Email:* patrick.ploetz@isi.fraunhofer.de

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whose application depends significantly on the driving and charging patterns of vehicle users (Chan 2007; Jacobson 2009; Flath et al. 2013; Schneider et al. 2014). We distinguish in the following two PHEV operation modes: In charge depleting mode, the electric engine is responsible for propulsion and the combustion engine is switched off. In charge sustaining mode (usually applied when the battery has been fully depleted), the combustion engine is (mainly) used to keep the battery state of charge within a small window. In real operation also, mixed and blended modes are possible for some PHEVs (Serrao et al. 2011). From an analytical point of view, PHEV fuel consumption depends on their AER, typical distance driven between recharging, and fuel efficiency of its combustion engine. A major quantity characterizing PHEV fuel consumption is the utility factor (UF) that is the share of electrified kilometers (km) of total km driven of a PHEV.

However, despite the relevance of PHEVs for CO_2 emission reduction, there is presently no comprehensive empirical analysis of PHEV fuel consumption. In literature, PHEVs are currently included into official driving cycles by simplified rules, and estimates for their empirical fuel consumption are presently based on simulation (Gonder et al. 2007; Millo et al. 2014; Silva et al. 2009), fleet averages (Smart et al. 2014), or small samples (Ligterink and Eijk 2014; Davies and Kurani 2013). Elgowainy and colleagues (2009) estimate electric driving shares based on the U.S. National Household Transportation Survey (NHTS) (NHTS 2009) and obtain an average UF of 23.2% for a PHEV with an AER of 16 km (10 miles). For an AER of 32, 48, 64, and 97 km, they obtain an UF of 40.6%, 53.4%, 62.8%, and 74.9%, respectively. Neubauer and colleagues (2013) use global positioning systems data of a traffic choice study (398 profiles with 3-month observation period) to simulate the economics of different vehicle concepts. They calculate fuel savings of PHEV usage for different vehicle designs and charging scenarios that can be interpreted as UF and find 50% for 24 km (60% if work charging is added) and 70% to 80% for 56 km AER. Analogously, using over 100 one-day driving profiles from Kansas City, Moawad and colleagues (2009) find fuel savings to be 48% for a PHEV with a battery capacity of 4 kilowatt-hours (kWh) (approximately 20 km AER), 62% for 8 kWh (approximately 40 km AER), and 88% for a 16 kWh (approximately 80 km AER) battery. Axsen and colleagues (2011), on the other hand, use driving reports of 877 car buyers in California and find a UF of PHEVs with an AER of 32 km to be 35% for home charging and 43% for home and additional work charging as well as a UF of 70% and 79% for an AER of 64 km. The influence of the UF on PHEV's fuel consumption has been further analyzed by Bradley and Quinn (2010). They calculate the sensitivity of the average UF with respect to vehicle type, age, annual vehicle kilometers traveled (annual VKT), and garage availability as well as charging behavior. A PHEV with an AER of 68 km was found to have a UF of 64% if fully charged once a day compared to 86% if fully charged before every trip. As expected, the UF strongly depends on annual VKT as with higher trip-length UF decreases. To conclude, several studies have simulated UF of PHEV with different AER, but a systematic understanding of the importance of individual factors is lacking.

Real-world driving data on PHEV usage patterns and fuel consumption are rare. Ligterink and colleagues (Ligterink et al. 2013; Ligterink and Eijk 2014) analyze Dutch refueling data and find a UF of 24%, which includes an important group of business users who hardly charge. Excluding them, the UF rises to 33%. The two PHEVs, Toyota Prius and Opel Ampera, are found to have an effective fuel consumption of about 4.5 l per 100 km (52 miles per gallon [MPG]) compared to 5.3 l per 100 km (44 MPG) for the Volvo V60 PHEV and 6.6 l per 100 km (36 MPG) for the Mitsubishi Outlander PHEV (Ligterink and Eijk 2014). The corresponding UFs were estimated from the fuel savings compared to a similar conventional vehicle and amount to 18% for the Toyota Prius PHEV (we will suppress "PHEV" in "Toyota Prius PHEV" and the other models from now on), 30% for the Chevrolet Volt/Opel Ampera, 31% for the Mitsubishi Outlander, and 16% for the Volvo V60. Davies and Kurani (2013) report results on 25 converted Toyota Prius and find fuel consumption to be between 4.3 and 6.5 l per 100 km (36 to 55 MPG) in charge sustaining mode for an AER of 40 to 60 km. In a second step, using the obtained data to simulate different PHEV usage scenarios, they calculate a UF of 30% for a PHEV with an AER of 24 km for charging at home only, which rises to 50% if workplace charging is added. In summary, studies of PHEV fuel consumption up to now are only based on data from simulation and little real-world data, which rely, however, on small sample sizes (with the exception of Ligterink and Eijk [2014], who do not provide details characterizing their sample, e.g., in terms of annual VKT and a survey by Idaho National Laboratory [2015] of 1,800 Volts across the United States who observed a UF of 74% for the Chevrolet Volt).

The objective of this paper is to present detailed estimates of real fuel consumption and direct CO_2 emissions for current PHEVs based on empirical data and compared to official test-cycle fuel consumption and simulations. We use a database of self-reported real fuel consumption data from about 2,000 PHEV users covering 44 million vehicle km in total. We analyze different influencing factors, such as the annual VKT and AER, by descriptive and inductive statistical methods. Additionally, we give estimates on resulting potentials of mitigating CO_2 emissions.

In the following, we first give an outline of the analyzed data sets and methods before the results are presented. Here, we focus on actual fuel consumption of the five PHEV models under investigation (Chevrolet Volt, Toyota Prius, Mitsubishi Outlander, Volvo V60, and Opel Ampera), their direct CO_2 emissions and influencing factors, and also highlight the CO_2 emission mitigation potential by PHEVs. A summary and conclusions complete our paper.

