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# REAL-WORLD USAGE OF PLUG-IN HYBRID ELECTRIC VEHICLES

## FUEL CONSUMPTION, ELECTRIC DRIVING, AND $CO_2$ EMISSIONS

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## EXECUTIVE SUMMARY

Plug-in hybrid electric vehicles (PHEVs) combine an electric and a conventional combustion engine drive train. They offer potential to reduce global greenhouse gas (GHG) emissions and local air pollution if they drive mainly on electricity. PHEVs account for about one third of the global electric vehicle fleet and their fleet is expected to grow further (IEA 2020). However, there is limited evidence on how much driving PHEVs actually do on electricity and how much conventional fuel they use in real-world operation. The present report provides an analysis of real-world usage and fuel consumption of approximately 100,000 PHEVs in China, Europe, and North America. The analysis arrives at the following main findings:

**PHEV fuel consumption and tail-pipe $CO_2$ emissions in real-world driving, on average, are approximately two to four times higher than type-approval values**. The deviation from New European Drive Cycle (NEDC) type-approval values spans much larger ranges than for conventional vehicles. Real-world values are two to four times higher for private cars and three to four times higher for company cars (Figure ES1). Making use of a limited dataset of PHEVs that are type-approved to the newly introduced Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP), the deviation found is about the same as for PHEVs type-approved to the NEDC.

**The real-world share of electric driving for PHEVs, on average, is about half the share considered in the type-approval values**. For private cars, the average utility factor (UF)—an expression for the portion of kilometers driven on electric motor versus kilometers driven on combustion engine—is 69% for NEDC type approval but only around 37% for real-world driving. For company cars, an average UF of 63% for NEDC and approximately 20% for real-world driving was found. Similar deviations are to be expected also for WLTP. There are noteworthy differences between the markets analyzed, with the highest real-world UF found for Norway at 53% for private vehicles and the United States at 54% for private vehicles. The lowest UFs were for China at 26% for private vehicles, Germany with 18% for company cars and 43% for private vehicles, and the Netherlands with 24% for company cars (Figure ES2).

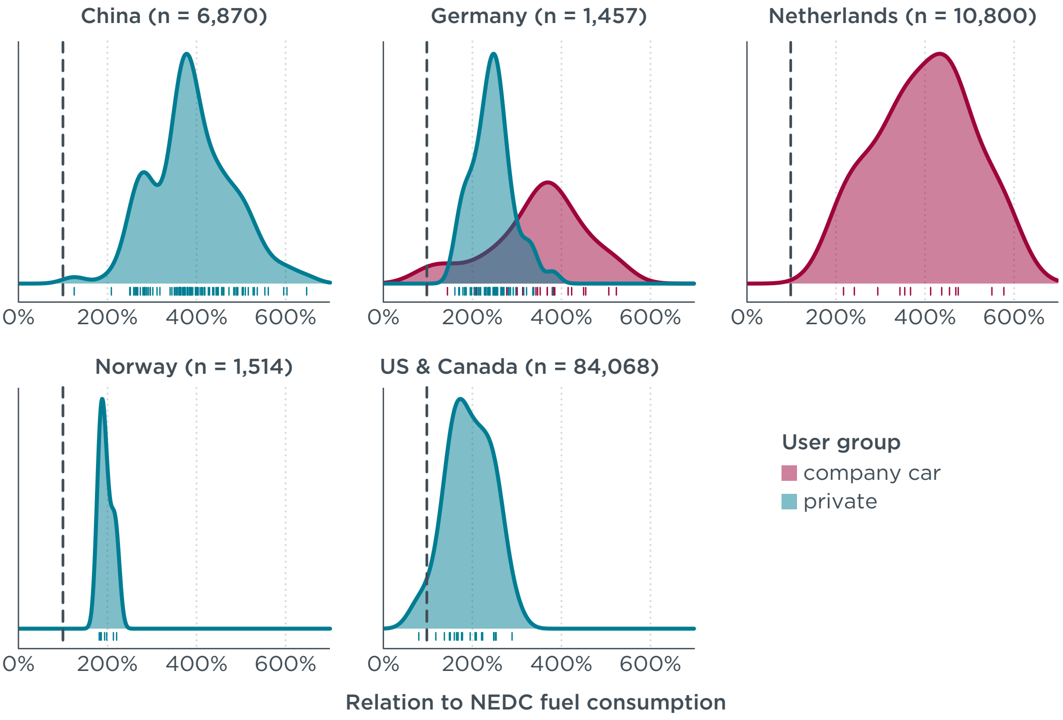

**Figure ES1. Distribution of real-world fuel consumption in relation to NEDC test cycle**. Shown is the distribution by country. The vertical dashed line at 100% corresponds to real = test cycle. Private users in blue and company car users in red. Small rugs next to the x-axis indicate individual observations at PHEV model variant level. Total number of vehicles in the sample is included by country.

**PHEVs are not charged every day.** Private users in Germany charge their PHEVs an average of three out of four driving days. For company cars, charging takes place only about every second driving day. The low charging frequency clearly reduces the share of kilometers driven on electricity. The very low UF for PHEVs in China indicates low charging frequency there, too, whereas PHEVs in Norway and the United States appear to be charged more often than in Germany or China.

**PHEVs show high annual mileage and many long-distance trips**. In Germany, the average annual mileage of PHEVs is higher than the car stock average. While for company car PHEVs, the mileage of 30,000 km is similar to that of average company cars, the mean annual mileage of private PHEVs of 21,000 km is significantly higher than the approximately 14,000 km private-car average. This higher total mileage indicates more-frequent long-distance car travel. As the all-electric range of most current PHEVs is limited to an average of around 50 km (according to NEDC), this reduces the share of kilometers driven on electricity. In the United States, the average annual mileage is similar to the national average.

**PHEVs electrify many kilometers per year**. Most PHEVs have type-approval all-electric ranges of 30–60 km (NEDC) and electrify 5,000–10,000 km a year, increasing with range. PHEVs with high all-electric ranges of 80 km or more achieve 12,000–20,000 km mean annual electric mileages, which are values comparable to the mean total annual mileage of the car fleet in Germany and the United States. The high mean annual number of electric kilometers reflects high annual mileages of PHEVs despite low UFs. If the fuel consumption of PHEVs at empty battery is assumed to be similar to the fuel consumption of conventional cars, the share of kilometers that PHEVs electrify on average results in a total of 15%–55% less tailpipe $CO_2$ emissions compared to conventional cars. Such savings depend on the PHEV model, user group and country. Overall, they are much lower than expected from type-approval values.

**Decreasing combustion engine power while increasing all-electric range and frequency of charging improve real-world fuel consumption and $CO_2$ emissions of PHEVs.** Real-world fuel consumption and $CO_2$ emission levels decrease by 2%–4% with each 10 kW of system power taken out of a PHEV. At the same time, adding 10 km of all-electric range improves real-world values by 8%–14%.

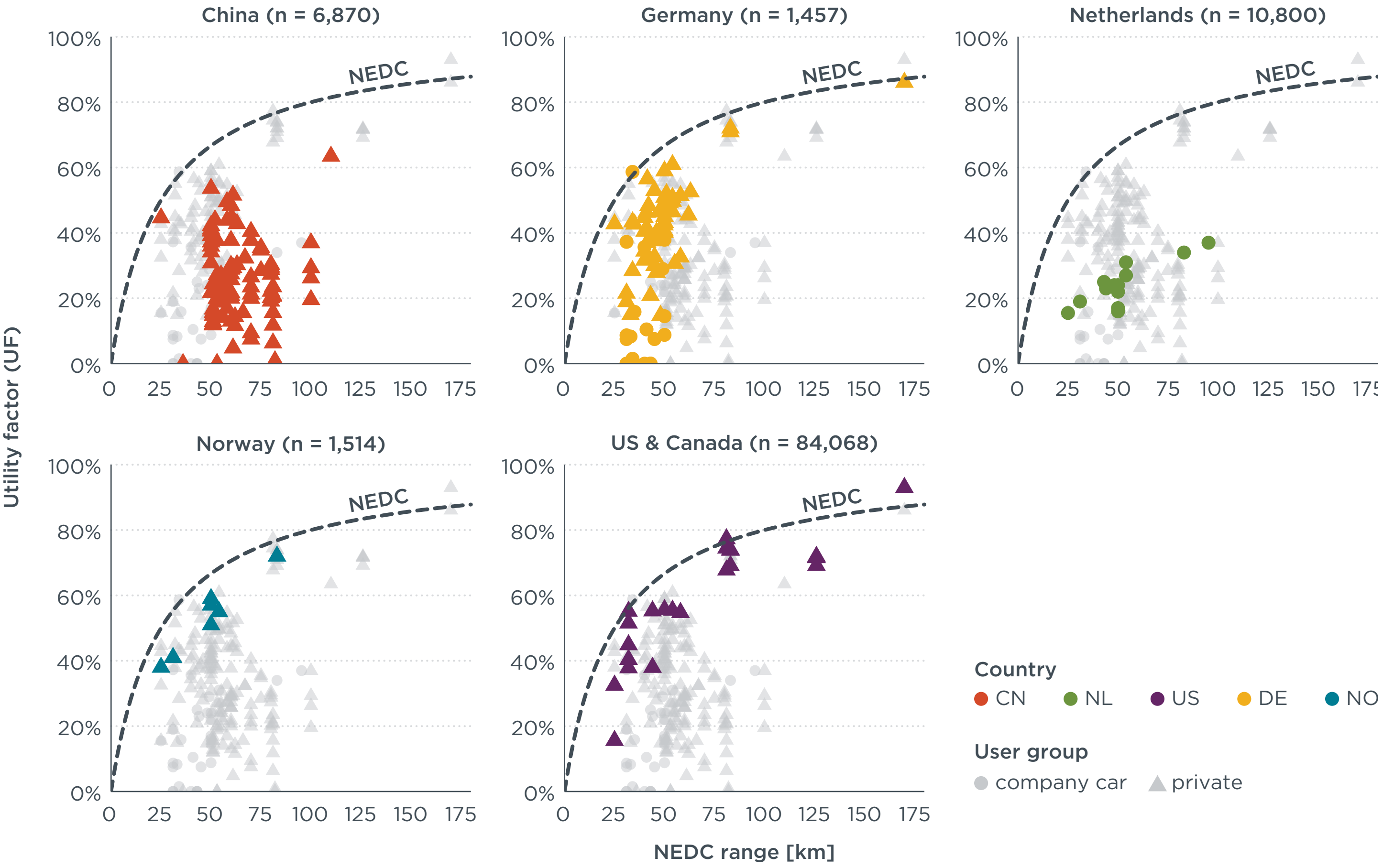

**Figure ES2. Utility factor of PHEVs with different all-electric range by country**. The average specific utility factors (UFs) of individual PHEV model-variants are shown as observed in our sample for private vehicles (small triangles) and company cars (small circles) with the NEDC UF (dashed line). Total number of vehicles in the sample is included by country. The grey dots are the full sample and each small plot emphasizes the data from one country by country specific color.

# RECOMMENDATIONS

PHEVs can electrify many kilometers if they provide sufficiently long all-electric ranges and are driven mainly on electricity. However, current PHEV policies do not fully support these aspects. Based on our findings, we provide the following recommendations:

**Vehicle manufacturers** should increase the all-electric range of their PHEVs from an average of about 50 km today to a level of about 90 km in future years. This would be sufficient to cover the full daily distance driven electrically on about 85% of driving days or approximately 70% of total distances driven by German private car owners if charged every day. Some PHEV models on the market today provide an all-electric range on this order and already show mean UFs greater than 50%. Furthermore, manufacturers should limit the power of PHEV combustion engines. This could be achieved by deciding on a maximum ratio for electric motor power to combustion engine power. It is important that any limitation on combustion engine power apply not only for urban driving but also for extra-urban driving, which accounts for the majority of annual mileage of a typical PHEV. Generally, manufacturers should make sure to inform customers about the pros and cons of PHEVs and to encourage them to select a PHEV only if the vehicle fits a customer’s driving and charging behavior.

**Fleet managers** should carefully assess which of their company car users’ driving and usage behavior is appropriate for PHEVs. They should incentivize frequent charging of PHEVs, for example by allowing unlimited re-charging of electricity while limiting the budget for gasoline or diesel on a fuel card provided by the company.

**Regulators** should revisit incentives for PHEVs to take into account real-world usage.

- At **the European Union level**, super credits are granted for vehicles with an emission level of 50 grams of $CO_2$ per kilometer ($gCO_2$/km) and lower in WLTP terms. Based on our findings, this translates into a real-world level of 100–200 $gCO_2$/km tailpipe emissions of PHEVs, which is above the 2020-21 $CO_2$ target and significantly higher than the 2025 and 2030 benchmarks. The $CO_2$ emission threshold for super credits should be lowered, or the qualification of a specific PHEV model should be demonstrated by using real-world usage data, for example collected from on-board fuel consumption meters. Similarly, the threshold for providing Zero- and Low Emission Vehicle (ZLEV) credits should be adapted to real-world data and the current multiplier of 0.7 should be removed to avoid any incentive for PHEVs with a low electric range. In parallel, the testing procedures for PHEVs, and in particular the UF assumptions of the WLTP, should be updated to better reflect real driving and usage patterns.
- At **the national level**, fiscal and other incentives should prefer PHEVs with a high all-electric range and a high ratio of electric motor power to combustion engine power. Whenever possible, incentives should be tied to demonstrating proper real-world performance of the vehicles, for example by using UF data collected from on-board fuel consumption meters or during regular technical inspections. This applies to incentives at the time of purchase, such as for private vehicle buyers, as well as tax incentives, such as for company cars. Furthermore, the legal and financial barriers for the installation of home charging points should be reduced. In parallel, a portion of PHEV purchase incentives should be bound to the installation of a home or workplace charging point or alternatively handed out as public charging vouchers. At the same time, company-car PHEV incentives could be issued only to companies that provide a sufficient workplace charging infrastructure or support employees in home or public charging. The overall public charging infrastructure needs to be expanded; there should be nondiscriminatory access to public charging stations; and the introduction of a universal charging card or simple and universal payment methods such as credit cards should be further pursued. However, as public charging is most likely less than 20% of charging events for PHEVs, the impact on the mean UF of such policies is probably limited. The attractiveness of driving on conventional fuel should be reduced by lowering charging costs, raising fuel prices, or limiting tax deductibility of costs for conventional fuels for organizations.

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# 1. INTRODUCTION

Plug-in hybrid electric vehicles (PHEVs) can use electricity as well as conventional fuel for propulsion (Bradley & Frank, 2009). Mass production PHEVs have been available for almost ten years. In the first half of 2020, PHEVs accounted for about 3.5% of all new passenger car registrations in Europe, about 1.1% in China and about 0.3% in the United States. As of 2019, PHEVs were about one third of the global plug-in electric vehicle fleet and their total fleet is expected to grow further until 2030 (IEA, 2020).

The potential of PHEVs to reduce local pollutant and global greenhouse gas emissions strongly depends on their real-world usage and the share of kilometers driven on electricity, the so-called utility factor (UF) (Chan, 2007; Jacobson, 2009; Flath, Ilg, Gottwalt, Schmeck, & Weinhardt, 2013). Assessing fuel consumption of PHEVs is challenging as PHEVs use both electricity and conventional fuel for propulsion in a ratio that depends strongly on the driving and charging patterns of vehicle users as well as on vehicle characteristics. Despite growing PHEV market shares, little is publicly known about their real-world usage. There has been no systematic investigation, at least for Europe. PHEV fuel consumption values are commonly assessed in standardized testing procedures, or test cycles, such as the New European Driving Cycle (NEDC) or the Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP). But the UFs used in the WLTP and NEDC test procedures are based on outdated information provided largely by vehicle manufacturers and may overestimate UFs and underestimate the real emissions of PHEVs.

The aim of this study is to better understand the real-world usage of PHEVs in China, Europe, and North America, with a focus on Germany, the largest PHEV market in Europe. For this purpose, data sources on PHEV usage are statistically evaluated. Additionally, driving profiles of conventional combustion engine cars are taken, and the fuel consumption and emissions performance of PHEVs are simulated. Based on the results, policy recommendations are identified and discussed.

Section 2 introduces the data sources for this report. The results are presented in section 3, starting with an overview of average deviation between actual and test-cycle PHEV fuel economy in Section 3.1, followed by a discussion of the impact of vehicle-specific factors on fuel economy, namely the all-electric range and the system power. Section 3.3 analyzes more individual vehicle factors such as the frequency of long-distance driving, charging behavior, and ambient temperature, followed by a discussion in section 3.4. We close with policy recommendations in section 4.

# 2. DATA AND METHODOLOGY

The data and methodology section consists of three parts. First, we give a rough overview of the data sources used for this study and depict their main characteristics. Second, we describe in detail the individual data sources forming the basis for our empirical dataset. Third, we outline our methodology for rounding up our dataset.

## 2.1. OVERVIEW

We collected data on real-world usage of PHEVs from existing literature, research institutions, companies, and online databases. The focus of our data collection was on gathering data providing information on real-world usage such as real-world fuel consumption, annual vehicle kilometers traveled (VKT), UF, charging behavior, ambient temperature, and others.

Our data covers six countries: Canada (CA), China (CN), Germany (DE), the Netherlands (NL), Norway (NO), and the United States (US). It includes data from private and company cars, or vehicles owned by an organization that are assigned to an individual user and can also be used for private purposes. Table 1 gives an overview of the total sample sizes by country and user group.