Data

For our analysis, we use publicly available data representing real-world driving behavior from two online sources, where individuals self-report regularly several PHEV-related data:

Table 1 Overview of PHEV fuel consumption data sources

	voltstats.net	*spritmonitor.de*
Available data	Total miles, electric miles, different fuel consumption values, residence	Fuel consumption and distance driven between refueling
Derivable data	Annual distance traveled, utility factor	Annual distance traveled, utility factor
PHEV models and sample size	Chevrolet Volt ($N = 1,831$)	Toyota Prius ($N = 89$), Mitsubishi Outlander ($N = 46$), Opel Ampera ($N = 25$), Volvo V60 ($N = 15$). BMW i3REX ($N = 3$), VW Golf GTE ($N = 12$), Audi a3 e-tron ($N = 5$)
Data collection	Collected via interface to OnStar (telematic system)	Fuel quantity and odometer reading after each refueling reported by driver
Data availability	2012–2014	2007–2015 (PHEV subset)
Fleet structure	Mainly private cars	Mainly private cars

Note: PHEV = plug-in hybrid electric vehicles.

Voltstats.net and spritmonitor.de. Voltstats.net is an online database that collects automatically (from an additional device) real-world fuel consumption performance data of Chevrolet Volt, mainly in the United States with more than 1,800 reported Chevrolet Volts driven in the United States and Canada (Voltstats 2014). Spritmonitor.de is a German online Web service for car drivers to calculate real-world km cost, including all operating cost. This database contains self-reported information for different vehicle types, including PHEVs. The number of reported PHEVs is smaller than in the voltstats.net database and contains information about various PHEV models, not only the Chevrolet Volt. Table 1 summarizes the available PHEV data from the two sources.

Voltstats.net focuses on fuel consumption performance of Chevrolet Volt mainly in the United States and Canada. It comprises data from registered users with a comprehensive set of user specific performance data. The average number of days observed per vehicle is 442 days with a minimum of 17, median of 382, and maximum of 1,327 days (c.f. table 2). On the basis of the available data, we calculated the following parameters: The average total monthly distance traveled was extrapolated to annual values. The individual UF is obtained by dividing all electric km by total km driven. The individual total fuel consumption c_{tot} is the product of fuel consumption in charge sustaining mode c_{cs} and the share of conventional driving, that is, $1 - \text{UF}$.

Spritmonitor.de is an online Web service for car drivers to calculate real-world km cost, including all operating cost. Among other information, registered car drivers report their fuel demand in liters and the corresponding cost as well as the vehicle odometer reading after each refueling. The resulting average fuel consumption and cost are calculated automatically. As spritmonitor.de is an online service mainly targeted at conventional vehicles, a distinction into electric and nonelectric miles is not provided. Detailed information on distances traveled and the respective fuel consumption for every registered driver and every single trip between two refuelings (or recharges) are accessible freely on the website. Mock and colleagues (2014) indicate a good representativeness of spritmonitor.de for the German car fleet. For the analysis in the present paper, we will mainly focus on the Toyota Prius, Mitsubishi Outlander, Opel Ampera, and Volvo V60.

As spritmonitor.de is not designed for PHEVs only, PHEV users report distances traveled in different ways. Most of the users (82.5%) report total VKT, thus the calculated average fuel consumption equals average total fuel consumption c_{tot}. For this user group, information on electric km traveled is not available. In contrast, the remaining 17.5% of users report total electricity consumed as well as total fuel consumed related to electric and nonfully electric VKT. However, for these users, no information is available neither on operation mode (i.e., charge sustaining or blended mode) nor on total VKT. Altogether, for both user groups, it is not possible to directly deduce electric driving shares. We therefore use an approximation and determine UF as difference between unity and the ratio of average c_{tot} and fuel consumption in charge sustaining mode c_{cs}: $\text{UF} = 1 - c_{tot}/c_{cs}$. For the 17.5% of users who do not report c_{tot}, we determine total VKT-based single-trip distances as well as on electric and nonfully electric km to calculate c_{tot}. As an approximation for c_{cs}, we take for every user the maximum average fuel consumption of all trips. If this value is not available or lies below the fuel consumption in charge sustaining mode according to the New European Driving Cycle (NEDC), we take the NEDC c_{cs} value as a proxy (for 15% of users). For the remaining 85% of users from which we take the "original" c_{cs} value, the c_{cs} value is 36% higher as the NEDC value. Drivers with more than 30 liters (L) per 100 km average fuel consumption (below 7.8 MPG) have been removed from the data as outliers. Annual distance traveled is calculated as extrapolation from the average daily distance traveled.

Both data sets are based on self-selected PHEV drivers and may show bias. First, PHEVs in the present market phase are

Table 2 Summary statistics of Voltstats.net and Spritmonitor.de PHEV data

PHEV	*N*	*Variable*	*min*	*median*	*mean*	*SD*	*max*
Chevrolet Volt	1,831	Annual distance traveled [km]	660	16,317	**17,422**	8,269	106,286
		Utility factor (UF)	11.7%	81.9%	**78.5%**	15.4%	100%
AER: 61 km		Total Fuel Cons. c_{tot} [L/100 km]	0.00	1.23	**1.45**	1.02	6.55
		Observation days	17	382	**442**	310	1,327
Opel Ampera	25	Annual distance traveled [km]	6,927	13,744	**16,209**	9,399	49,228
		Utility factor (UF)	27%	77%	**72%**	21%	100%
AER: 61 km		Total Fuel Cons. c_{tot} [L/100 km]	0.00	1.74	**1.91**	1.58	6.81
		Observation days	31	459	**521**	356	1,159
Mitsubishi Outlander	46	Annual distance traveled [km]	7,648	21,649	**21,937**	9,238	50,584
		Utility factor (UF)	0%	47%	**47%**	21%	94%
AER: 37.5 km		Total Fuel Cons. c_{tot} [L/100 km]	0.37	4.31	**4.31**	1.56	8.06
		Observation days	29	267	**278**	160	576
Toyota Prius	89	Annual distance traveled [km]	1,903	18,129	**20,859**	11,894	63,906
		Utility factor (UF)	2%	28%	**30%**	19%	80%
AER: 18 km		Total Fuel Cons. c_{tot} [L/100 km]	0.84	4.13	**4.01**	1.36	6.60
		Observation days	18	363	**475**	**462**	2,794
Volvo V60	15	Annual distance traveled [km]	9,820	23,052	**23,127**	8,969	40,552
		Utility factor (UF)	29%	47%	**49%**	14%	73%
AER: 39 km		Total Fuel Cons. c_{tot} [L/100 km]	2.72	4.31	**4.51**	1.02	6.84
		Observation days	75	385	**387**	196	843

Note: PHEV = plug-in hybrid electric vehicles; AER = all electric range; km = kilometers; L/100 km = liters per 100 kilometers; Cons. = consumption; min = minimum; SD = standard deviation; max = maximum.

early adopters, for example, with a high likelihood of above-average income and education (cf., Plötz et al. 2014; Rezvani et al. 2015). Second, even the subsample providing automatically selected data for Voltstats.net or the self-reported data for spritmonitor.de show higher interest in fuel efficiency and might therefore be show more fuel-efficient driving than other PHEV drivers. Nevertheless, the high number of observations and their homogeneity is highly convincing. Therefore, and due to the lack of alternatives, we take this data set as a basis for our calculation.

Results

Real World Plug-In Hybrid Electric Vehicle Fuel Consumption

The range and average empirical PHEV fuel consumption from the different data sources are summarized in table 2; box plots and individual values are shown in figure 1. In the following, we state AER according to U.S. Environmental Protection Agency (US EPA) if available and 75% of NEDC AER (which we found to approximate the EPA findings well where a comparison is possible).

We observe a broad range of PHEV fuel consumption in our sample ranging from 0 to 8.06 l per 100 km. The average automatically tracked and transferred fuel consumption of the 61 km AER Chevrolet Volt is 1.45 ± 0.05 L/100 km (at 95% confidence level), and the average electric driving share is 78.5 ± 0.7%. Surprisingly, the self-reported fuel consumption for the technically identical Opel Ampera is higher (i.e., 1.9 ± 0.6 L/100 km and 72 ± 9%, correspondingly). The self-reporting (spritmonitor.de) effect seems to have no significant influence compared to the automatically transferred data from the Voltstats.net database. The 39 km AER Volvo V60 PHEV consumes 4.5 ± 0.5 L/100 km at an average electric driving share of 49 ± 7%. These numbers are similar to the 37.5 km AER Mitsubishi Outlander PHEV with 4.3 ± 0.5 L/100 km and 47 ± 5%. Finally, the Toyota Prius has only 18 km AER with 4.0 ± 0.3 L/100 km and 30 ± 4% electric driving share.

Compared to official test-cycle values, the observed average UFs, that is, the share of electrified km, are in line with test-cycle values for the long-range vehicles Chevrolet Volt and Opel Ampera. However, the UFs are noteworthily lower than expected from test-cycles for Toyota Prius, Volvo V60, and Mitsubishi Outlander. Similarly, the median fuel consumption for the Volt and Ampera are close to the test-cycle values, but differ strongly (by a factor of 2) for other three shorter-ranged PHEV models. For the Toyota Prius and the Chevrolet Volt, test-cycle ratings for the United States (US EPA 2015) are available for comparison: The Prius has been rated with 29% UF and the Chevrolet Volt with 66% UF.

However, the observed results could be biased by the high annual VKT in the sample and may not be representative for a general PHEV fleet. The latter would be important for long-term CO_2 fleet regulations as growing market diffusion would probably lead to PHEVs being used by a fleet that is closer