**Table 1. Overview of PHEV sample by country and user group, numbers of vehicles.**

| User group | Country | Sample |
|---|---|---:|
| **Private** | China | 6,870 |
| **Private** | Germany | 1,385 |
| **Private** | Norway | 1,514 |
| **Private** | US & Canada | 84,068 |
| **Company car** | Germany | 72 |
| **Company car** | Netherlands | 10,800 |
| **TOTAL** | | **104,709** |

In total, we collected data from primary and secondary sources of more than 100,000 PHEVs. Our sample is dominated by North American vehicles, but the sample sizes for individual countries are still sufficiently large to discern general patterns and draw conclusions. For Germany, for example, our sample accounts for 1% of the total stock of PHEVs and for all of Europe, 1.5% of the total stock (EAFO 2020). While most of the vehicles in our sample are private, a substantial number of more than 10,000 PHEVs are company cars, allowing significant analyses for this user group.

For about 13,000 PHEVs from Germany and North America, individual vehicle data such as real-world fuel consumption, annual mileage, or UF are available. This allows us to study differences between individual users of the same PHEV model in the same country. Thus, we gain deeper insights into the data and into individual usage than by just analyzing summary statistics, such as mean or median, which might conceal a distorted distribution of real-world usage. Table 2 gives an overview of the individual sources. While aggregated data in the literature is mostly limited to few specific PHEV models, online databases or sources such as Spritmonitor.de, MyMPG, or Xiao Xiong You Hao include a large variety of models.[1] In total, the data includes 66

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[1] In our data and our analyses, we specified PHEVs according to their brand name (e.g. Toyota, BMW, Volvo, etc.), model name (e.g. Prius, 3 series, XC60), model variant name (e.g. Prius 1.8 Plug-In Hybrid, 330e iPerformance, XC60 T8 Twin Engine), and model year or period. This differentiation is required because it is only at this detailed level that important vehicle parameters, potentially having impact on real-world usage (such as test-cycle fuel consumption, engine or system power, and all-electric range), are usually identical. If necessary, a further differentiation using equipment or accessory packages or engine types was carried out.

models, among which 202 model variants can be differentiated. A full list of mean fuel consumption and mean UF by PHEV model, country, and user group is in the appendix.

**Table 2. Detailed view of data sources.** Overview of individual and aggregated vehicle data sources. Characterization by number of PHEV models and model variants covered, sample size, predominant user group, and country.

| Source | PHEV models | PHEV model variants | Sample size | User group | Country |
|---|---|---|---|---|---|
| **Individual vehicle data** | | | | | |
| **Spritmonitor.de** | 27 | 51 | 1,385 | private | DE |
| **German company** | 14 | 21 | 72 | company car | DE |
| **Voltstats.net** | 1 | 3 | 11,073 | private | US & CA |
| **MyMPG** | 10 | 20 | 326 | private | US |
| **UC Davis** | 3 | 4 | 95 | private | US |
| **Aggregated data** | | | | | |
| **Xiao Xiong You Hao** | 60 | 92 | 6,614 | private | CN |
| **Figenbaum & Kolbenstvedt, 2016** | 7 | 7 | 1,514 | private | NO |
| **Zhou et al., 2018** | 6 | 6 | 192 | private | CN |
| **Xu et al., 2016** | 1 | 1 | 50 | private | CN |
| **Mengliang et al., 2014** | 1 | 1 | 14 | private | CN |
| **Van Gijlswijk & Ligterink, 2018 / TNO** | 11 | 11 | 9,600 | company car | NL |
| **Ligterink & Eijk, 2014 / TNO** | 3 | 3 | 1,200 | company car | NL |
| **CARB, 2017 Appendix G / GM** | 1 | 1 | 48,000 | private | US |
| **INL, 2014** | 5 | 5 | 14,750 | private | US |
| **CARB, 2017 Appendix G / UCD** | 1 | 1 | 8,309 | private | US |
| **Smart et al., 2014** | 1 | 2 | 1,405 | private | US |
| **Raghavan & Tal, 2020** | 4 | 4 | 110 | private | US |
| **TOTAL** | **66** | **202** | **104,709** | | |

## 2.2. INDIVIDUAL DATA SOURCES

In the following, we describe the individual data sources that we used for gathering primary data.

### Spritmonitor.de

Spritmonitor.de is a free German web service that allows users to track fuel consumption of their vehicles. It was established in 2001 and provides users with an easy-to-use app and web tool to monitor the fuel consumption of their vehicles and to compare their fuel consumption with that of other users. Additionally, the real-world fuel consumption data are available to the public. The database comprises almost 850,000 vehicles from more than 550,000 registered users. Spritmonitor.de is available in German, English, French, and Spanish. The predominant share of users, however, are assumed to be located in Germany.

Spritmonitor.de requires a free registration with a unique user name. A single user can register several vehicles. When registering a vehicle, the user must provide various specifications, such as brand, model, model variant such as engine type or equipment line, fuel type and build year, vehicle power, and transmission type.

Before starting to track fuel consumption, users are asked to fill the fuel tank as the first fueling serves as the reference for calculations of fuel consumption. Users can provide various data, such as main odometer reading, distance traveled since the last refueling, fuel volume added, type of tire, driving behavior, route type, and use of air conditioning.

Data available for analysis includes total mileage, total fuel consumption, and the resulting real-world fuel consumption of each vehicle. Consumption is calculated as the total fuel used by the vehicle divided by total mileage. For alternative-fuel vehicles running entirely or partly on electricity, in some cases the total all-electric mileage and total electricity consumption were given by the users. The UF was calculated according to the methodology explained in section 2.3.

After data cleaning,[2] the initial dataset of 3,376 users was reduced to a sample of 1,385 with annual VKT ranging from 2,500 km to 89,000 km and a mean of 21,000 km. The sample represents 1% of the German PHEV stock and thus can be considered representative, except that the annual mileage in the sample is higher than the German fleet average.

### UC Davis field trial

The University of California Davis collected driving data of battery electric vehicles (BEVs), PHEVs, and internal combustion engine vehicles (ICEVs) in the "Advanced Plug-in Electric Vehicle Travel and Charging Behavior" project (Tal et al., 2020). Data collection took place in three phases between June 2015 and July 2018 in 264 California households. In-vehicle global positioning system-enabled data loggers were used, allowing the automated collection of detailed data on driving and charging behavior.

Among other values, the number of observations days, total all-electric and conventional mileage, as well as average daily mileage were logged from on-board metering, thus allowing the calculation of the UF by dividing all-electric mileage by total mileage. Real-world fuel consumption (FC) was calculated by multiplying charge-sustaining fuel consumption of each individual vehicle according to the U.S. Environmental Protection Agency (EPA) 5-cycle test by 1 minus the real-world UF: $FC^{real} = FC_{cs}^{EPA} \times (1 - UF^{real})$. The subsample received from UC Davis consisted of 95 individual PHEVs from three models, the Chevrolet Volt, Ford C-MAX Energi, and Toyota Prius PHEV. The observation periods ranged from half a year up to more than one year, and total distance, between 7,000 km and 55,000 km, with a mean of 22,500 km. As UC Davis carefully selected representative households for its data acquisition and made use of automated data logging, validity of the data is considered high.

### Voltstats.net

Voltstats.net is an online database that automatically collects from an additional device real-world fuel consumption data of Chevrolet Volt users in the United States and Canada. Data for 11,703 Chevrolet Volts was obtained from registered users of the website at the time of retrieval in January 2020. Every user profile contains individual cumulative daily data on electric and gasoline-powered mileage, including the number of gallons burned daily in driving, plus summary statistics on the UF, total average miles per gallon (MPG) and charge-sustaining-mode MPG.

The dataset comprises information reported between April 2011 and January 2020, with a total of 4.3 million driving days. The data was pre-processed, cleaned and

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[2] For this study, Spritmonitor.de provided a dataset comprising all PHEV data entries. Data cleaning and validation consisted of several steps. In a first step, vehicle models for which fewer than five users provided data were sorted out as well as users with fewer than seven observation days, total mileage of less than 1,500 km, total fuel consumption of less than 50 liters, or missing odometer readings—thus ensuring sound data with an adequate level of comparability for subsequent analyses. In a second step, mild-hybrid-electric vehicles (HEVs) that were incorrectly declared as PHEVs were sorted out. Several criteria were used as an indicator for PHEV models: the specification of values for all-electric mileage driven or electricity consumption, clear information in the model or model variant specification ("plug-in," "PHEV" or according to manufacturer's classification) as well as build year or system power corresponding to PHEV models available in Germany (see paragraph "PHEV model list" in section 2.2 for details). The VKT per vehicle were obtained by dividing the total mileage (latest main odometer reading minus first entered main odometer reading) by the number of observation days (latest date minus first date) and by multiplying the result by 365 days. Finally, test-cycle values for fuel consumption and all-electric range were assigned to the Spritmonitor.de user's individual vehicles based on the PHEV model list. The UF was calculated according to the methodology explained in section 2.3.

cumulative mileage values converted to daily driven kilometers. Data cleaning involved the exclusion of values with daily VKT greater than 1,500 km and with higher electric VKT than total VKT per day. After data cleaning, the average number of driving days per vehicle was 410 with a median of 303 and maximum of 2,500 days.

Based on the available data, we calculated the following parameters: electric vehicle kilometers traveled, gasoline vehicle kilometers traveled, and total vehicle kilometers traveled. The average distance traveled was extrapolated to annual values. The individual UF per user was obtained by dividing all-electric kilometers by total kilometers driven during the observation period.

### German company fleet data

From a large private company in Germany with more than 10,000 employees, we obtained a comprehensive dataset of a corporate company car PHEV fleet. The data covers leased PHEVs for which the leasing contract had already ended. The vehicles were used by specific employees and only available to the specific employees. The utilization period was between half a year and four years, covering 2016–2020.

Detailed vehicle specifications are available, such as vehicle brand, model, and model variant. Driving data comprises the main odometer reading when returning the vehicle after the end of the leasing contract and real-world fuel consumption over the entire observation period. The UF was calculated according to the methodology explained in section 2.3. For this study, a sample of 72 vehicles was available. Annual VKT ranged between 12,000 km and 55,000 km, with a mean of 30,000 km.

### MyMPG on Fueleconomy.gov

MyMPG is a tool allowing users to track their fuel consumption and to share and compare it with that of other users or with official EPA fuel economy ratings. MyMPG is embedded in Fueleconomy.gov, which is an official website of the U.S. government, providing information for consumers on fuel-efficient driving and for making informed vehicle purchasing decisions with respect to environmental effects. The website is maintained by the U.S. Department of Energy, and data is provided by the EPA. Currently, more than 100,000 users are active on MyMPG.

Users are asked to provide fuel log data by either monitoring the main odometer reading or trip odometer reading as well as added fuel volume when refueling. By dividing the difference of main odometer readings at two subsequent refueling events or the trip odometer reading by the refueled fuel volume, the real-life fuel consumption can be calculated. As an alternative, car-computed average fuel consumption and respective trip odometer readings can be entered. Annual VKT and observation period of the individual users are not publicly available. The UF was calculated according to the methodology explained in section 2.3.

Because MyMPG users enter fuel consumption data on a voluntary basis, there is a risk of self-selection bias in the data for consumers who are particularly concerned about fuel economy (Tietge, Diaz, Yang, & Mock, 2017). The mean fuel consumption in the MyMPG sample could thus be lower than average and vehicles could be used more intensely than on average.

### Xiao Xiong You Hao data

Xiao Xiong You Hao (xiaoxiongyouhao.com) is an automobile information and evaluation company. It provides a mobile application for drivers to know their individual real-world fuel consumption based on self-reported gas filling data. The application was launched in 2010 and had more than 5.27 million downloads by the middle of 2020. The company has real-world fuel consumption data for more than 1 million drivers and nearly 32,000 vehicle models.

To start using the application, users select their specific vehicle model version. After each refueling, users record fuel volume and odometer readings. Based on users' real-world average fuel consumption, the actual average fuel consumption of each vehicle model is calculated and displayed in the application.

The dataset provided by Xiao Xiong You Hao has detailed information on the 32,000 vehicle models including average fuel consumption, number of samples, and the following specifications: brand name, series name, model name, NEDC $CO_2$ emissions, engine power, curb weight, and NEDC fuel consumption. For a few models, WLTP fuel consumption values were also available.

### PHEV model variant list

For the planned analyses, detailed vehicle specifications were required. One is system power, or the maximum combined power of electric and combustion engine, which is not necessarily the sum of the two values. Others are fuel type; fuel consumption, including charge-depleting, charge-sustaining, and combined;[3] and all-electric range according to NEDC, WLTP, and EPA test cycles. Most data sources did not contain all of this information. Using the ADAC-Autokatalog (ADAC, 2020), the required information for PHEV models available on the European market was obtained showing NEDC and WLTP values for combined fuel consumption and all-electric range of the latest models. Additionally, Fueleconomy.gov provided a list of PHEV models for the U.S. market showing EPA values for combined fuel consumption and charge-depleting consumption derived from $CO_2$ emissions. The Xia Xiong You Hao database provided NEDC combined fuel consumption as well as NEDC all-electric range for PHEVs available in China.

## 2.3. METHODOLOGY FOR UF CALCULATION

In cases where the actual UF is missing, we estimate the real-world UF from the real-world fuel consumption $UF^{real} = 1 – FC^{real} / FC_{cs}^{real}$ with CS indicating charge sustaining mode. Here, $FC_{cs}^{real}$ is approximated by taking NEDC values with 50% addition for real-world driving: $FC_{cs}^{real} = 1.5\ FC_{cs}^{NEDC} = 1.5\ FC^{NEDC}/(1 – UF^{NEDC})$. In cases with very high real-world fuel consumption, this approach can lead to negative UF. We set the estimated UF to zero in these cases. If EPA values are available, we use EPA values for charge-sustaining-mode fuel consumption: $FC_{cs}^{real} = FC_{cs}^{EPA}$ . Likewise, when the real UF is known, the real-world consumption can be estimated by inverting the above equations: $FC^{real} = FC_{cs}^{real}(1 – UF^{real}) = 1.5\ FC_{cs}^{NEDC}\ (1 – UF^{real})$. For all WLTP cases with UF missing, NEDC fuel consumption values were available and the NEDC imputation procedure was applied.

We compared different approaches of estimating the UF from average fuel consumption. An alternative method takes the largest average fuel consumption of a larger sample of vehicles from one PHEV model and assumes this maximum is approximately equal to the charge-sustaining-mode fuel consumption. However, this method is applicable only with a sufficiently large number of vehicles observed per PHEV model and can also be biased when a sample is very large.

The method explained above is slightly optimistic as a 50% deviation from NEDC is slightly above the fleet average deviation for HEV (cf. Tietge et al., 2019), as we increase the denominator in the second term of $UF^{real} = 1 - FC^{real} / FC_{cs}^{real}$, thereby making UF larger. This uniformed approach can have different level of impact on data from different regions as the gap between real-world and NEDC fuel consumption has

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[3] 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 and conventional fuels are (mainly) used to keep the battery state-of-charge within a small window. In real operation, mixed and blended modes are also possible for some PHEVs.

been estimated the be 37% for the EU in 2014 and 25% in China (Tietge, Díaz, Yang, & Mock 2017). So, this 50% assumption likely enlarges the UF factor more for China than for EU. Finally, we compared the average UF estimated from both methods and obtained a mean UF of 40% from taking the largest in-sample fuel consumption as charge-sustaining-mode fuel consumption compared with the estimate from NEDC values, with a 50% increase for real-world driving in charge-sustaining mode leading to 39% average UF.

# 3. RESULTS: REAL-WORLD PHEV USAGE AND FUEL CONSUMPTION

Our analysis of real-world PHEV usage is divided into three parts. In the first part, section 3.1, average values and distributions for UF and fuel consumption are presented. In section 3.2, we then analyze the impact of vehicle properties, mainly all-electric range and system power, on the UF and fuel consumption. Lastly, section 3.3 provides information on how external factors at the individual level, such as long-distance driving, charging behavior, and ambient temperature, affect the UF and fuel consumption of PHEVs.

## 3.1. AVERAGE REAL-WORLD PHEV USAGE

In a first step, an analysis of the real-world usage of PHEVs is conducted. Real-world fuel consumption and UF are employed as main indicators for real-world usage. In descriptive analyses they are compared with test-cycle fuel consumption and test-cycle all-electric range. This gives a good first indication of potential factors influencing UF and real-world fuel consumption.

### 3.1.1. Fuel consumption compared with test cycle

We use the full sample to compare actual real-world fuel consumption with test-cycle values. Figure 1 shows the distribution of actual fuel consumption in relation to NEDC values.[4] The dashed vertical lines at 100% represent perfect agreement between actual and test cycle values.

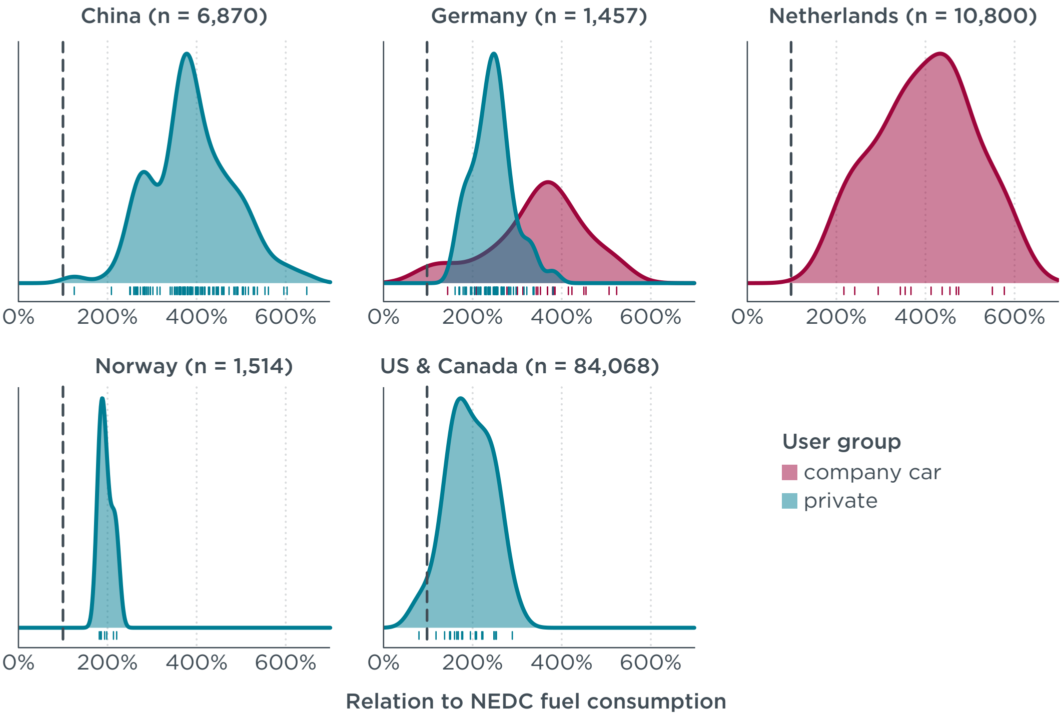

**Figure 1. Distribution of real-world fuel consumption in relation to NEDC test cycle**. Shown is the distribution by country. 100% (vertical dashed line) corresponds to real = test cycle. Private users in blue and company car users in red. Small rugs next to the x-axis indicate individual observations at PHEV model variant level. Total number of vehicles in the sample is included by country.