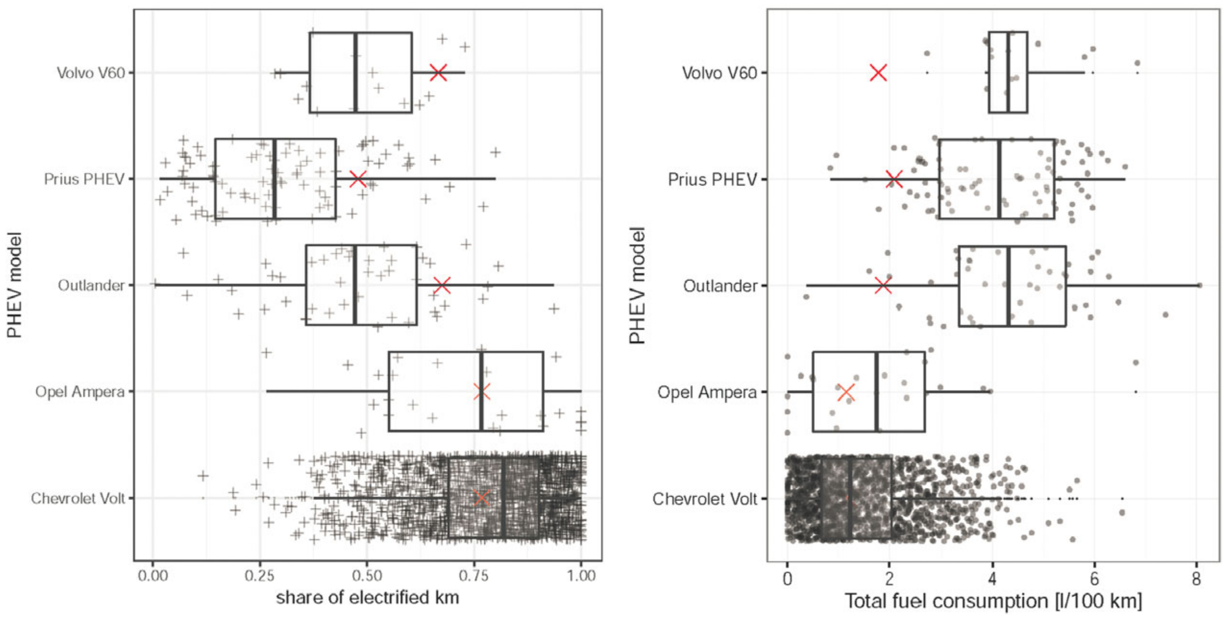

Figure 1 Fuel consumption of PHEVs. Shown are emprical individual values (small dots) and box plots for the five PHEV models. The left panel shows the share of electrified kilometers, that is, the utility factor (UF). The right panel shows the fuel consumption in liters per 100 kilometers (l/100km). The crosses indicate official driving cycle values. PHEVs = plug-in hybrid electric vehicles.

to the average car stock and less dominated by today's early adopter. In particular, the Prius, Volvo V60, and Outlander with average annual VKT between 20,800 and 23,100 km exceed the average European VKT of about 12,800 km almost by a factor of 2. Higher annual VKT is correlated with more frequent long-distance driving and thus lower UF. To quantify this effect and to adjust the observed PHEV fuel consumption data to an average European annual VKT, we performed two linear regressions (see figures S1 and S2 in the supporting information available on the Journal's website). The regression results are now used to harmonize the average fuel consumption values for the five PHEV models with respect to average VKT (the regression results have been used by all models for consistency). The results for the VKT-adjusted UF and fuel consumption are given in column "data adj." of table 3. As expected, the UF increases for all models (except the Volvo V60 with a very small sample) when lower annual VKT is assumed and the total fuel consumption decreases. Despite their different AER, the average PHEV model fuel consumption can be compared via their test-cycle fuel consumption. Even though many PHEVs indicate lower fuel consumption, the average deviation from driving cycle values ranges from $+21 \pm 4\%$ for the Chevrolet Volt to $+130 \pm 23\%$ for the Outlander, which must be compared to the average deviation for conventional vehicles of 20% to 45% (Mock et al. 2014; Ntziachristos et al. 2014; Zhang et al. 2014). After the VKT adjustment, the average deviation of official test-cycle values for fuel consumption decreases, too.

In summary, we provided empirical UF and fuel consumption results for five mass-market PHEV models. The observed average values are all above European test-cycle fuel consumption estimates. The deviation is reduced for all models when normalized to national average annual VKT, both using the PHEV fuel consumption data and simulated UFs. Yet, the deviation values between test-cycle and real-world fuel consumption remain above the values for conventional vehicles except for the Chevrolet Volt and Opel Ampera.

Direct Carbon Dioxide Emissions of Plug-In Hybrid Electric Vehicles

In the previous section, average UFs and fuel consumptions as observed in real-world PHEV data and adjusted to average an VKT were discussed. The average direct CO_2 emissions for the different PHEV models are directly obtained by multiplication of the average fuel consumption with CO_2 content factors. The aim of this section is to quantify the effect of PHEV model characteristics such as AER and engine power on average direct CO_2 emissions by PHEV. Please note that direct CO_2 emissions and fuel consumptions are, of course, directly linked, and the results of the present section apply to both.

Besides these direct measurable CO_2 emissions also indirect emissions occur due to the increased electricity demand. These emissions differ widely between countries and depend strongly on the national power plant portfolio, which generates the electricity. In regions with a high share of fossil-fuel–based power plants, such as lignite or hard coal, the emission reductions by PHEVs are strongly limited (Tamayao et al. 2015; Jochem et al. 2015).

Here, we focus on the average direct CO_2 emissions for the different PHEV models from our empirical data (cf. figure 2 and Table 3). Figure 2 shows the sample average direct CO_2

Table 3 Summary statistics of PHEV fuel consumption

PHEV	*Range [km]*	*N*	*NEDC*	*Observed*	*Data adj.*
Average electric driving shares					
Chevrolet Volt	61	1,831	77%	78.5 ± 0.7%	82.1 ± 2.7%
Toyota Prius	18	88	50%	30 ± 4%	33 ± 16%
Opel Ampera	61	25	77%	72 ± 9%	76 ± 27%
Volvo V60	39	15	67%	49 ± 7%	45 ± 48%
Mitsubishi Outlander	37.5	46	68%	47 ± 5%	51 ± 26%
Average fuel consumption [L/100 km]					
Chevrolet Volt	61	1,831	1.19	1.45 ± 0.04	1.21 ± 0.06
Toyota Prius	18	88	2.09	4.05 ± 0.30	3.88 ± 1.69
Opel Ampera	61	25	1.15	1.79 ± 0.68	1.58 ± 1.23
Volvo V60	39	15	1.78	3.94 ± 0.41	3.94 ± 4.66
Mitsubishi Outlander	37.5	46	1.87	4.30 ± 0.43	4.09 ± 2.26
Average specific emissions [gCO$_2$/km]					
Chevrolet Volt	61	1,831	28	34.0 ± 1.0	28.5 ± 1.3
Toyota Prius	18	88	49	95 ± 7	91 ± 40
Opel Ampera	61	25	27	42 ± 16	37 ± 31
Volvo V60	39	15	48	106 ± 11	106 ± 123
Mitsubishi Outlander	37.5	46	44	101 ± 10	96 ± 53
Average fuel consumption deviation from driving cycle [0% = NEDC]					
All PHEVs		**2,005**		**+28 ± 4%**	**+10 ± 7%**
Chevrolet Volt	61	1,831	0%	+ 21 ± 4%	+ 2 ± 5%
Toyota Prius	18	88	0%	+ 94 ± 13%	+91 ± 81%
Opel Ampera	61	25	0%	+ 56 ± 50%	+37 ± 113%
Volvo V60	39	15	0%	+120 ± 30%	+121 ± 156%
Mitsubishi Outlander	37.5	46	0%	+130 ± 23%	+118 ± 121%

Note: AER = all electric range; km = kilometers; PHEV = plug-in hybrid electric vehicles; L/100 km = liters per 100 kilometers; gCO$_2$/km = grams of carbon dioxide per kilometer; NEDC = New European Driving Cycle; Data adj. = data adjusted.

emissions as empty circles with 95% confidence bands. As expected, the Chevrolet Volt and Opel Ampera with about 60 km AER drive mainly electrically and show low direct CO_2 emissions. For the Chevrolet Volt, we observe 34 ± 1 grams of carbon dioxide per kilometer (gCO$_2$/km) of direct CO_2 emissions (and 29 ± 1 gCO$_2$/km when normalized to average European VKT; errors are 95% confidence intervals). For the Opel Ampera, we obtain 42 ± 16 gCO$_2$/km (37 ± 31 gCO$_2$/km normalized). The other vehicles show higher direct emissions: 95 ± 7 CO$_2$/km for the Toyota Prius (91 ± 40 gCO$_2$/km when normalized to average European VKT), 106 ± 11 gCO$_2$/km for the Volvo V60 (106 ± 123 gCO$_2$/km normalized), and 101 ± 10 gCO$_2$/km for the Mitsubishi Outlander (96 ± 53 gCO$_2$/km normalized).

Again, the comparability of different PHEVs is limited. Not only the AER, but also the engine size and power influence the direct CO_2 emissions since they affect fuel consumption during nonelectric mode. High power also acts as a proxy for high vehicle mass (both are almost collinear; Pearson correlation equals 0.975) and is assumed to increase the likelihood of more aggressive and thus fuel-consuming driving. To separate the effect of different vehicle power and AER, we perform a regression of the specific direct CO_2 emissions from vehicle power and AER. The aim of the regression analysis is again not to establish the sign of the effect by strict statistical methods (the sign is clear from general considerations), but to quantify and separate the effects of vehicle range and power in our limited sample of PHEV models. Since the direct emissions are strictly non-negative, we use an exponential for the effect of AER (equation 1):

$$\mathrm{CO2emissions} = \mathrm{Power}^{\beta_1} \exp(\beta_0 + \beta_2 \mathrm{AER}) + \varepsilon. \quad (1)$$

Here, the system power (*Power*), that is, combustion engine power plus electric motor power measured in kilowatts (kW), has been used as a proxy for engine displacement, weight, and model-specific aggressiveness of driving. The chosen dependence on AER and power are: For AER → 0, the direct CO_2 emissions approach a finite value (i.e., the emissions in the charge sustaining mode) and is decreasing to zero for AER → ∞ (i.e., a negative β_2). Likewise, the direct CO_2 emissions approach zero for Power → 0 and grow with increasing power (i.e., positive β_1). The inclusion of weight as additional covariate does not alter the results shown below.

The regression is performed after taking logarithms (cf. equation 2)

$$\ln(\mathrm{CO2emissions}) = \beta_0 + \beta_1 \ln \mathrm{Power} + \beta_2\ \mathrm{AER} + \tilde{\varepsilon} \quad (2)$$

by ordinary least squares. The regression results are summarized in table 4. The model itself and the coefficients are significant ($p < .05$), and the coefficients have the expected signs ($\beta_1 > 0$

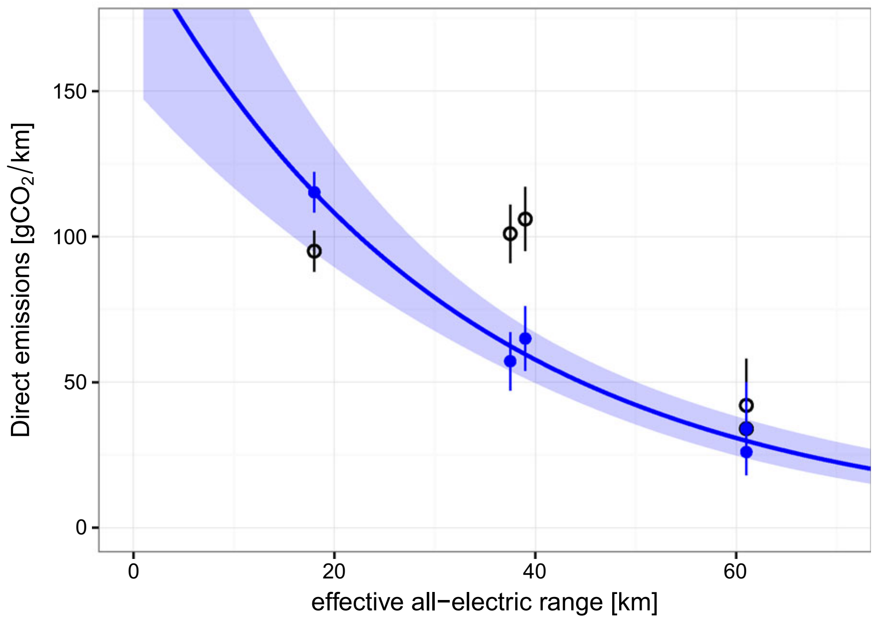

Figure 2 Direct CO_2 emissions of PHEVs with different all electric ranges (AERs). The average specific CO_2 emissions of the five PHEV models are shown as observed in our sample (empty symbols) and adjusted for their different propulsion system powers (filled symbols) with regression result (solid line). The blue bands indicate 95% confidence bands. CO_2 = carbon dioxide; gCO_2/km = grams of carbon dioxide per kilometer; PHEVs = plug-in hybrid electric vehicles.