We observe a broad distribution of actual real-world fuel consumption values, much broader than for conventional combustion engine vehicles (Tietge et al., 2019). The average deviation from test-cycle values differs among countries, but on average, **real**

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[4] Data for the United States is only for PHEV models with NEDC fuel consumption available too (23 of 40 observations).

**fuel consumption is two to three times higher than the test-cycle values for private cars and three to four times higher for company cars.** Table 3 below summarizes the mean relation between actual and test-cycle fuel consumption, and thus $CO_2$ emissions. For private vehicles, the mean relation is 300%–340% (the range indicates the mean with two standard errors) and 135%–235% for the sample-size weighted mean.[5] The latter is noticeably smaller as North American vehicles—mainly the Chevrolet Volt, Toyota Prius, and BMW i3 REX, with small test-cycle deviation—dominate the full sample. For company cars, with data from Germany and the Netherlands, the deviation is even higher. The mean relation is 305%–395% and the sample-size weighted mean relation is 340%–410% (including two standard errors).

**Table 3. Overview of mean relation to NEDC fuel consumption**.
Range of relation includes two standard errors.

| User group | Mean relation | Sample-size weighted relation |
|---|---|---|
| **Private** | 300–340% | 135–235% |
| **Company car** | 305–395% | 340–410% |

For the country-specific analysis, the most recent data is from 2019 and 2020 for Germany and China. For both countries, the average gap between the official NEDC and real-world fuel consumption values for PHEVs of private owners is high. In China, the difference is 395% ±20% and in Germany, 247% ±13%. Those compare with 195% ±20% in the United States and 195% ±10% in Norway.[6] The particularly large deviation from test-cycle values for China is noteworthy. China has a much smaller share of the population living in detached or semi-detached houses, and fewer people have garages compared with Western Europe or North America (Li, Plötz, & Zhang, 2020). Accordingly, many PHEV users in China probably have no access to easy home charging. This is consistent with the low UF in China (see below).

Company car data is available only for Germany and the Netherlands, with greater sample sizes for the Netherlands. The distribution of real-world fuel consumption in Germany and the Netherlands for company cars is comparable though, with a peak of around 400%, or four times higher than according to the NEDC, with a broad distribution.

In Europe the NEDC has been replaced by the WLTP, which is assumed to more accurately reflect real-world fuel consumption. As the WLTP is rather new, the current PHEV stock is still dominated by NEDC models. Real-world PHEV usage data was available only for a limited number of WLTP models. Figure 2 shows the distribution of real-world fuel consumption as compared with test-cycle values for WLTP-certified PHEV models. The total number of vehicles in the sample is limited—137 vehicles for Germany and 150 for China—but general patterns are clear. Similarly to the NEDC models, the actual fuel consumption is four times higher in China and two times higher in Germany.

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[5] Individual model variants are represented in the data by varying numbers of observations. Thus, to ensure comparability of values on a model variant level (as represented in most graphs) the average values are sample-size weighted.

[6] All estimates are the unweighted mean ± two standard errors. The sample-size weighted result for China is 412% ±21%. The sample-size weighted result for Germany is 240% ±10%. The respective results for company cars in Germany are 350% ±45% for the unweighted mean and 375% ±34% for the weighted mean. The sample-size weighted result for the United States is 160% ±33% and for Norway 204% ±14%. For company cars in the Netherlands the unweighted mean is 400% ±58%.

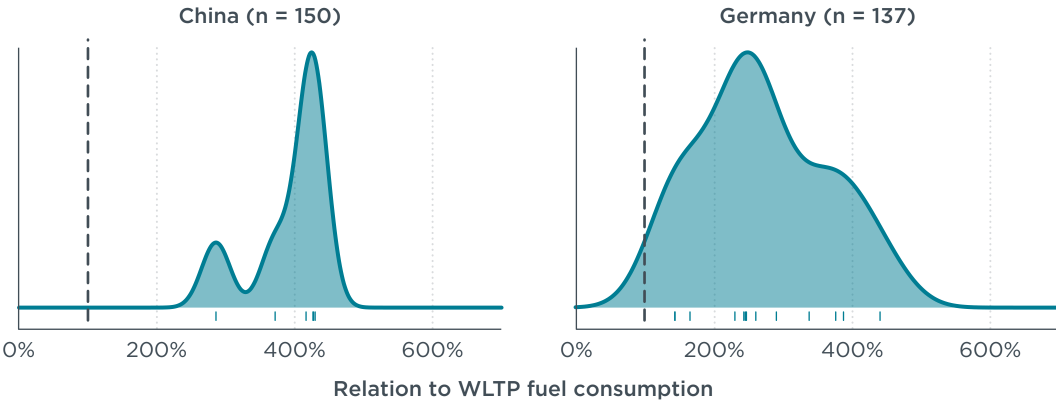

**Figure 2. Distribution of real-world fuel consumption in relation to WLTP test cycle**. Distribution by country. 100% (vertical dashed line) corresponds to real = test cycle value. Shown are only private users. Small rugs below the x-axis indicate individual observations.

The distribution of real-world fuel consumption is much broader for PHEVs than for ICEVs as the UF is an additional quantity that can vary substantially among individual vehicles. If the UF is fixed, the distribution is narrow, similar to fuel consumption distribution in combustion engine vehicles. Figure 3 demonstrates this effect for 10,304 Chevrolet Volt vehicles from the Voltstats.net sample. We take subsamples with approximately the same UF, allowing vehicle mean UF to fluctuate by only ±2 percentage points, and in Figure 3 show the distribution of real-world fuel consumption in liters/100 km for UF = 20%, 30%, and as high as 90%. For each UF we observe a narrow distribution of actual consumption, similar to conventional combustion engine vehicles (cf. Tietge et al., 2019).

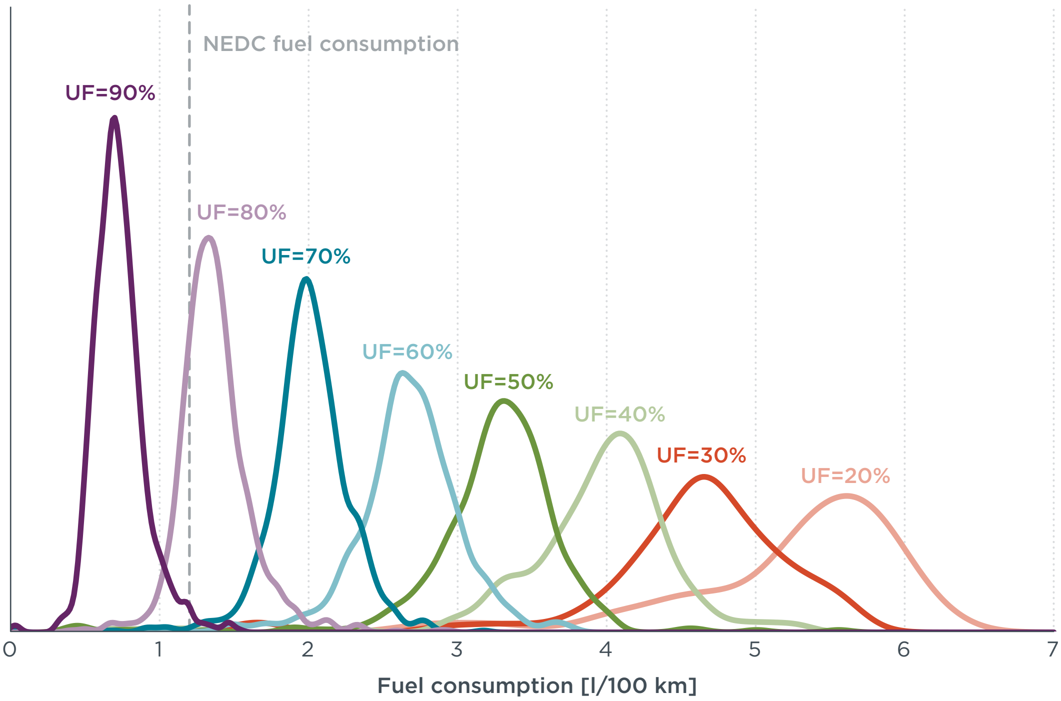

**Figure 3. Distribution of fuel consumption of Chevrolet Volt vehicles for fixed UF.** The distribution shows the average fuel consumption of Chevrolet Volt vehicles in the Voltstats.net database for fixed UF. Here, UFs have been rounded by ±2 percentage points, so UF = 80% are all vehicles with 78% < UF < 82%. The dashed vertical line indicates the NEDC fuel consumption of 1.2 l/100 km.

In summary, PHEVs in all countries in the sample show a clear deviation from test-cycle values, irrespective of the cycle. The range of deviations is much larger than for conventional combustion engine vehicles due to the large range of UFs.

### 3.1.2. Utility factors

A key indicator of PHEV usage and the potential environmental benefit is the share of kilometers driven on electricity, the UF. The UF is calculated as the total of electric kilometers divided by the total distance traveled by a vehicle.

Figure 4 shows the average UF as a function of all-electric range for all vehicles in the sample compared with UFs assumed by the NEDC and European WLTP test cycles.[7] Almost all average real-world UFs are below test-cycle values. In the sample, PHEVs with ranges below 60 km on the WLTP, or below 80 km on the NEDC, show particularly high deviation from test-cycle values. Long-range PHEVs in the sample tend to come closer to test-cycle values.

Comparing privately owned vehicles and company cars, we observe lower average UFs for a given range for company cars throughout the sample. Accordingly, the deviation from test-cycle UF is even higher for company cars.

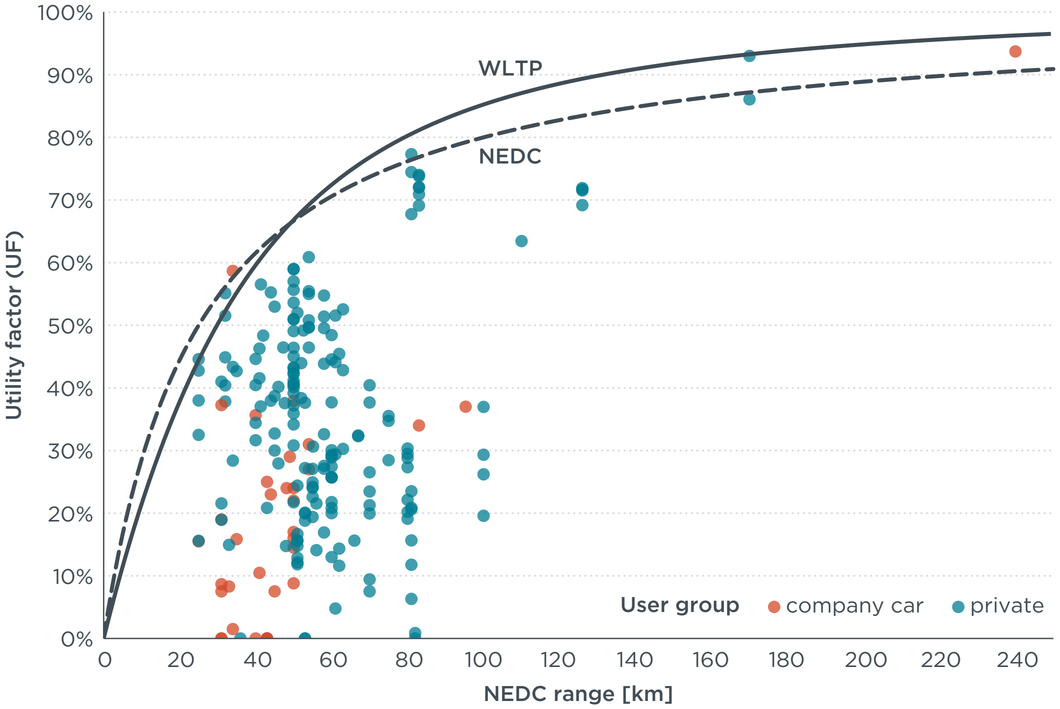

**Figure 4. Average utility factors (UFs) of all PHEVs in the sample versus all-electric range**. The all-electric range is given as approximate WLTP range where the WLTP range is assumed to be three-quarters of the NEDC range. Shown also are the WLTP UFs (solid line) and NEDC UFs (dashed line).

The deviation between average UF in the sample and test-cycle values shows noteworthy differences among countries (cf. Figure 5 and Table 4). It shows the largest deviation from test-cycle values in China and for company cars in the Netherlands but is closest to test-cycle values for privately owned vehicles in Norway and the United States. Furthermore, UFs in most countries show a tendency to increase with all-electric range, as expected.

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[7] The NEDC UF is $UF^{NEDC} = AER^{NEDC} / (AER^{NEDC} + 25\text{ km})$ where $AER^{NEDC}$ is the NEDC all-electric range. The WLTP UF in Europe is given by $UF^{WLTP} = 1 - \exp[-\Sigma_i = 1...10\ c_i(AER^{WLTP} / d_n)^i]$ where $AER^{WLTP}$ is the WLTP all-electric range and the numerical constants $c_i$ and $d_n$ for Europe are $d_n = 800$, $c_1 = 26.25$, $c_2 = -38.94$, $c_3 = -631.05$, $c_4 = 5964.83$, $c_5 = 25095$, $c_6 = 60380.2$, $c_7 = -87517$, $c_8 = 75513.8$, $c_9 = -35749$, $c_{10} = 7154.94$ according to (EC 2017).

Table 4 shows mean UFs according to the NEDC, actual mean UFs, and the mean of the ratio between real and NEDC UFs by country and user group.[8] Again, private vehicles in Norway and the United States come closest to the NEDC values, whereas the deviation is highest for private vehicles in China and for company cars. Globally, private vehicles achieve only about half the NEDC UF, and company cars only a third. As the UF curves for NEDC and WLTP are highly similar (Figure 4), similar deviations can be expected from WLTP UFs.

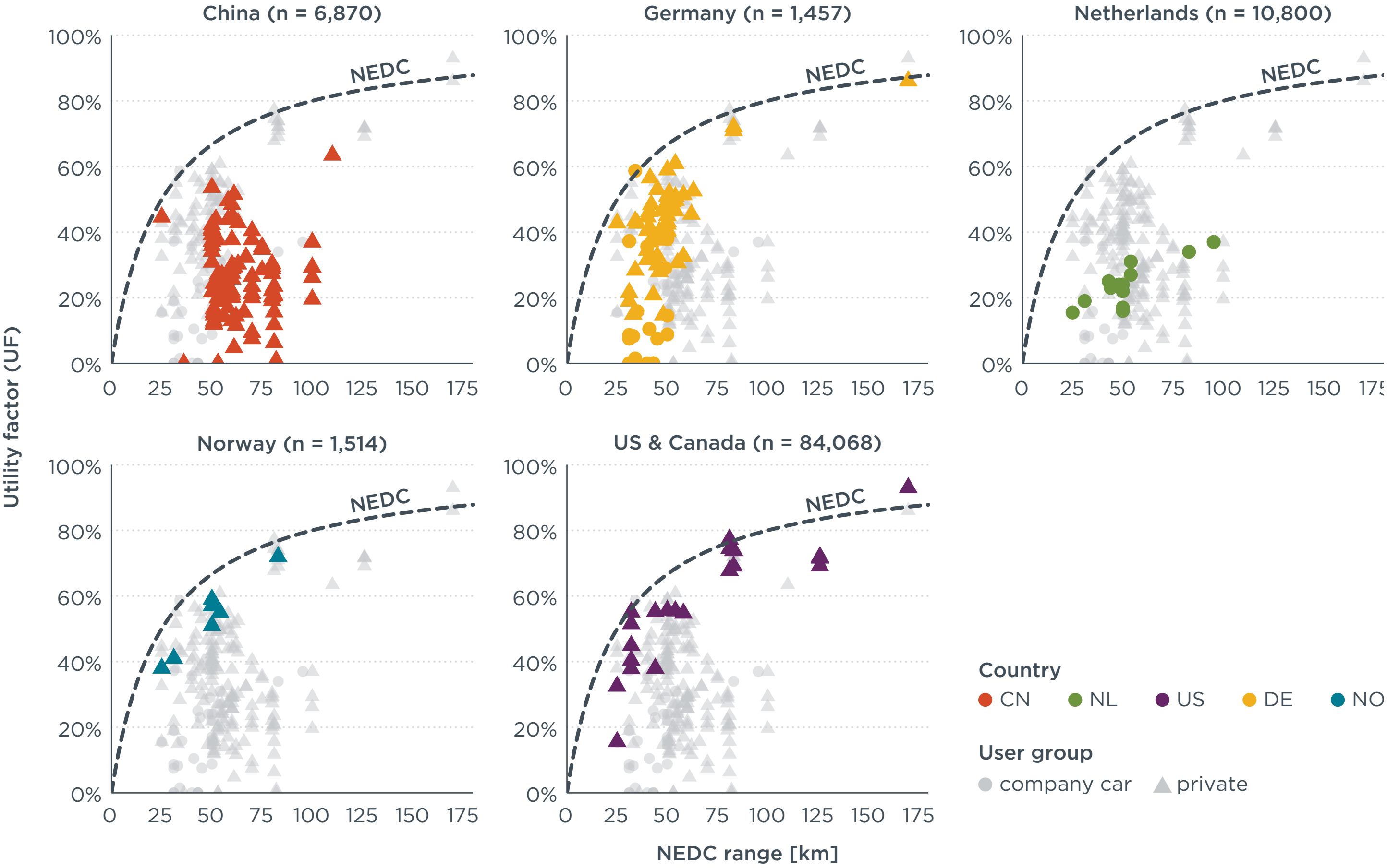

**Figure 5. Utility factors of PHEVs with different all-electric ranges by country.** The average specific UFs of individual PHEV model variants are shown as observed in our sample for private vehicles (small triangles) and company cars (small circles) with the NEDC UF (dashed line). Total number of vehicles in the sample is included by country. The grey dots are the full sample, and each small plot emphasizes the data from one country by country-specific color.