Table 4 Regression results for the specific direct CO_2 emissions

	Estimate	*SE*	*t statistic*	*p value*
Intercept β_0	-2.724	1.729	-1.58	0.256
Power β_1	1.604[a]	0.343	4.67	0.043
All electric range β_2	-0.031[a]	0.003	-9.01	0.012

[a]Sign.at 5% level, N = 5, df = 2, F-statistic: 41.6, p value = 0.024, R^2 = 0.977, Adjusted R^2: 0.953.
CO_2 = carbon dioxide; SE = standard error.

and $\beta_2 < 0$) for AER and is significantly different from zero. The effect of system power is only marginally significant, which is not surprising due to the few observations. The absolute values of parameters should be interpreted with caution. Nevertheless, the regression results are noteworthy to be mentioned as a first estimation of the underlying effects.

As expected, the regression results indicate that higher AER leads to lower average direct CO_2 emissions since the UF increases. Within the range of our data, the direct CO_2 emissions are reduced by about 3.1 ± 0.9% with each additional km of AER, that is, every 22 km of AER increase the direct CO_2 emissions are halved (95% confidence interval: 15 to 42 km). Furthermore, a 1% increase of power is connected to an increase of the average direct CO_2 emissions by 1.6%.

Again, we used the result of the regression for a simulation for normalize all considered PHEVs to the same 150 kW system power. This allows as a harmonized comparison of direct specific emissions (cf. filled symbols in figure 2). Using the regression results, a 50 km AER PHEV model with 150 kW would show about 43 ± 2 gCO_2/km of average direct CO_2 emissions in real driving.

Electrification of Vehicle Fleet

The overall share of annual VKT in a large car fleet that can be electrified by an average PHEV depends on the PHEVs' AER. Higher AERs lead to higher UFs and thus lower direct CO_2 emissions. Yet, on the other hand, higher AER requires larger batteries and is connected to higher indirect CO_2 emissions from PHEV production since the production of large batteries is energy-intense (Dunn et al. 2015; Bauer et al. 2015) (here, we assume 40 kilograms of carbon dioxide equivalent per kilowatt-hour [$kgCO_2$-eq/kWh]) and implies a trade-off in CO_2 emission savings between vehicle production and vehicle usage. In this trade-off, one can expect an AER that minimizes total (i.e., direct plus indirect) CO_2 emissions. We analyze this effect by comparing the well-to-wheel (WtW) CO_2 savings of fleet electrification level as compared to the usage of a conventional vehicle. The aim of the present section is to identify this minimum by simulating a large fleet of conventional vehicles as PHEVs.

We simulate each driving pattern individually as BEVs or PHEVs with different AERs based on a comprehensive database of conventional vehicles from Germany (the data set is described in the Supporting Information on the Web). We assume a complete recharge every night and electric driving until the PHEV model-specific AER has been reached and conventional driving thereafter. Furthermore, we assume that all the trips by the conventional car from the database should be

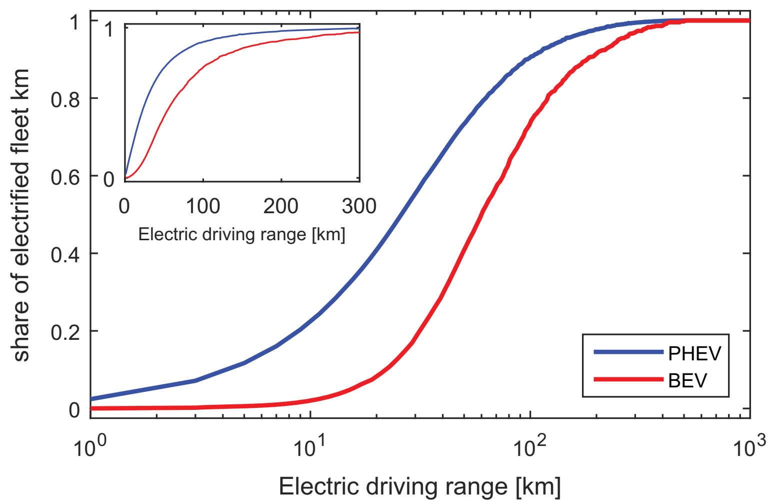

Figure 3 Share of electrified fleet kilometers for different electric ranges. Insert graph shows detail for short driving range on linear scale. BEV = battery electric vehicles; km = kilometers.

replaced—there is no alternative for longer trips such as public transport or car sharing. The simulation is performed for every vehicle and its specific annual VKT under the assumption of 20 kWh/100 km in charge depleting mode and 5.5 L/100 km of gasoline in charge sustaining mode (cf. the Supporting Information on the Web). For each AER, the share of km electrified by all vehicles is summed and divided by the total VKT of all vehicles. This share of electrified fleet km is an estimator for electrification of a vehicle fleet and aggregates many individual UFs. Note that it is different from the average UF since vehicles with higher annual VKT have lower UF, but higher weight, in the total mileage than vehicles with short annual VKT.