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[8] Note that the mean of the ratio is shown and not the ratio of the means. Sample-size weighted averages are missing for the Netherlands as vehicle individual sample size was not available for company cars in the Netherlands.

**Table 4. Overview of mean UF and relation to NEDC UF by country and user group**. Shown are means and sample-size weighted means for the NEDC UF, the actual UF and the mean relation between actual and NEDC UF.

| Country | User group | Means | | | Sample size weighted means | | |
|---|---|---|---|---|---|---|---|
| | | $UF^{NEDC}$ | $UF^{real}$ | $UF^{real}/UF^{NEDC}$ | $UF^{NEDC}$ | $UF^{real}$ | $UF^{real}/UF^{NEDC}$ |
| **CN** | Private | 71% | 26% | 37% | 72% | 25% | 34% |
| **DE** | Private | 65% | 43% | 65% | 66% | 47% | 71% |
| **NO** | Private | 64% | 53% | 82% | 67% | 55% | 82% |
| **US** | Private | 69% | 54% | 80% | 76% | 69% | 90% |
| **All** | Private | 69% | 37% | 54% | 75% | 65% | 86% |
| **DE** | Company car | 62% | 18% | 27% | 60% | 12% | 19% |
| **NL** | Company car | 65% | 24% | 36% | - | - | - |
| **All** | Company car | 63% | 20% | 31% | - | - | - |

Some country-specific effects can partially be explained by country-specific factors and the data sources. For the United States, only private vehicles are in the sample, and many of the observations are from early adopters who purchased their PHEVs some years ago when PHEVs were still quite uncommon. These users are expected to have been more likely to purchase a PHEV only if they had an option to recharge the vehicle regularly. In addition, 21 of the 23 PHEV model variants in our U.S. sample are Chevrolet Volt, BMW i3, and Toyota Prius PHEVs. Those are probably preferred options for vehicle buyers with above-average environmental concerns and tend to be frequently charged. Lastly, the information on all-electric ranges and realistic fuel consumption stems from EPA testing, which is closer to real-world values than the NEDC (Tietge et al., 2017). Accordingly, PHEV users in the United States are more likely to buy a PHEV that actually fits their range requirements.

In Norway, battery electric vehicles receive higher incentives than PHEVs, so PHEVs are probably not bought mainly to benefit from the lower purchase price or taxation as could be the case for company cars, but only if the users intend to use them appropriately. In addition, Norway has low electricity prices and high gasoline prices, making electric driving particularly attractive from an economic point of view. Furthermore, a small additional effect could come from the comparative ease of public charging in Norway, as there is a single card that enables charging at almost all public charging points across the country (Figenbaum & Kolbenstvedt, 2016).

The mean UFs in China show a large variation even for a fixed range and only a slight tendency to increase with range. Chinese authorities monitor the real-world performance of PHEVs, but there is no enforcement or regulation that effectively encourages car owners to increase electric driving or charging, and there are no requirements on how frequently PHEV users should charge their vehicles. Furthermore, the lower availability of garages and private parking spots in China makes it more likely that PHEV users lack a regular night-charging option (Li et al., 2020). The restrictions on driving and purchase of conventional-fuel vehicles in first- and second-tier cities such as Beijing, Shanghai, and Hangzhou make PHEVs highly attractive irrespective of actual usage. When purchasing PHEVs in Shanghai, proof of having charging conditions is required, which can be domestic charging points or public charging points at workplaces.[9] No further measures are provided to ensure that car-owners charge their vehicles. According to the findings of the “2019 Shanghai New Energy Vehicles Big Data Research Report,” (Eefocus.com, 2019) most PHEV users charge their vehicles only one or two days a week, regardless of their weekly mileage.

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[9] At present, self-owned brands occupy an absolute dominant position in China’s PHEV market. Among them, BYD and SAIC passenger cars account for a larger share of the market. Due to local protectionism, Shanghai has the largest number of PHEVs in China.

Many PHEVs show high daily kilometers traveled (Eefocus.com, 2019). In summary, consumers' motivations for purchasing PHEVs mainly include the government's preferential policies and low dependence on charging. In the case of inconvenient charging, PHEVs will be used more directly as conventional-fuel cars.

The Netherlands had high incentives for PHEVs as company cars from 2012 to 2016, leading to a strong sales increase in PHEVs for company cars. However, no additional incentives for company car charging were enacted. Instead, many PHEV company car users in the Netherlands still have fuel cards that allow free refueling, while they have to pay privately for charging their PHEVs at home. All PHEV users within the Dutch sample are in possession of a fuel card (van Gijlswijk & Ligterink, 2018). Because of these common financial disincentives, many PHEV company car users simply did not frequently charge their PHEVs, resulting in particularly low UFs.

Lastly, for Germany the data is quite recent, mainly from 2019 and early 2020. Home charging should not be a problem in Germany for the vast majority of PHEV users as about three-quarters of passenger cars in Germany are parked in private garages or car ports overnight (MiD, 2018). The proportion may be even higher for PHEV owners reflecting higher household incomes required for covering higher costs of PHEVs. (Plötz, Schneider, Globisch, & Dütschke, 2014b; Frenzel, Jarass, Trommer, & Lenz, 2015). Company car users in Germany, on the other hand, have similar financial disincentives as those in the Netherlands. Although they receive a tax benefit if they use a PHEV, it is not conditional on electric driving, and many can be expected not to pay for conventional fuel as in the Netherlands.

In summary, **real-world UFs are typically only half the test-cycle values for private vehicles and are even lower for company cars**. Yet some private users achieve as much as 80% of the test-cycle UF, and users in Norway and the United States in our sample are closer to test-cycle UF compared with other countries.

### 3.1.3. Annual electric mileage

The environmental benefit of PHEVs depends not only on the share of kilometers driven on electricity but also on the total annual number of electric kilometers, as this determines the amount of conventional fuel saved in comparison with driving conventional combustion-engine cars. Annual mileage data in our sample is available for vehicles in Germany and the United States.

Figure 6 shows the annual electric mileage for PHEVs in Germany and the United States where annual mileage information is available as a function of NEDC all-electric range. Also shown is a local regression, the shaded area, that indicates how the expected annual electric mileage increases with all-electric range. **Most PHEVs in the sample have NEDC ranges between 30 km and 60 km with annual electric mileage around 5,000–10,000 km, which increases with range. PHEVs with high all-electric ranges of 80 km or more[10] achieve 12,000–20,000 km mean annual electric mileages.** Those values are comparable to the mean total annual mileage of the car fleet in Germany, or about 14,000 km a year, and in the United States, or about 21,700 km a year (see below). The high mean annual electric kilometers despite low UFs are possible due to high annual mileages of PHEVs (see section 3.3.1 below). The same results hold when annual electric mileage is analyzed separately for PHEVs and range-extended electric vehicles (see appendix).

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[10] These long-range PHEVs are technically also known as range-extended electric vehicles, such as the Chevrolet Volt, Opel Ampera, and BMW i3 REX. They show much lower deviation between actual and test-cycle UF than other vehicles in the sample and data from other countries.

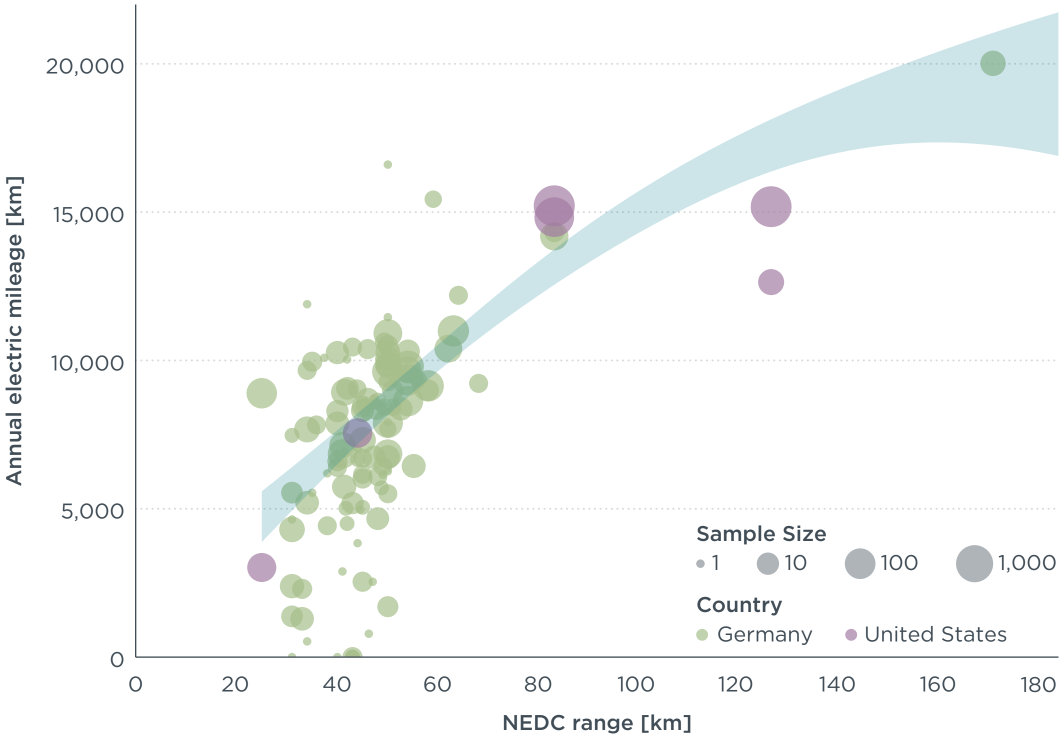

**Figure 6. Annual electric mileage by NEDC range**. Mean annual electric mileage by PHEV model variant for the United States (squares) and Germany (circles). Every data point corresponds to a PHEV model mean with different sample sizes (indicated by the size of the symbol). The shaded area is a sample-size weighted local smoother (95% confidence bands of generalized additive model).

In summary, we observe a clear expansion of annual electric kilometers with increasing NEDC range. Long-range PHEVs can achieve as many as 15,000 km of annual electric distance. This is consistent with earlier findings (Plötz, Funke, Jochem, & Wietschel, 2017).

## 3.2. IMPACT OF VEHICLE PROPERTIES: ALL-ELECTRIC RANGE AND SYSTEM POWER

The comparability of different PHEVs is limited. Not only the all-electric range but also the engine size and power influence fuel consumption and direct $CO_2$ emissions, since they affect fuel consumption during nonelectric driving mode. High power also acts as a proxy for high vehicle mass (Plötz, Funke, & Jochem, 2018a) and is assumed to increase the likelihood of more aggressive and thus fuel-consuming driving. Likewise, different user groups may have different driving and charging behaviors, and different countries could have different charging infrastructure and other framework conditions. In the present section, we analyze the effects of different vehicle properties while controlling for user group and country effects.

As a background to the impact of range, Figure 7 shows the all-electric ranges of PHEVs, differentiated by the date of model introduction. Focusing on those vehicle models introduced since 2018, most NEDC-certified PHEVs had 30–50 km of all-electric range with a tendency toward 50 km. For WLTP-certified PHEVs, all-electric ranges are 40–50 km, with an increasing tendency. However, both NEDC and WLTP ranges do not correspond to average real-world ranges (Dornoff, Tietge, & Mock, 2020).

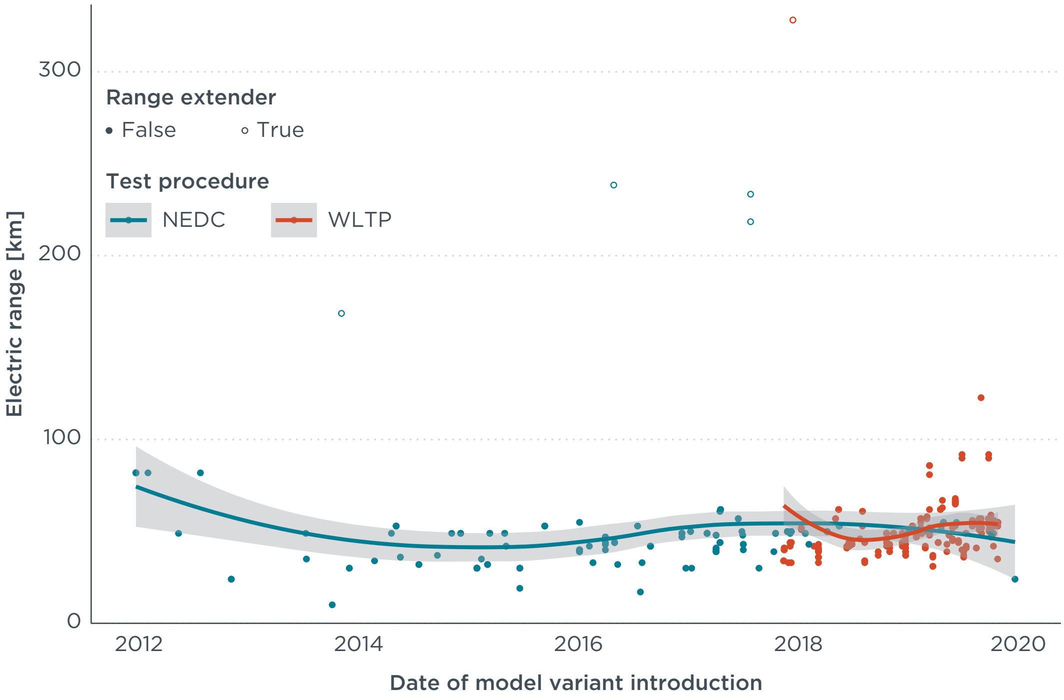

**Figure 7. All-electric range of PHEV models by date of model variant introduction**. Small circles indicate individual model variants with NEDC ranges in blue and WLTP ranges in orange. The solid lines are local regression plot smoothers.

### 3.2.1. Methodology

To separate the effect of different levels of vehicle power and all-electric range, we regress the actual fuel consumption and UF on vehicle power and all-electric range. The aim of the regression analysis is to quantify the effect size and to separate the effects of vehicle range and power in our sample of PHEV models. As the different subsamples have very different sample sizes and cover different models, we compare sample-size weighted and unweighted regression models including user group and country as control variables. The regression model details are given in the appendix.

The data for the present section is the full sample as range and system power are available for all models.

### 3.2.2. Results

We start with the effect of system power and all-electric range on fuel consumption and thus tail-pipe $CO_2$ emissions. For all-electric range we use the NEDC range as it is readily available for almost all models. System power, or combustion engine power plus electric motor power, is measured in kW.[11] System power is used as a proxy for engine displacement, weight, and model-specific aggressiveness of driving. Table 5

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[11] Strictly speaking, the system power is the maximal power available for propulsion. For most PHEV models, this is the sum of engine and electric motor power. Yet, for some vehicles, notably range-extended electric vehicles such as the Chevrolet Volt or the BMW i3 REX, the engine is not directly used for propulsion but to charge the battery, so the system power is smaller than the sum of engine and electric motor power.

summarizes the impact of range and power on fuel consumption.[12] The regression results show relatively high goodness of fit (adjusted $R^2 > 0.8$).

**Table 5. Factors impacting real-world average fuel consumption**. Range of effects according to aggregated data sources and regression analysis. Changes are in percent around expectation values and controlled for user group and country-specific effects.[13]

| | Change in expected fuel consumption |
|---|---|
| **+10 km all-electric NEDC range** | -8% to -14% |
| **+10 kW system power** | +2.5% to +3.5% |

Controlling for user group and country-specific effects, we find that **a 10 km increase in NEDC all-electric range decreases the fuel consumption by 8%–14%** with all other parameters fixed. The range of the estimate includes a 95% confidence interval from the regression. Within the range of our data, fuel consumption and thus direct $CO_2$ emissions are reduced by 1.1% with each additional kilometer of range, so for every 63 km of all-electric range the direct fuel consumption and direct $CO_2$ emissions are halved, with 50–87 km as the 95% confidence interval.

As most PHEV models have about 50 km of NEDC all-electric range, a 20% increase in range, corresponding to 10 km, leads to a decrease of 8%–14% in fuel consumption. Conversely, **an increase in system power by 10 kW leads to an increase in fuel consumption of about 3%**. System power in the PHEV models in our sample covers a range of 90–674 kW with a mean of 225 kW. So a 20% increase in system power—45 kW—would lead to an increase in fuel consumption of 11%–16%, keeping all other factors constant.