Figure 3 shows simulation results for the share of total fleet km that can be electrified by PHEVs. For PHEVs, a share of each vehicle's daily VKT can be electrified even for small ranges. Accordingly, PHEVs show an early growth of electrified km. Due to some vehicles showing long-distance trips and since long-distance trips contribute heavily to a fleet's overall VKT, 100% of electrification is very difficult to achieve and possible only at very high AER (over 300 km). Similar simulations for BEVs show that the difference in electrification potential between PHEVs and BEVs is maximal at about 30 km of range where PHEVs can electrify more than 50% of the total fleet km and BEV about 17% of the fleet kilometers.

Based on the PHEV fleet simulation, we calculate the annual WtW CO_2 savings over a vehicle lifetime of 12 years from the electrification of a large car fleet by PHEVs for recharging with different electricity types as compared to a 130 gCO_2/km conventional vehicle. The fleet CO_2 savings have been normalized by the number of vehicles to obtain the average WtW per vehicle. The results are shown in figure 4 for five different carbon contents of electricity generation: renewable energies (10 gCO_2/kWh, blue), natural gas (495 gCO_2/kWh, green), the current German mix (585 gCO_2/kWh, red), hard coal (835 gCO_2/kWh, cyan), and lignite (950 gCO_2/kWh, purple). Since the CO_2 savings are obtained from comparison with a conventional vehicle (130 gCO_2/km), only charging electricity from renewable energy generation (2 gCO_2/km), natural gas power plants (99 gCO_2/km), and the current German mix (117 gCO_2/km) can achieve actual savings. In all other cases, the energy-intense battery production and the CO_2 content of the electricity assumed for recharging leads to higher WtW emissions than for a conventional vehicle. With respect to major PHEV markets, the CO_2 emission factors of France, Sweden, and Norway are close to renewable generation, the average U.S. electricity generation is slightly above the German mix, and China's electricity generation shows specific CO_2 emissions comparable to hard coal.

The trade-off between longer electric range and higher CO_2 emissions from battery production leads to a maximum in fleet emission savings or a minimum in WtW emissions for low-carbon electricity. For PHEVs, a range of 185 km is optimal when charging electricity from renewable sources with about 1.7 tonnes CO_2 (tCO_2) per vehicle and year and about 0.3 tonnes CO_2 (tCO_2) per vehicle and year at 95 km range when using natural gas. The optimal ranges are reduced to 115 and 65 km when only 4 years are assumed as vehicle usage time. Thus, PHEVs can achieve savings at realistic ranges. As a comparison, the highest savings for BEVs of about 1.6 tCO_2 per vehicle and year can be achieved at a range of 280 km for renewable energies and of 0.3 tCO_2 per vehicle and year at 150 km range.

In summary, high AERs come at the cost of high CO_2 emissions from vehicle production. This trade-off leads to an optimal PHEV electric driving range in terms of WtW CO_2 emission savings. Similar calculation for BEVs show that the optimal range is smaller for PHEVs than BEVs since PHEVs can electrify higher shares of fleet km with the same range as BEVs.

Discussion

The presented PHEV fuel consumption results are consistent with results from numerical simulations and other studies (Gonder et al. 2007; Smart et al. 2014; Ligterink and Eijk 2014;

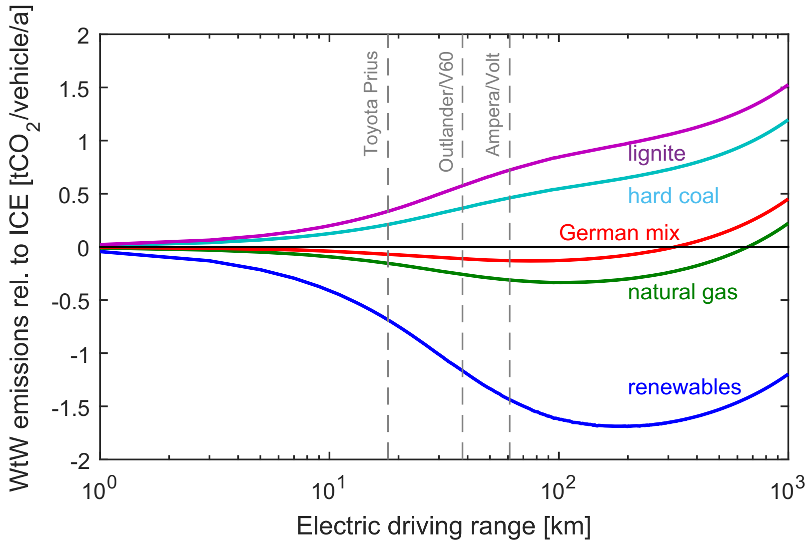

Figure 4 Well-to-wheel (WtW) CO_2 emissions in tonnes per vehicle and year for PHEV as compared to a conventional vehicle versus all electric ranges (AERs) for different electricity types (blue: renewable energies; green: natural gas; red: German mix; cyan: hard coal; purple: lignite). CO_2 = carbon dioxide; km = kilometers; PHEV = plug-in hybrid electric vehicles; rel. to ICE = relative to internal combustion engine; tCO_2/vehicle/a = tonnes of carbon dioxide per vehicle per annum.

Davies and Kurani 2013). Other studies (Ligterink et al. 2013; Ligterink and Eijk 2014) have not yet analyzed the effect of annual VKT, but find higher CO_2 emissions for the highly powered Volvo V60 and Mitsubishi Outlander (as indicated by the regression of propulsion system power).