A positive effect of range on fuel consumption is expected as longer ranges imply more electric driving and less use of combustion engines. But the effect of system power is also comparatively strong in terms of percentage change. The effect of system power is also clearly visible in an analysis of the mean fuel consumption by range and system power in Figure 8. Between 25 km and 70 km of all-electric range, little impact of the range is visible, though it can be detected statistically, but higher power clearly leads to higher fuel consumption.[14]

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[12] Since fuel consumption is strictly non-negative, we use an exponential function for the effect of range and power and control for user group and country-specific effects with the following regression model $FC^{real} = \exp(\beta_0 + \beta_1 Power + \beta_2 range + \beta_3 usergroup + \beta_4 country) + \varepsilon$. Here, the system power (Power) in kW, has been used as a proxy for engine displacement, weight, and model-specific aggressiveness of driving. The chosen dependence on all-electric range and power are: For range→0, the fuel consumption approaches a finite value (i.e. the fuel consumption in the charge-sustaining mode) and is decreasing to zero for range→∞ (i.e. a negative $\beta_2$). Likewise, the fuel consumption approaches zero for Power→0 and grows with increasing power (i.e. positive $\beta_1$). The regression is performed after taking logarithms of the above equation In $(FC^{real}) = \beta_0 + \beta_1 Power + \beta_2 range + \beta_3 usergroup + \beta_4 country + \varepsilon$ by ordinary least squares. The model itself and all coefficients are significant ($p < 0.05$) and the coefficients have the expected signs ($\beta_1 > 0$ and $\beta_2 < 0$). The details are given in the appendix.

[13] We controlled for user group and country. Results for range and system power are highly significant ($p<0.01$). Reference categories for categorical variables are “private” for user group and “Germany” for country. Change is not significantly different from zero for Norway and the United States. The effect of company cars is between +10 and +50%; the effect of China as compared with Germany is between +35 and +55%; and for the Netherlands, between +10 and +30%.

[14] As every circle in the figure corresponds to one PHEV model variant and the highest number of different PHEV model variants is present in the Chinese Xiao Xiong You Hao sample, models in use in China dominate the figure in terms of high fuel consumption and high number of models. More important than the visual impression are the statistically significant regression results below, which also control for country-specific effects.

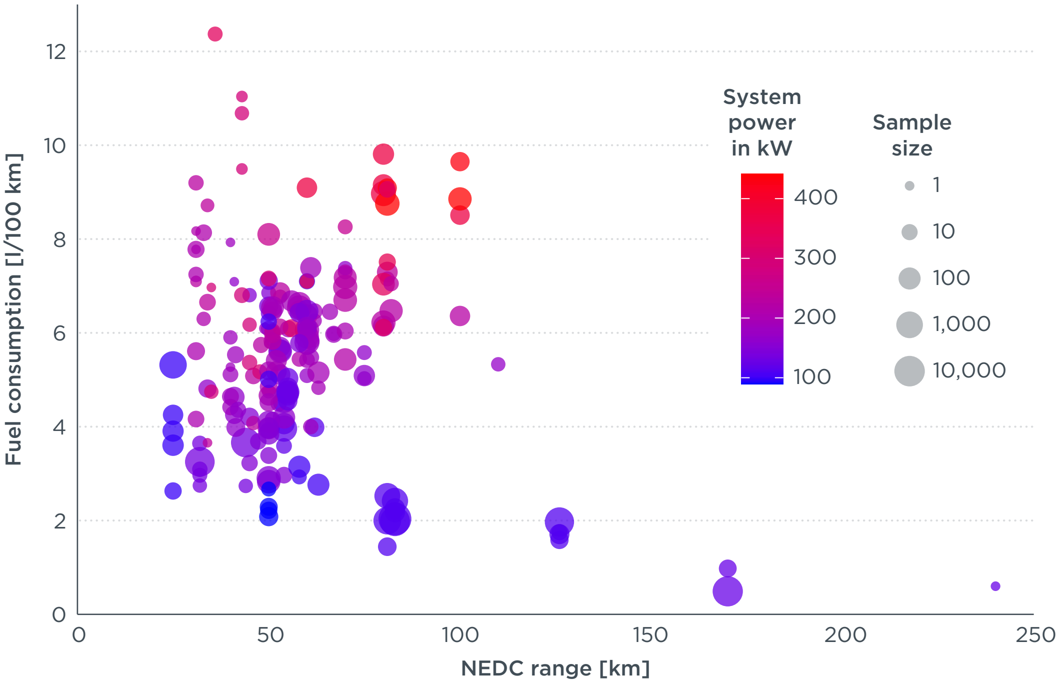

**Figure 8. Fuel consumption of PHEVs by range and system power**. The average fuel consumption of PHEV model variants is shown as circles with the size of the circle indicating the sample size and the color indicating the system power (from low in blue to high in red). The full sample of all countries and user groups is included.

As the UF shows country-specific effects, we also analyze the impact of range on fuel consumption by country in Figure 9.[15] Consistent with the country-specific UF results, we observe high fuel consumption for private vehicles in China and company cars in the Netherlands. Yet, all other countries clearly show the effect of decreasing fuel consumption with increasing all-electric range.[16]

The model-variant average fuel consumption is also determined by the model-variant average UF. We show the effects of increase in range or system power in Table 6.[17]

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[15] The regression results above already control for country-specific effects as the countries have been included as control variables.

[16] A comparison of selected PHEVs and corresponding ICEVs showed a 95% higher fuel consumption of ICEVs. We used the Mitsubishi Outlander, VW Golf GTE, VW Passat GTE, BMW 225xe, and Audi A3 e-tron for comparison. These were the five PHEV models with the highest sample size in the Spritmonitor.de data with a respective ICEV not having mild-hybrid function and a sample size of 10 of more. We selected the appropriate ICEV model according to the PHEV model's first build year and system power in hp (with a range of ±20 hp to account for inaccurate database entries).

[17] The regression contains the same explanatory factors as before (range, power, user group, and country), but the dependent variable is the UF. As the dependent variable is a percentage, we perform fractional logit regression, and the table shows so-called marginal effects at mean.

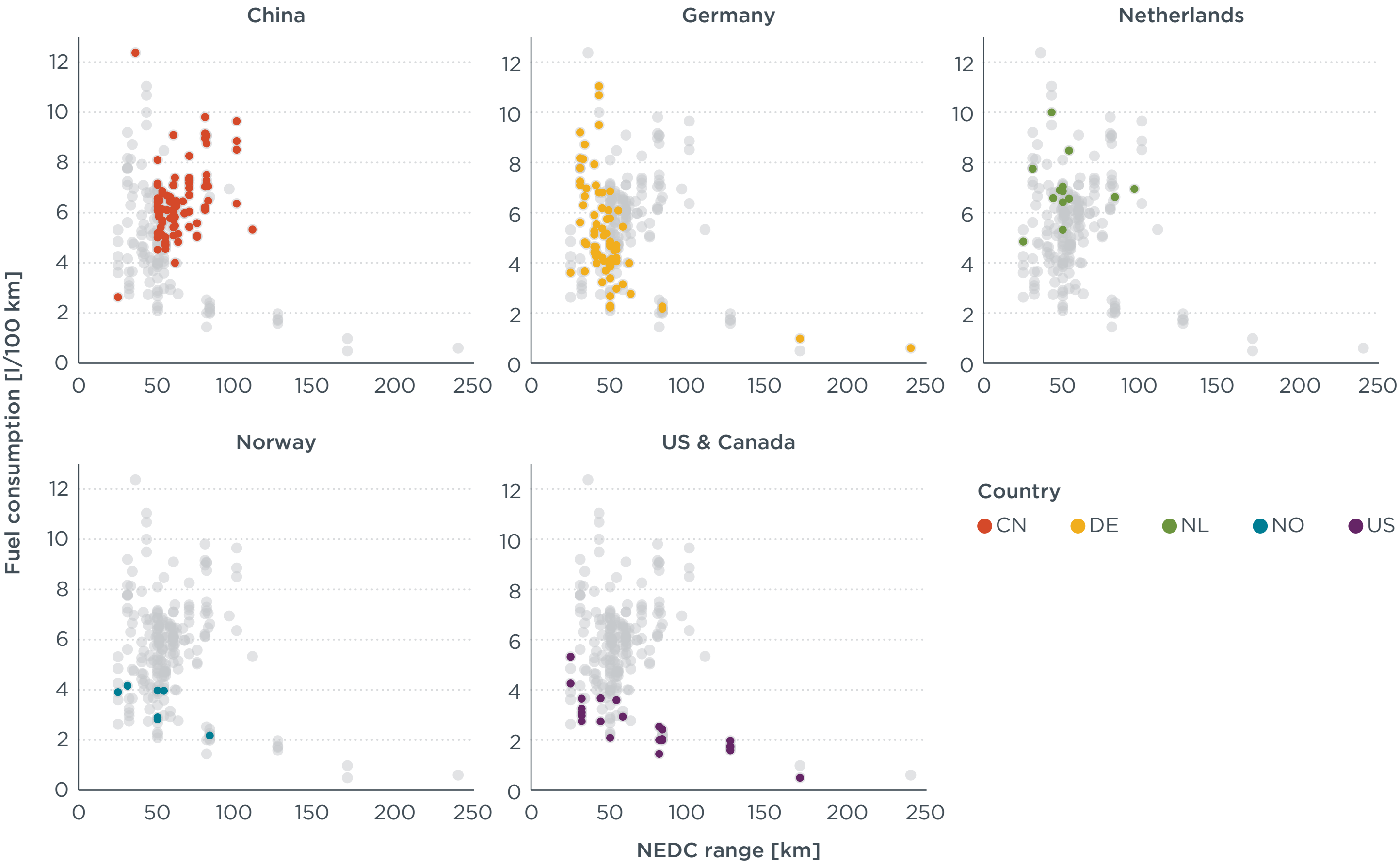

**Figure 9. Fuel consumption by range and country**. The average fuel consumption values of PHEV model variants are shown as colored circles. The grey dots are the full sample, and each small plot emphasizes the data from one country by country-specific color. The full sample of all countries and user groups is included.

**Table 6. Factors impacting average UF**. Range of effects according to aggregated data sources and regression analysis. Changes are in percentage points around mean values.[18]

| | Change in expected UF in percentage points |
|---|---|
| **+10 km all-electric NEDC range** | +3 to +5 percentage points |
| **+10 kW System power** | -1 to -3 percentage points |

As expected, the results indicate that higher all-electric ranges lead to higher UFs. More specifically, **an increase in NEDC all-electric range by 10 km leads to an increase in UF of 3–5 percentage points** at a 95% confidence interval. On the other hand, **an increase in system power by 10 kW leads to a reduction in expected UF by 1–3 percentage points**. The results for range are consistent with adding annual mileage as control variable (see section 3.3.1 below), but the effect of system power is slightly smaller when annual mileage is included, by -½ to -1 percentage point).

The decrease in UF from increasing system power might be surprising as the all-electric range should be the main vehicle attribute impacting the share of electric driving. However, vehicles with small electric motor power and higher combustion engine power tend to be programmed and used differently. As extreme examples, a range-extended electric vehicle could have a very small combustion engine power sufficient

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[18] Reference categories for categorical variables are "private" for user group and "Germany" for country. Company cars have 10 to 30 percentage points lower UFs compared with private vehicles. PHEVs in China have 10–30 percentage points lower UFs than in Germany and PHEVs in Norway have 4–12 percentage points higher UF. The change in UF is not significantly different from zero for the Netherlands and the United States.

to charge the battery during driving with the engine programmed to start only in cases of empty battery. Compare this with the case of a sports-type vehicle where the electric motor is used to provide additional torque and acceleration. Such a vehicle would have very high system power and high fuel consumption as the combustion engine would have high displacement and would be used often. Additionally, such vehicles are more likely to be driven by users with sportive or aggressive driving styles, further increasing real-world fuel consumption.

**In summary, increasing all-electric range decreases fuel consumption and leads to increasing UFs. On the other hand, system power has a smaller but significantly negative effect on fuel consumption and UF.**

## 3.3. ANALYSIS OF INDIVIDUAL USER BEHAVIOR

Not only PHEV model-specific factors impact the fuel consumption of PHEVs, but also external and user-specific factors. The present section analyzes the effects of annual mileage and long-distance driving (section 3.3.1), the difference between private and company car users (section 3.3.2), the impact of charging on the UF (section 3.3.3), and the impact of ambient temperature (section 3.3.4). The aim in each section is to quantify the effect of these factors on the UF and thus PHEV fuel consumption.

### 3.3.1. Impact of long-distance and annual driving

Frequent long-distance driving leads to lower UFs if other factors such as annual mileage and charging overnight are kept constant as the battery will be depleted on longer tours. Thus, frequent long-distance travel can have a noteworthy impact on average UF. High annual mileage is correlated with more frequent long-distance travel. The aim of the present section is to measure the effect of annual mileage on the mean UF and mean fuel consumption as well to indicate typical frequencies for long-distance travel in conventional car and PHEV usage.

#### Data and method

We use all PHEV data sources mentioned in section 2 that contain information on annual mileage either on an individual-vehicle level or on a model-aggregated level. This includes Spritmonitor.de; Voltstats.net; the UC Davis data; MyMPG; Xu, Hewu, and Minggao (2016); Figenbaum and Kolbenstvedt (2016); CARB (2017); INL (2014); Raghavan and Tal (2020); Smart, Bradley, and Salisbury (2014); and the German company car data.

We compare average annual VKT of PHEVs in Germany and the United States with car stock averages in these countries. For PHEVs in all countries, regression analysis on an individual-vehicle level and model averages are used to measure the impact of annual VKT on average UF and average fuel consumption.

#### Average annual mileage

Table 7 shows the average and standard deviation of annual mileage in kilometers by country and brand in the sample. The uncertainty of the average is given by the standard error, or the standard deviation divided by the square root of sample size. Accordingly, the standard errors for most of the brands covered in the table are less than 1,000 km.

The average annual mileage in the German PHEV sample is 21,400 km, or about 46% higher than the average mileage of about 14,700 km for the German vehicle stock (MiT, 2017). When separating the PHEV sample by private and company-car ownership, it can be seen that the annual mileage of company-car PHEVs at 30,200 km is similar to the average for conventional company cars at 30,700 km. For private PHEVs, the annual mileage of 20,950 km is higher than the average for conventional private cars of 14,700 km (MiT 2017).[19]

For U.S. and Canada PHEVs, the mean is 22,000 km and thus only marginally above the overall U.S. average of 21,700 km (FHWA, 2020). For Norway, the mean annual mileage of PHEVs is similar to the national car fleet average and between 12,000 km and 16,500 km per year (Feigenbaum & Kolbenstvedt, 2016).

Since PHEVs in Germany show higher annual mileage than the German average, they are likely to show more frequent long-distance driving resulting in lower UFs than expected from simulation of the German passenger car stock in section 3.3.3. The high annual mileage of PHEVs in Germany can lead to lower UFs than expected from the NEDC and WLTP test cycles as the test cycles are designed to cover European car fleet averages.

**Table 7. Average and standard deviation annual kilometers traveled by PHEVs in Germany and the United States by brand**. Shown are average (mean) and standard deviation (SD) by country and PHEV brand with the number of PHEVs in the sample and the number of models covered by brand.

| Country | Brand | Sample | # Models | Average annual km | SD annual km |
|---|---|---|---|---|---|
| **Germany** | Audi | 90 | 1 | 18,800 | 7,800 |
| **Germany** | BMW | 227 | 5 | 20,400 | 9,600 |
| **Germany** | Chevrolet | 5 | 1 | 19,500 | 9,700 |
| **Germany** | Hyundai | 97 | 1 | 21,500 | 9,200 |
| **Germany** | Kia | 144 | 3 | 19,600 | 9,800 |
| **Germany** | Mercedes | 107 | 10 | 27,800 | 11,800 |
| **Germany** | Mini | 40 | 1 | 19,100 | 7,600 |
| **Germany** | Mitsubishi | 316 | 1 | 20,200 | 10,300 |
| **Germany** | Opel | 39 | 1 | 20,800 | 10,800 |
| **Germany** | Porsche | 16 | 5 | 19,600 | 5,900 |
| **Germany** | Toyota | 117 | 1 | 21,900 | 10,300 |
| **Germany** | VW | 229 | 2 | 20,800 | 10,500 |
| **Germany** | Volvo | 133 | 8 | 26,000 | 11,500 |
| **U.S./Canada** | Chevrolet | 10‘152 | 1 | 21,970 | 10,200 |
| **U.S.** | Ford | 31 | 1 | 24,200 | 11,200 |
| **U.S.** | Toyota | 16 | 1 | 23,700 | 11,500 |
| **TOTAL** |  | **11,759** | **41** | **21,900** | **10,300** |

### Effect of annual mileage on UFs

To demonstrate the effect of annual mileage on UFs, Figure 10 and Figure 11 show the relation between UF and annual mileage as scatter plots for individual vehicles. We generally observe a large range of UFs even for fixed annual mileage. This is mainly for two reasons (Plötz et al., 2018b). First, the same annual mileage can be achieved with highly different distributions of daily kilometers traveled. For example, driving almost the same short distance every day or making only a few long-distance trips a year can result in the same total. Second, the UF is influenced by user charging behavior.

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[19] Interestingly, the annual mileage of private and company-car PHEVs in our sample resembles the averages for private diesel cars of 20,100 km and company diesels of 33,000 km. By comparison, mileage for private gasoline vehicle is 12,400 km and for company gasoline cars, 24,400 km. Correcting for vehicle age does not change the picture much as the average annual mileage for private vehicles up to four years old in Germany is 15,600 km compared with 14,000 km for older vehicles (MiT 2017). Company cars up to four years old drive about 32,000 km a year compared with 24,400 km for older company cars.

The local mean for given annual mileage (solid line in Figure 10) shows the overall trend of UFs with changing annual mileage. For the given vehicle, a Chevrolet Volt / Opel Ampera with about 80 km of NEDC range, the UF of PHEVs with 10,000 km of annual mileage is about 80% and decreases by about 6 percentage points with every 10,000 km of annual mileage. This leads to an average UF of about 60% for PHEVs with 40,000 km of annual mileage and a UF of about 30% for 80,000 km of annual mileage.

Similar trends can be observed for other PHEVs, including the BMW 225xe, Audi A3 e-tron, VW Golf GTE, Hyundai Ioniq PHEV, Kia Niro, Mitsubishi Outlander, VW Passat GTE, and Toyota Prius PHEV. There is a large range of individual UFs for given annual mileage but a clear decrease in average UFs with increasing annual mileage for all models.

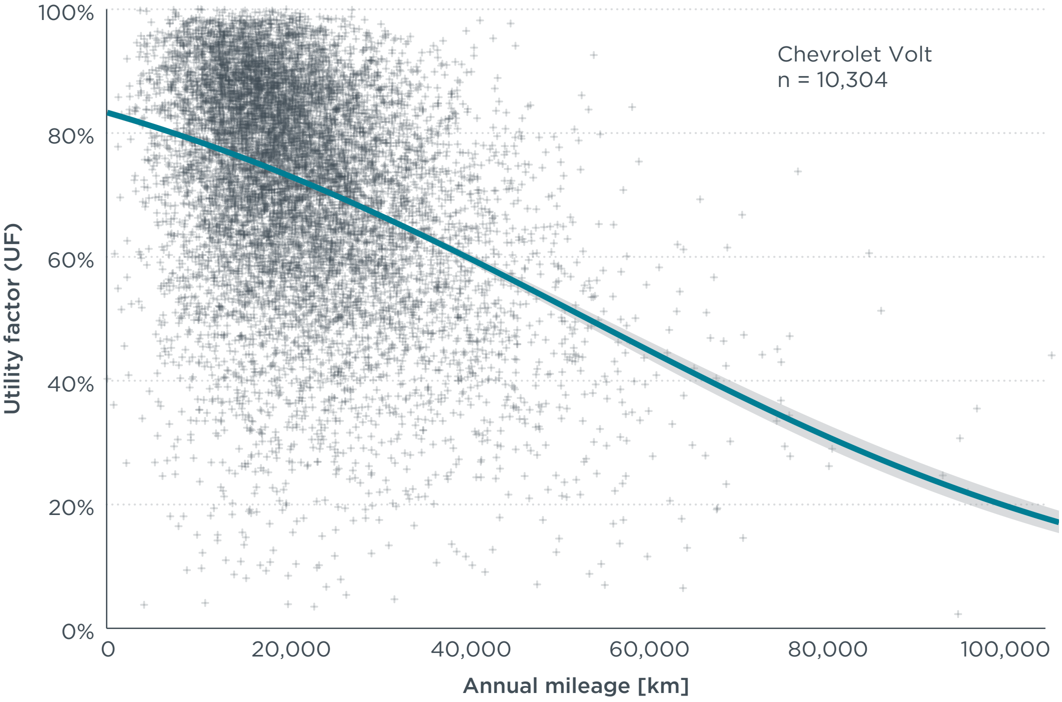

**Figure 10. UF versus annual mileage for Chevrolet Volt PHEV.** The individual UF is shown against annual vehicle kilometers traveled for more than 10,000 individual Chevrolet Volt vehicles (small crosses) together with local mean values for given annual mileage (solid line) including 95% confidence interval (shaded area).

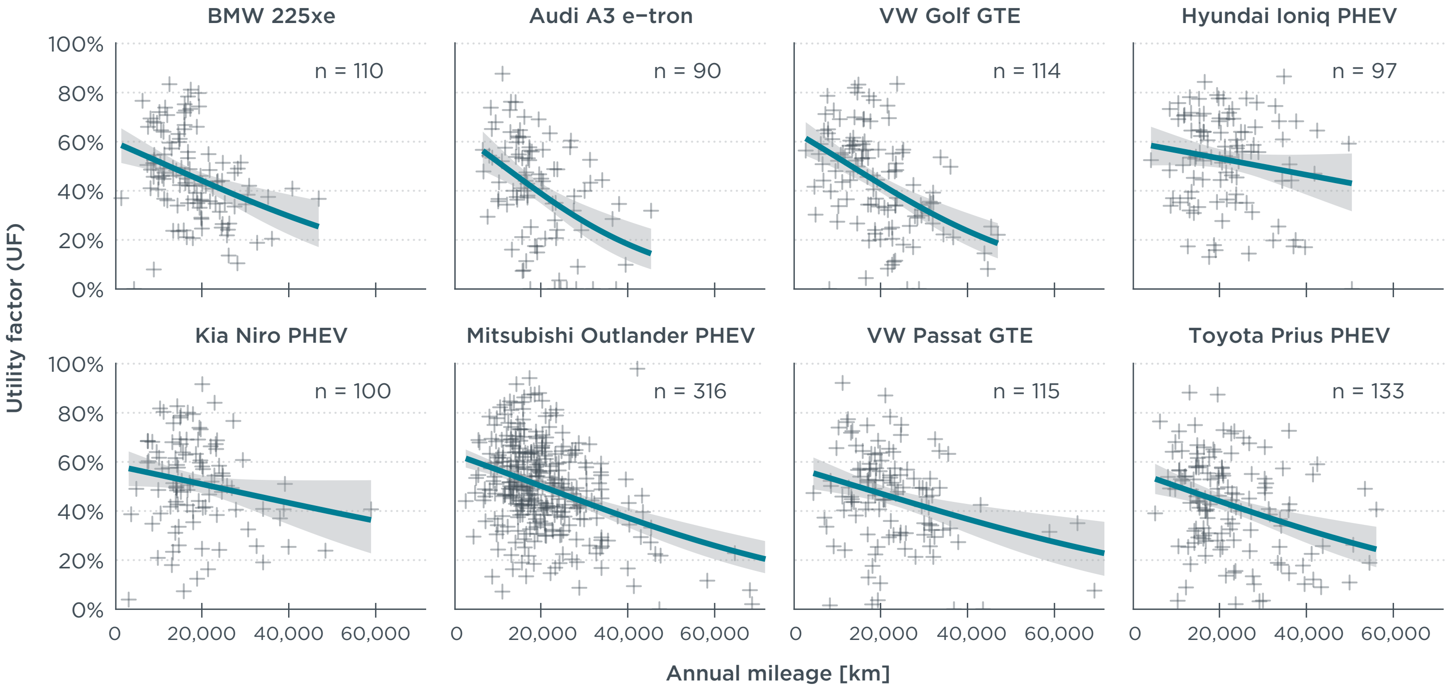

**Figure 11. UF versus annual mileage for different PHEVs.** The individual UF[20] is shown against annual vehicle kilometers traveled for several individual vehicles (small crosses) together with local mean values for given annual mileage (solid line) including 95% confidence interval (shaded area).

**Table 8. Typical change in UF when changing mileage, range, or system power.** Shown are changes in percentage points when keeping all other variables at mean values. The ranges include two standard errors.[21]

| Variable | Change in UF in percentage points |
|---|---|
| **+1,000 km annual mileage** | −0.55 to −0.71 |
| **+10 km all-electric range** | +3 to +5 |
| **+10 kW system power** | −0.5 to −1.0 |

Regression analysis for individual vehicle data has been performed to calculate the effect of annual mileage on UF. Table 8 shows the average change in UF when changing annual mileage while controlling for all-electric range, system power, user group, and country. **We observe a clear decrease of the UF by about 0.6 of a percentage point with every 1,000 km above average**. Accordingly, if the 21,000 km annual mileage of private PHEVs in Germany were similar to the 14,700 km average for all private passenger cars (MiT, 2017), the UF would be 3.5–4.5 percentage points higher, leading to an average UF of around 47% instead of the current 43%.

## Frequency of long-distance driving

Not only the average annual mileage but also the distribution of daily kilometers traveled is important for the share of electric driving. This leads to the frequency of long-distance travel and its role in annual distance traveled. Longitudinal travel data with several days of observation is required to understand the impact of a few long-distance events on annual mileage. We analyze the Voltstats.net PHEV driving data and driving data of the German Mobility Panel (MOP, 2010), for which data was collected

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[20] Some PHEVs show a UF of zero, which is due to the methodology used for the determination of UF (see section 2.3). PHEVs having real-world fuel consumption greater than 150% of the NEDC charge-sustaining fuel consumption are assumed to have a UF of zero.

[21] The underlying regression models can be found in the appendix. We also controlled for user group and found that private users had 20–30 percentage points higher UFs than company cars. The effect for all-electric range is the same as for the regression without annual mileage in section 3.2, but the effect of system power is somewhat smaller after controlling for different annual mileages (cf. section 3.2).

over the duration of one week of conventional cars in Germany, including 5,812 private and 212 company cars. The results are summarized in Table 9.

**Table 9. Long-distance driving in different datasets**. We used a subset of the Voltstats.net data with at least 100 observation days and sequences of missing values shorter than two weeks (N = 3,098) as well as the German Mobility Panel dataset (MOP 2010).

| | **Voltstats.net** (n = 3,098) | **Germany private cars** (n = 5,812) | **Germany company cars** (n = 212) |
|---|---|---|---|
| **Average annual km** | 21,970 | 12,100 | 27,800 |
| **Above 100 km daily driving** | | | |
| **mean share of observation days** | 18% | 7% | 24% |
| **mean share of driving days** | 20% | 9% | 28% |
| **mean share of annual mileage** | 42% | 19% | 47% |
| **Above 200 km daily driving** | | | |
| **mean share of observation days** | 4% | 2% | 9% |
| **mean share of driving days** | 5% | 3% | 11% |
| **mean share of annual mileage** | 16% | 8% | 25% |

According to the German Mobility Panel data, company cars show higher annual mileage and more long-distance trips of more than 100 km of daily distance than privately owned vehicles. For the Voltstats.net sample, we find that long-distance travel occurs on 18% of the observation days but accounts for 42% of annual distance. The Voltstats.net sample seems to have many long-distance drivers, potentially with long commutes of more than 50 km in one direction. In the German data, **long-distance driving occurs on 7% of the days observed for private and 24% for company cars but accounts for 19% of annual mileage for private autos and 47% for company cars**.[22] Despite the difference in samples and user groups, a few long-distance driving days clearly account for a noteworthy share of annual mileage.

If future PHEVs had real-world ranges of 75 km, corresponding to WLTP range of 90 km[23], the mean share of driving days with more than 75 km would be 15% for private and 39% for company cars. This would correspond to 11% of observation days for private vehicles and 32% for company cars and to 28% of annual kilometers driven for private autos and 60% for company cars.

The share of long-distance driving in annual mileage has implications for the share of kilometers driven on electricity, the UF. When reflecting on their vehicle usage, many car users do not think of the days with exceptional driving and perceive their vehicle usage as mainly electric. However, for the UF, the share of total kilometers and not the share of days traveled on electricity is decisive. If 25% of annual mileage is from long-distance driving with a high share of nonelectric kilometers, this reduces the total UF. For example, we have 22,000 km of mean annual mileage for the PHEVs in our sample. If 19% of these annual kilometers, or 4,200 km, come from 25 days, or 7% of the days in a year, and the vehicle has a real-world range of 36 km, the vehicle would drive 890 km of the 4,200 km on electricity and 3,310 km on fuel. If the same auto ran entirely

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[22] The values for MOP are likely to be slightly too low as the survey week explicitly excludes nonusual behavior like annual vacations and is supposed to represent a regular working week. Furthermore, long-distance trips could also be underrepresented in the MOP data as people on long-distance trips are less likely to participate in the survey. The mean annual kilometers for the privately owned vehicles has been extrapolated from one week of observation and is slightly below the national German average of 14,700 km, indicating that long-distance trips are underrepresented in the sample. However, the shares are consistent with one-day cross-sectional share of a second survey for Germany where 5% of vehicles had more than 100 km daily VKT on the survey date and 2% more than 200 km on the day (MiD, 2018). Yet, the share of long-distance days by user group cannot be reproduced as the MiD distinguishes only private and commercial owners.

[23] Assuming 20% higher real-world electricity consumption similar to 20% real-world fuel consumption according to Dornhoff, Tietge & Mock (2020).

on electricity the rest of the year, these 3,310 km of nonelectric driving alone would reduce the UF to 85%. Assuming that the daily distances in the rest of the year are equally distributed and driven as much on electricity as charging once a day allows, the UF would be about 60%.[24]

**In summary, PHEVs in Germany show a higher annual mileage than conventional passenger cars, largely due to the above-average annual mileage of private PHEVs, while in the United States, PHEVs show similar annual mileage as the overall average car fleet. Every additional 1,000 km of annual mileage reduces the UF by 0.6 of a percentage point if all other factors remain constant. Furthermore, a few long-distance driving days significantly lower the actual UF.**

### 3.3.2. Impact of user group: Company versus private cars

The deviations between test-cycle and real-world driving data show noteworthy differences between private vehicles and company cars. Private vehicles are owned by private individuals. Company cars are “vehicles provided to employees for the employee to use for business and personal travel,” and “the vehicles are considered part of employee compensation and are therefore part of their tax liability.” (Hardman et al., 2017). Company cars play a large role in passenger car sales in Europe, mainly in countries with a domestic car industry.

PHEVs have received significant tax incentives in several markets, for example in the Netherlands from 2012–2016 but reduced thereafter, as well as in Germany and Sweden (EAFO, 2020). Accordingly, a notable share of PHEVs can be expected to be used as company cars in Europe. For Germany, the share of commercially owned PHEVs in the car stock is about 58% (cf. Figure 12), most of which can be assumed to be company cars.[25]

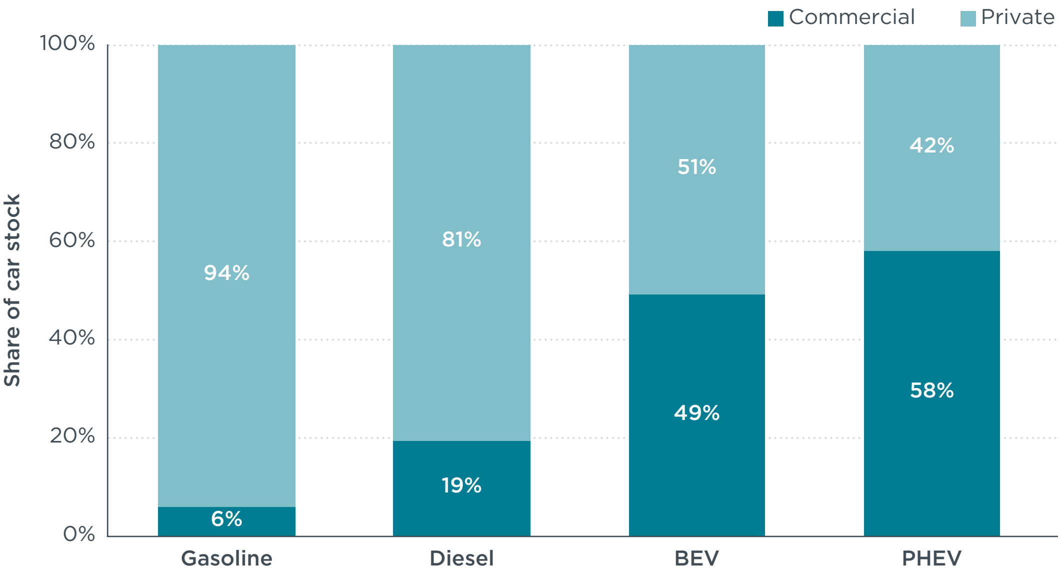

**Figure 12. Passenger car stock in Germany by fuel and owner group**. Passenger car stock in Germany as of April 1, 2020. Source: Calculation based on KBA (2020b).

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[24] Of course, this calculation is overly optimistic as the vehicle will not be used every day of the year and will not drive exactly the same distance on the short-distance driving days or long-distance driving days. Also, the car could not drive the rest of the year on electricity with one full charge per day, as the remaining 340 days could only lead to 12,240 km, which together with the long-distance mileage is still less than the assumed annual mileage. Charging 1.5 times per day would be needed if every day of the year were driven.

[25] Commercially owned vehicles are company cars and fleet vehicles. Fleet autos cannot be used for private purposes and are not assigned to a person within a company. As PHEVs receive much stronger incentives via income taxation than fleet vehicles, we can assume that most commercially owned PHEVs in stock are company cars.

In sections 3.1 and 3.2 we analyzed private and company vehicles separately. The sales data for Germany demonstrates that PHEVs are an important group in company car stock and will diffuse into private stock soon as holding times are typically short for company cars (Plötz et al., 2014a).

We performed simple nonlinear regression to analyze typical values for UF as a function of real-world range.[26] Figure 13 shows the actual UF in our sample together with the regression results.

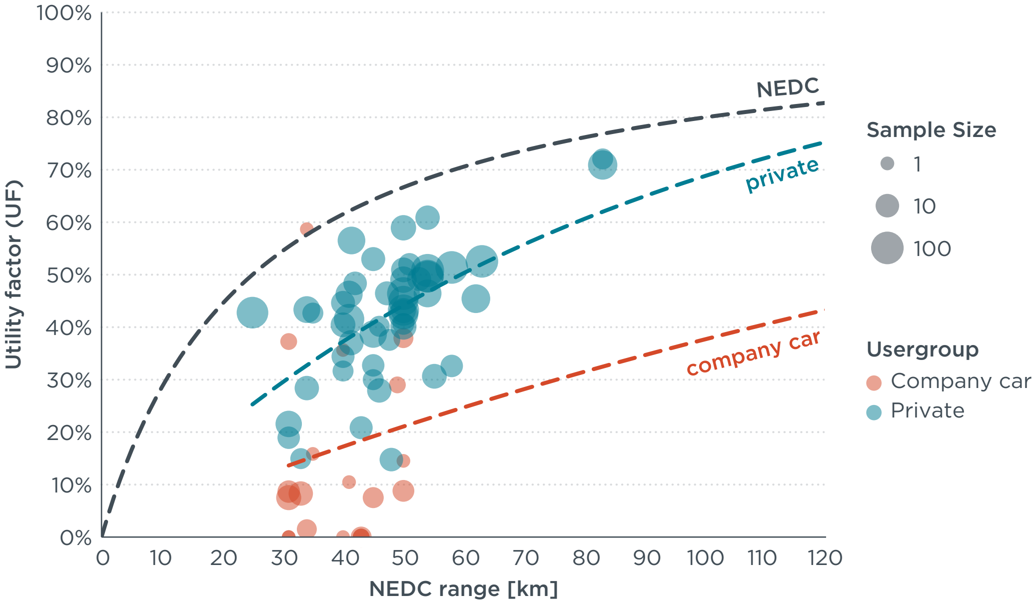

**Figure 13. UF regression by user group in Germany**. Subsample mean UF on PHEV model variant level for Germany for private vehicles (green) and company cars (red) with the sample size indicated by the circle size and regressions (dashed lines).