We analyzed data of PHEV self-recorded in the United States, Canada, and Germany by PHEV users. The United States is the second-biggest market for passenger cars whereas Germany is an important European market for passenger cars. Altogether, actual market conditions are well represented by our data set. However, comprehensive fuel consumption data for PHEV in China, the most important and growing market, is not available yet. This raises the question of transferability of results to the rest of the world, especially with regard to charging conditions. The present-day early adopter of PHEVs analyzed in this work (i.e., men, and people with high income and education are over-represented—according to Rogers [2003]) may have special conditions favorable for PHEV adoption, as it is, for example, the availability of a home charging point. Furthermore, the PHEV fuel consumption data might be biased to lower fuel consumption as users reporting their fuel consumption could be more aware of their driving behavior. Finally, we assume the reported car usage in the reporting period to be representative for the overall driving behavior of the user. However, due to the long reporting periods of more than a year and the sample size, our results can be assumed robust and might give an upper bound of discrepancy to official NEDC values.

The fleet electrification simulation relies on several simplifying assumptions, such as one full recharge overnight and fixed energy consumption per km for all electric ranges. Whereas the first seems a reasonable approximation for actual user behavior, the latter seems questionable since increased range derives from larger batteries with higher vehicle mass. Thus, energy consumption should increase with electric driving range. However, the effect should be small for not too large ranges (up to 300 km) and our overall results should thus not be affected by inclusion of range-dependent energy consumption. An installation of fast charging stations, which allows the users to recharge vehicles conveniently at resting facilities along the highway, would definitely have a strong impact on our results and makes BEVs more competitive to PHEVs.

The CO_2 saving potentials depend on the assumed vehicle lifetime. Since vehicle battery production is carbon-intense and PHEV as well as BEV usage is connected with low CO_2 emissions, the CO_2 savings grow with the lifetime assumed. Here, we used 12 years of usage, which is the average vehicle lifetime for newly purchased vehicles in Germany (Plötz et al. 2013). Furthermore, the actual CO_2 emissions from battery production are uncertain and estimates in the literature show a broad range of 35 and 250 $kgCO_2$-eq/kWh (Ellingsen et al. 2014). The 40 $kgCO_2$-eq/kWh chosen for our simulations are close to the lower border of the values since they reflect statements of several manufacturers to use renewable electricity for battery production. Assuming higher CO_2 content from battery production increases the slope at the right-hand end of figure 4 and would shift the optimal AER to smaller values. In addition, CO_2 emissions from battery production scale with battery capacity. Here, we use an average battery capacity for all vehicles modeled. However, batteries will most probably be scaled with vehicle size. As annual VKT is positively correlated with vehicle size, the use of an average battery size for all vehicles might put a disadvantage on BEVs as for high annual VKT PHEVs, we expect electrified km to outweigh the effect of an oversized battery in smaller vehicles, while this might not be the case for BEVs. Finally, higher additional investment and operating cost for the conventional drive train of PHEV might favor lower battery sizes than for BEV. We ignored this effect as we do not expect this effect to influence our general results.

Summary and Conclusion

We analyzed real-world PHEV fuel consumption data from more than 2,000 PHEVs covering mainly five PHEV models. We found noteworthy deviations from test-cycle fuel consumption of the order of 50% to 100% mainly for short-ranged PHEVs. Furthermore, with every km of AER the average real-world direct CO_2 emissions decrease by 2% to 3%. This implies that AER is a major factor for actual CO_2 savings from PHEVs and that increased AERs should be incentivized to reduce actual CO_2 emissions or that driving cycles should distinguish between PHEVs according to their AER (see, e.g., CARB 2012). Yet, the inclusion of battery production in WtW CO_2 emission savings of PHEVs revealed that the AER ranges should not exceed 200 to 300 km, depending on the electricity used for battery production.

Several other factors impact direct CO_2 emissions of PHEV, too. System power is relevant, aggressiveness of driving, but also factors not covered in the present analysis, for example, recharging behavior. PHEV supporting programs not taking recharging behavior into account might have a misleading function with the PHEV being used as a subsidized conventional vehicle (see, e.g., Ligterink and Eijk 2014). Frequent recharging from renewable electricity instead of big conventional engines will reduce CO_2 emissions of PHEVs in the future. In conclusion, our findings indicate that policy making and regulations of PHEVs should (1) be based on real-world fuel consumption measurements, (2) take into account charging behavior and annual mileages, and (3) incentivize long-ranged PHEV. The first two steps would greatly increase the accuracy of fuel economy standards and help close loopholes. The third one helps to increase electric driving and achieve more greenhouse gas (GHG) savings from PHEVs.

The recent decline in battery cost will make both BEVs and PHEVs economically competitive with conventional vehicles. Today, PHEVs are highly accepted by customers and they offer the only option to electrify vehicles with occasional long-distance driving. By using smaller batteries than BEVs implying lower emissions from vehicle production, PHEVs can thus contribute to GHG emission reduction, especially for higher annual VKT, and the electricity used for recharging remains as a major factor for PHEV GHG reduction potential. In the future, the decarbonizing electricity system might lead to a recovering of BEVs in this regard. Future political actions need to take the user-specific annual VKT, frequent charging, as well as the electricity generation (especially when compared to all-electric vehicles) into account.

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Supporting Information

Supporting information is linked to this article on the *JIE* website:

Supporting Information S1: This supporting information consists of five sections and a glossary. Section 1 describes the driving data used for the simulation of PHEV driving shares as well as the emission factors used to determine average PHEV CO_2 emissions. Sections 2 and 3 provide the methodology and the results of the regression analysis to analyze the effect of annual vehicle kilometers traveled (VKT) on achievable electric driving shares. Finally, sections 4 and 5 show further data on international PHEV sales and average European annual VKT, respectively.