As discussed above, average UFs increase with all-electric range for private and company cars, but the mean values for company cars are much lower for a given range than for private vehicles. In the following section 3.3.3, we compare simulated UFs of passenger cars in Germany for both user groups with these local regressions.

There is a third group of vehicle usage, fleet vehicles. These are commercially owned vehicles that cannot be used for private purposes. Electric vehicles have potential as fleet vehicles, such as in postal services, delivery, and other usage scenarios (Gnann, Plötz, Funke, & Wietschel, 2015; Figenbaum, 2018), but there is a lack of real-world usage data for PHEVs in commercial fleets. For a small sample of 19 PHEVs in Germany that have been tracked with data logging devices, 14 were used in city or commercial fleets (NOW, 2020). The average UF was 65% at an NEDC range of 50–70 km and a mean annual mileage of 14,120 km. The vehicles showed two charging events on average per day (NOW, 2020). Apart from this, there is little data on PHEV usage in commercial fleets, and further research is required.

### 3.3.3. Impact of charging behavior: Empirical data and simulation

The present section reviews studies on PHEV charging behavior based on the U.S. Voltstats.net sample and compares the observed UFs for private and company car PHEVs in Germany with simulated UFs from different charging assumptions.

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[26] Similar to the regression models presented above, we choose the following function form: $UF = 1 - \exp(-AER^{NEDC}/L)$ where $AER^{NEDC}$ is the NEDC all-electric range and $L$ is a user group specific parameter. For private vehicles we obtain $L$ = 80 ± 5 km (best fit ± 2 standard errors) and for $L$ = 330 ± 160 km company cars, which is obtained from numerical minimization of the sum of squared deviations.

### Empirical PHEV charging data

Mandev, Plötz, and Sprei (2020a & b) analyzed charging behavior in the Voltstats.net sample in great detail. The dataset comprises information from April 2011 to January 2020 with 4.3 million driving days. The authors estimate the frequency of additional daytime charging and the frequency of no overnight charging by comparison of simulated and observed UF for each day and user.[27] Results for the Chevrolet Volt show that additional over-day recharging happens on 3%–8% of days and no recharging overnight happens less often, on 3%–6% of days. Additionally, fuel consumption increases by 0.75 liter of gasoline with every 10% of driving days without charging, adding to tailpipe emissions. Charging more than once per day decreases fuel consumption by 0.1 liter for every 10% of driving days with additional charging (Mandev, Plötz, and Sprei, 2020a & b).

In a comprehensive study of driving and charging behavior of 166 PHEVs in the United States, Tal et al. (2020) observe a high average number of charging events per day: 0.99 for Toyota Prius PHEV, 1.11 for Ford CMAX Fusion, 1.02 for Chevrolet Volt with 16 kWh battery, and 0.77 or Chevrolet Volt with 18 kWh battery. In a subsequent study, Chakraborty, Hardman, and Tal (2020) show that reasons for PHEVs in the United States not to charge are lack of home charging availability, high price for charging, low electric driving range, and low electric motor power.

Actual data from vehicle manufacturers on PHEV charging is rare. One analysis for Germany finds a median of 0.5 charging events per day for several thousand small, compact, and SUV vehicles mainly driven by private users (NPM, 2020). The vehicles in the sample have NEDC ranges of 31–92 km and achieve median UFs between 24% and 42%. The median number of charging events per PHEV model range from 1.2–2.2 per 100 km of driving. The average number of charging events is thus lower than the values from the comparison of mean UFs and simulated UFs discussed below, but the mean UFs are in a comparable range.

### PHEV charging behavior from simulations

We use driving data of conventional vehicles to simulate the full charging frequency and range-depended UFs of PHEVs. Therefore, we use the vehicle driving data from the German Mobility Panel (MOP, 2010). The data contains the distance and purpose of trips reported by individuals who have been assigned to vehicles in the individual's households (cf. Plötz et al., 2014a). We thus obtain distance per vehicle and trip, including trip purposes and additional vehicle and household information for about 6,000 German vehicles mainly representative of German passenger car stock.

To simulate the UFs, we vary the number of full charging events per day and vehicle and assume that the PHEVs are driven as much as possible on electricity according to the all-electric range. We convert NEDC all-electric ranges to real-world ranges as requried in the simulation.[28] The simulation is performed for all seven days of observation for each vehicle in the sample, and the total UF is calculated.

Figure 14 shows the simulated mean UF for one full charge per day for private vehicles and company cars. The simulated UFs quickly increase with all-electric range and reach

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[27] The simulated UF is simply given by $UF_{sim}$ = AER/daily VKT if daily VKT > AER and 1 otherwise. Here, AER denotes the EPA all-electric range. This is compared with the observed UF. The simulation implicitly assumes a full recharge overnight, as charging is not specifically simulated. If the observed UF is much higher than the simulated UF, the vehicle must have had at least one additional recharge during the day. Similarly, for the occurrence of no overnight charging, the observed UF must be much smaller than the simulated UF. For the occurrence of an additional over-day charging event, the authors use the assumption that the observed UF for a vehicle for that given day is at least 1.5 times higher than the simulated UF. For no overnight charging they use the assumption that the observed UF is smaller than half the simulated UF. The frequency of additional day charging is defined as the share of days with an over-day charging event within the total number of driving days for a given user. Similarly, the frequency of no overnight charging is defined as the share of days with no overnight charging within the total number of driving days.

[28] Real-world all-electric range is assumed to be 71% of the NEDC all-electric range.

75% for 40 km real-world all electric range, or about 56 km NEDC range, for privately owned vehicles and about 50% for company cars. The mean simulated UFs are always smaller for company cars than for private vehicles due to more frequent long-distance driving and higher daily and annual mileage for company cars.

Table 10 summarizes the simulation results for private and company cars in Germany for one full charge per day and charging three out of four days as well as the mean values by range as observed in Germany (cf. section 3.1). The simulated UFs for private and company cars are shown in Figure 14.

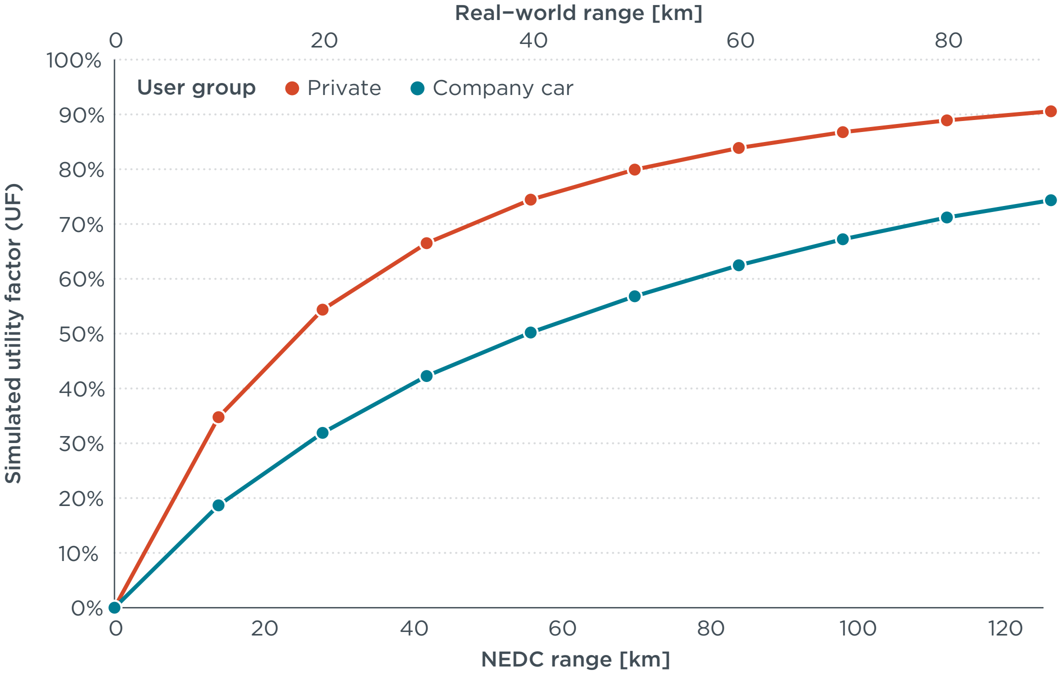

**Figure 14. Simulated UFs for private and company cars in Germany**. The figure shows the simulated UFs for Germany passenger cars based on the German Mobility Panel data. The simulation requires real-world ranges (top x-axis) and the figure shows an additional x-axis with NEDC ranges, calculated as +40% compared with real-world ranges.

**Table 10. Difference in simulated UF between private and company cars**. The simulated and observed UFs for private vehicles and company cars in Germany are shown. Simulation with charging every driving day and charging three out of four driving days.

| Real-world range in simulation | 20 km | 30 km | 40 km | 50 km | 60 km | 70 km | 80 km |
|---|---|---|---|---|---|---|---|
| **Approximate NEDC range** | 28 km | 42 km | 56 km | 70 km | 84 km | 98 km | 112 km |
| **NEDC UF (in %)** | 53 | 63 | 69 | 74 | 77 | 80 | 82 |
| **Simulation with one full charge per driving day** | | | | | | | |
| **Simulated UF private (in %)** | 54 | 67 | 74 | 80 | 84 | 87 | 89 |
| **Simulated UF company cars (in %)** | 32 | 42 | 50 | 57 | 62 | 67 | 71 |
| **Difference in percentage points** | 22 | 25 | 24 | 23 | 22 | 20 | 18 |
| **Simulation with one full charge in three out of four driving days** | | | | | | | |
| **Simulated UF private (in %)** | 41 | 50 | 56 | 60 | 63 | 64 | 67 |
| **Simulated UF company cars (in %)** | 24 | 32 | 38 | 44 | 45 | 52 | 55 |
| **Difference in percentage points** | 17 | 18 | 18 | 16 | 18 | 12 | 12 |
| **Observed UF for Germany (Sample-size weighted regression ± 2 standard errors)** | | | | | | | |
| **Observed UF private (in %)** | 30±2 | 41±2 | 50±3 | 58±3 | 65±3 | 71±3 | 75±3 |
| **Observed UF company cars (in %)** | 8±4 | 12±7 | 16±9 | 19±10 | 22±11 | 26±13 | 29±14 |

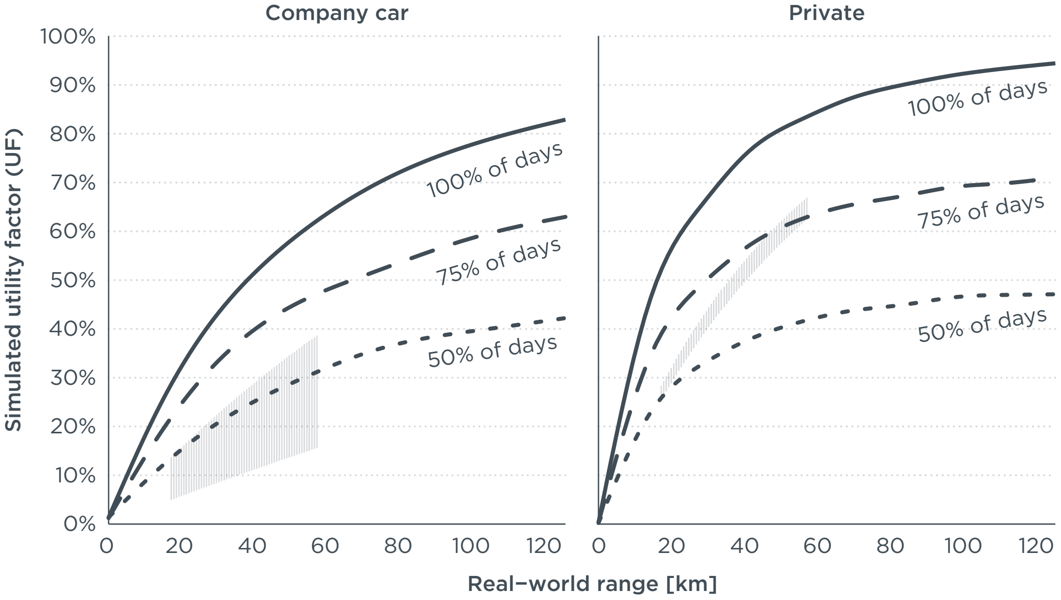

**Figure 15. Effect of charging frequency on simulated UF**. Shown are the simulated mean UFs for German driving data (n = 6,309, German Mobility Panel data MOP, 2010) of one full charge per day (solid line), in three out of four days (dashed line) and in one out of two days (dotted line) together with ranges of plausible mean UFs from the empirical data (shaded gray areas – cf. Figure 13, with real-world range = NEDC range / 1.4).

The simulated UFs with one full charge per day are close to the NEDC UFs (see Figure 4), if corrected for more realistic ranges. That is, 40 km real-world range PHEV simulated private UF corresponds well to 56 km NEDC range UF. However, the simulation shows that the long-distance driving of company cars leads to 18–25 percentage points lower UFs than for private vehicles if a full recharge every night is assumed for both user groups.

Charging frequency has a clear effect on the simulated UFs in both user groups.[29] Charging only three out four days on average leads to 13–23 percentage points lower UFs for private and 8–17 percentage points lower UFs for company cars in comparison with charging every day. This corresponds to simply 25% lower UFs as a full recharge takes place during only 75% of the days.

But how do the simulated UFs compare with the actual UFs observed for PHEVs in Germany? For private vehicles, the simulated UFs with charging during three out of four driving days are greater than the observed values for short ranges but larger for long ranges. Taking into account that the high annual mileages in the actual PHEV usage data as compared with the car fleet average annual driving in the simulation, the simulated UFs should be about 6 percentage points lower to correct for the high annual driving in the actual PHEV sample. After that, the simulated UFs for charging on three out of four days matches the actual UFs with an accuracy of 1 percentage point for all ranges under consideration. Thus, our best estimate for the typical charging frequency is about three out of four nights.

For company cars, actual UFs in Germany in our sample are below even the assumption of charging three out of four days. The mean annual mileage of company car PHEVs in the sample is 30,200 km, which is close to average of conventional company cars (30,700 km acc. to. MiT (2017)) and about 2,000 km more than in the company cars sample used for the simulation. Accordingly, the simulation overestimates company car UFs by only about ca. 1 percentage point. After subtracting this, the actual UFs

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[29] The mobility panel data contains seven days of observation for each vehicle in the sample. But as seven is not divisible by four, we treated charging as a binomial random variable in the simulation with success probability of 0.75 to decide for every day of every user for a full recharge with 75% probability.

are still not close to the values simulated from charging three out of four driving days. Accordingly, the actual charging of company cars in Germany is more likely to be about once every second driving day.

**The real-world UFs of private and company car PHEVs in Germany are clearly below the UFs simulated for one full charge per driving day. They rather indicate a charging frequency of three out of four driving days for private and one out of two driving days for company car PHEVs.**

### PHEV Charging Locations

Yet, the questions remains how much public charging infrastructure can support electric driving of PHEVs. This leads to the question how much electricity is generally charged in public places. The European Federation for Transport and Environment (T&E) assumes about 25% of public charging for PHEVs based on a consultation of experts in a scenario for the near future (T&E, 2020). In T&E (2018), however, an average share of 5% of public charging events are mentioned. In a survey of several thousand California drivers who were asked to recall plug-in charging events in the previous seven days, Tal et al. (2018) find PHEVs have 6%–11% of their charging events at publicly accessible installations. As the availability of public charging is likely to increase in the future and with more PHEV users who do not have a home charging option, the share of public charging could increase, but not quickly. **Less than 20% of public charging seems a plausible assumption**.

For Germany, Scherrer, Burghard, Wietschel, and Dütschke (2019) published results from a survey in 2019 among 432 users in Germany of plug-in electric vehicles (PEVs), including BEVs and PHEVs (cf. Figure 16). They found that 18% of all PEV charging events used public facilities, but the rate was only 13% for PHEVs. As expected, charging at work is much more important for company cars users, accounting for 60% of their charging events compared with 26% for all users.

More and easier access to public charging infrastructure is sometimes discussed as a measure to increase the electric driving share for PHEVs. The distribution of current charging locations, though, shows that for today's users, home and work are the dominant charging locations (Scherrer et al., 2019). Public charging accounts for only a minor share of charging, and even if public charging availability could be increased through policies, the effect on mean UF can be only limited except for users without access to home or work charging.

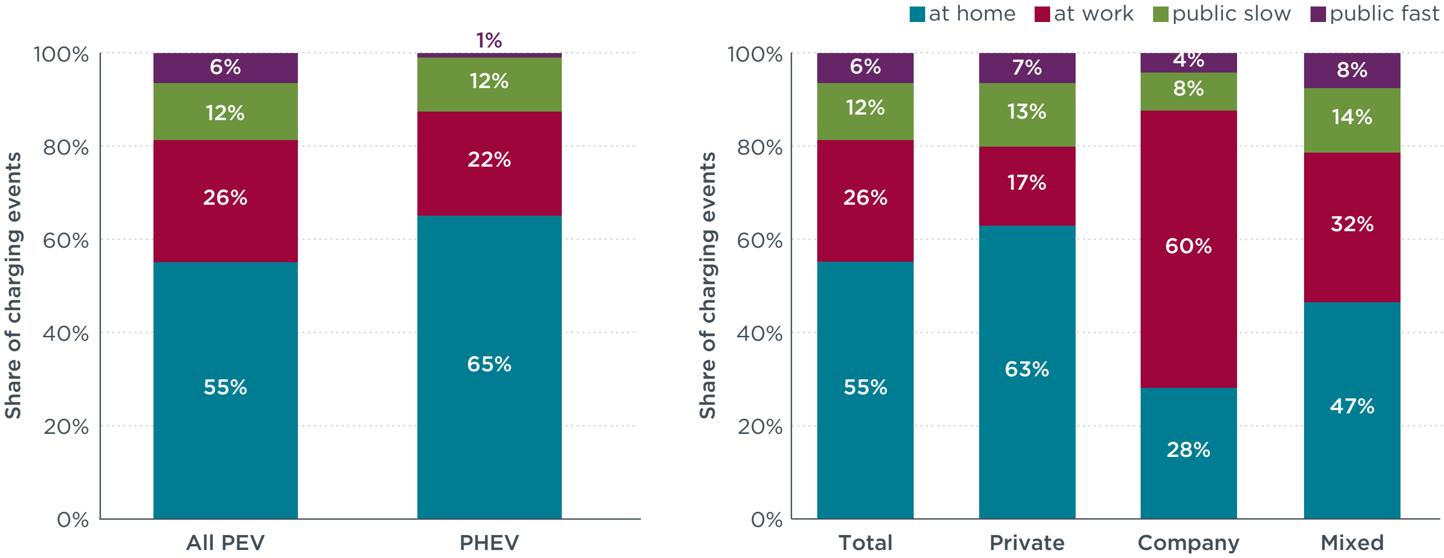

**Figure 16. Share of public BEV and PHEV charging in Germany**. Left: share of charging events by charging location and PEV type. Right: Share of charging events by location and vehicle usage for all plug-in vehicles (private usage, company usage and mixed private/company use). Source: Calculation based on Scherrer, Burghard, Wietschel, and Dütschke (2019)

For China, charging in public locations is probably more important than for most parts of Europe and North America. In a recent survey of 1,023 participants including 129 PEV users (cf. Table 11), only about a third of respondents had access to home charging and a quarter of PEV users did not have home charging (Li, Plötz, & Zhang, 2020). There are differences between major cities (tier 1 and tier 2 cities) and smaller (tier 3 and higher) cities in China, but most passenger car PHEVs are owned in the large cities.

**Table 11. Housing, parking, and home charging in China**. Results from a survey with 1,023 respondents including 139 PEV users. Source: Li, Plötz, & Zhang (2020)

| | | Full sample | PEV users in tier 1 & 2 cities[30] | PEV users in tier 3+ cities |
|---|---|---|---|---|
| **Housing type** | **House** | 19% | 7% | 33% |
| | **Building with up to six floors** | 29% | 28% | 28% |
| | **Building with more than six floors** | 37% | 60% | 36% |
| | **Dormitory** | 16% | 5% | 3% |
| **Charging at home** | **Available** | 37% | 72% | 76% |
| | **Unavailable** | 51% | 26% | 19% |
| | **Not sure** | 12% | 2% | 5% |
| **Charging near home** | **Available** | 30% | 79% | 50% |
| | **Unavailable** | 53% | 14% | 42% |
| | **Not sure** | 17% | 7% | 8% |

### 3.3.4. Impact of ambient temperature

PHEVs and other plug-in vehicles have shorter ranges in cold weather as additional energy is required for heating the vehicle cabin, and the battery is less active. The present section measures the effect of outside temperature on mean UFs of PHEVs. The first part of the present section analyzes empirical daily driving data from

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[30] Beijing, Shanghai, Guangzhou, Shenzhen, Chengdu, Hangzhou, Wuhan, Chongqing, Nanjing, Tianjin, Suzhou, Xi'an, Changsha, Shenyang, Qingdao, Zhengzhou, Dalian, Dongguan, Ningbo, Xiamen, Fuzhou, Wuxi, Hefei, Kunming, Harbin, Jinan, Foshan, Changchun, Wenzhou, Shijiazhuang, Nanning, Changzhou, Quanzhou, Nanchang, Guiyang, Taiyuan , Yantai, Jiaxing, Nantong, Jinhua, Zhuhai, Huizhou, Xuzhou, Haikou, Ürümqi, Shaoxing, Zhongshan, Taizhou, Lanzhou.

Chevrolet Volt vehicles in North America, and the second part looks at real-world driving in Norway.

### Empirical UF data for Chevrolet Volt vehicles

We use the highly detailed daily Voltstats.net data to look into the effect of ambient temperature. We take a subsample of 1,738 Chevrolet Volts from the United States. Each user has a personal website including the home location of the user. For each day and user, we compare the observed UF to a simple simulation of UF.[31] We retrieve the daily mean ambient temperatures for all locations and all driving days via web API for US national climate data.[32] This information was available for 76,867 driving days. We compare the difference between observed and simulated UF with the ambient temperature in Figure 17. The figure shows the mean difference between observed and simulated UF for different ambient temperatures, rounded to single digits in degrees Celsius.

The figure shows a clear effect of ambient temperature on UF. **The UF is reduced by about 1 percentage point per degree Celsius below 10°C**. The UF reduction is nonlinear and strongest for temperatures below 0°C, where additional cabin heating demand and the effects on the battery are greatest.

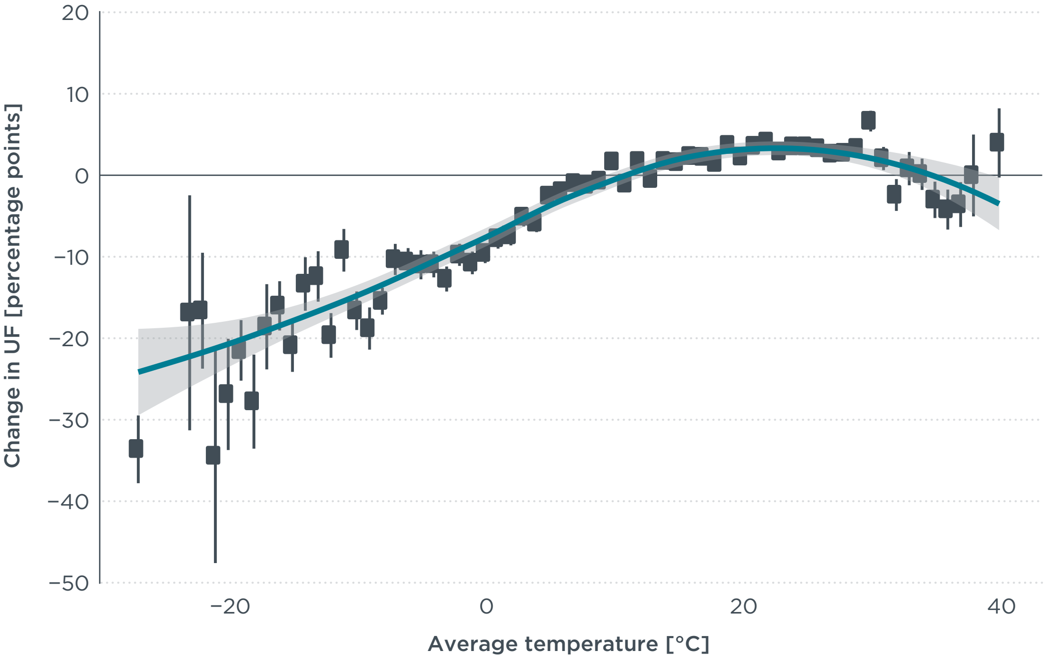

**Figure 17. Effect of ambient temperature on Chevrolet Volt UF**. We compare the actual daily UF with the simulated UF for 77,000 driving days of 1,738 Chevrolet Volt vehicles (cf. Plötz et al., 2018a). The average difference between observed and simulated UF in percentage points is shown as filled circles ± one standard error (i.e. SE=SD/√n) with a local scatter plot smoother (solid line).

### PHEV usage in cold weather: The Norwegian case

A second example of real-world experience in cold weather is from Norway. Figenbaum and Kolbenstvedt (2016) compare mean UFs during summer and winter in a survey of 1,515 PHEVs in Norway. We reproduce their results below in Table 12.

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[31] UF is simulated as UF = all-electric range / daily km if daily km>all-electric range and equal to one otherwise.

[32] Daily climate data from https://www.ncei.noaa.gov/. Original sample reduced to 31,193 since cases with perfect match between observed and simulated were excluded.

**Table 12. Mean UF in summer and winter in Norway for different PHEV models**. Summer and winter range in kilometers, difference between UF in percentage points (pp). Source: Figenbaum and Kolbenstvedt (2016).

| PHEV model | n | NEDC range | Summer range | Winter range | Mean UF | Summer UF | Winter UF | Difference |
|---|---|---|---|---|---|---|---|---|
| **Audi A3** | 197 | 50 km | 40 km | 29 km | 59% | 64% | 54% | 10 pp |
| **Opel Ampera** | 46 | 83 km | 68 km | 44 km | 72% | 77% | 68% | 9 pp |
| **Mercedes C350e** | 11 | 31 km | 23 km | 18 km | 41% | 44% | 38% | 6 pp |
| **VW Golf GTE** | 283 | 50 km | 40 km | 28 km | 57% | 62% | 52% | 10 pp |
| **Mitsubishi Outlander** | 806 | 52 km | 41 km | 30 km | 55% | 62% | 48% | 14 pp |
| **Toyota Prius PHEV** | 67 | 25 km | 20 km | 15 km | 38% | 43% | 33% | 10 pp |
| **Volvo V60** | 104 | 50 km | 46 km | 37 km | 51% | 55% | 48% | 7 pp |
| **Total** | **1,515** | **51 km** | **41 km** | **29 km** | **55%** | **61%** | **49%** | **12 pp** |

The Volvo data is consistent with other data sources. For example, data from the on-board computer in the Volvo V60 PHEV estimates a UF of 46.3% based on 341 Norwegian vehicles (Figenbaum & Kolbenstvedt, 2016). This is very close to the average for the German Volvo V60 D6 Hybrid from the Spritmonitor.de data with 42.4% but above the 35% for the Volvo V60 T8 Twin Engine PHEV and 31% for the Volvo V60 T6 Twin Engine PHEV in the Spritmonitor.de data.

The Norwegian data shows the clear impact of ambient temperature on the all-electric range of PHEVs. The summer range is typically 20% below the NEDC range, but the winter range is more than 40% below the NEDC range, or 57% of NEDC range on average. The actual mean UF varies significantly between summer and winter. **The mean UF is between 6 and 14 percentage points lower in winter, with a sample-weighted mean of 12 percentage points**. This is consistent with the impact of ambient temperature on UF of the Chevrolet Volt vehicles.

The impact of ambient temperature was also confirmed by laboratory measurements. A short summary of the findings is given in Appendix A: “The impact of ambient temperature on PHEV fuel consumption: A case study.”

# 4. DISCUSSION

The observed large deviation between real-world and type-approval test-cycle fuel consumption for PHEVs results from a 50% lower UF than expected based on test cycle results (cf. section 3.1.2) and higher fuel consumption in charge-sustaining mode. For combustion engine vehicles, there is an average gap of about 40% between NEDC and real-world fuel consumption (Dornoff et al., 2020). If we apply the same 40% to conventional fuel driving of an average PHEV, it would consume 1.4 times as much as expected in charge-sustaining mode operation. Taken together, the combustion engine is used about twice as often as assumed in the NEDC or WLTP cycles and consumes 40% more fuel. This leads to 2.8 or almost three times higher fuel consumption and would explain the observation of a real-world fuel consumption of two to four times higher than in the NEDC or the WLTP.

The low UF and high fuel consumption has direct consequences for real-world $CO_2$ savings from PHEVs. We observe 18%–54% mean UFs across user groups and countries. Let us assume the fuel consumption of PHEVs at 0% UF is comparable to the fuel consumption of a similar combustion engine vehicle. According to such an assumption, the UF would directly correspond to 18%–54% fewer tailpipe $CO_2$ emissions. A different estimate of the actual fuel savings compared to conventional vehicles uses the mean NEDC UF in our sample of 69%. With the assumption that the charge-sustaining mode fuel consumption of PHEVs is the same as the fuel consumption of comparable conventional cars, the NEDC fuel consumption of PHEV is thus equivalent to 31% of the NEDC value of conventional cars. As mean fuel consumption of PHEVs is actually 2–4 times higher than their test-cycle values, the real-world fuel consumption of PHEVs is about 60%–120% of the NEDC values of comparable conventional car models. When taking into account that the average deviation between real-world and NEDC fuel consumption for conventional vehicles is about 40% (Dornoff et al., 2020), the fuel consumption of PHEVs in real-world operation is 43%–86% of the fuel consumption of comparable conventional vehicles. In summary, both calculations arrive at **roughly 15%–55% savings in tailpipe emissions of PHEVs in real-world operation** compared to similar-sized combustion-engine vehicles.

There are three main reasons why the observed real-world UFs are significantly lower than expected based on NEDC type approval. First, PHEVs are charged much less often than the daily full charge assumed in the NEDC procedure. In Germany, private-car PHEVs are found to be charged on about three out of four driving days while company-car PHEVs are charged only every second driving day. Second, the actual all-electric range is much shorter in real-world driving than according to the NEDC. That is because real-world electricity consumption is likely to be higher than NEDC electricity consumption, similar to the deviation between test approval and real-world energy consumption in combustion-engine vehicles (Dornoff, Tietge, and Mock, 2020). Third, current PHEVs in use have high annual mileage. Although the annual mileage in the U.S. PHEV sample is similar to the U.S. fleet average, it is clearly above average in Germany (see section 3.3.1 above). For Germany, annual PHEV mileage is 7,000 km above the fleet average, reducing UFs by 3.5–4.5 percentage points compared with what would be expected based on fleet average (see chapter 3.3.1 for details).

Our sample includes data from five countries and two user groups covering a total of more than 100,000 PHEVs, including literature values as well as recent PHEV measurements. We lack data on other important PHEV markets such as the United Kingdom and Sweden. However, as framework conditions in these countries are comparable to those of other Western European countries with respect to the availability of home charging, typical driving distance, income, and financial incentives for company cars, no fundamentally different PHEV usage can be expected from these countries. **Preliminary analysis of U.K. data shows a similar**

**pattern**.[33] PHEV usage might be notably different in Japan or Korea, but no data was available for those countries.

Our country samples show different distributions of car brands and models. The U.S. sample, for example is dominated by the Chevrolet Volt, while the Chinese sample is dominated by various domestic car brands. The Dutch, Norwegian and German samples, on the other hand, show quite a broad distribution of brands and models. Consequently, model-or model variant-specific analyses among different countries would have been interesting. Sample sizes for single model variants, however, were mostly too small for comparisons.

Company-car data was available only for Germany and the Netherlands, with a small German company-car sample. Yet, the overall trends are the same for both countries, and the qualitative differences among private and company cars in charging behavior in particular can be expected from the existing financial framework conditions in both countries for PHEVs.

For most online data sources, including Spritmonitor.de, MyMPG and Xiao Xiong You Hao, registration and monitoring of fuel consumption is voluntary. It can be assumed that mainly those PHEV users who are sensitive to fuel economy register on these platforms. Thus, a certain self-selection bias overstating fuel economy could be present. Furthermore, on the Spritmonitor.de website most of vehicle specifications are provided in free-text boxes and are not selected from a pre-defined list, leading to inaccuracies and thus difficulties in assigning correct vehicle characteristics from the PHEV list. The rigid data cleaning process, however, assured a high level of accuracy. Additionally, there are no required fields for data entries on Spritmonitor.de, which might lead in some cases to incomplete entries.

A noteworthy gap in the data, which warrants further research, are fleet vehicles. No data source could be found that captures PHEV usage in purely commercial use.

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[33] We collected a small sample of fuel consumption values from PHEV user reports on carbuyer.co.uk, most likely private vehicles. For 33 Mitsubishi Outlander PHEVs, the mean real-world fuel consumption was 4.8 ± 0.8 l/100 km (mean ± two standard errors) or 2.2–3.1 times higher than the NEDC value. For seven Volkswagen Golf GTEs, the mean fuel consumption was 4.0 ± 1.0 l/100 km or 1.9–3.2 times higher than NEDC, and for three Volvo XC90 T8 Twin Engine hybrids it was 7.9 ± 2.3 l/100 km or 2.7–4.9 times higher than the NEDC. The mean annual driving distances were 22,000 km for the Outlander, 25,000 km for the Golf GTE, and 19,000 km for the Volvo. All these numbers are consistent with the findings for Germany.

# 5. POLICY RECOMMENDATIONS

### Governmental support for PHEVs and their accounting in the EU $CO_2$ targets should better reflect their environmental benefit.

With two to four times higher fuel consumption than indicated by the test-cycle values, the $CO_2$ and pollutant emission benefits of PHEVs are lower than expected. The inclusion of PHEVs in zero-emission vehicle (ZEV) mandates, such as in several U.S. states or the New-Energy Vehicle (NEV) credit system in China, as well their contribution to reaching manufacturers' $CO_2$ fleet targets should be carefully evaluated. Monitoring of real-world $CO_2$ emissions in the EU, making use of mandatory on-board fuel consumption meters, will shed further light on real-world PHEV usage in coming years.

We find similar deviations of real-world fuel consumption and UFs for both the NEDC and WLTP test cycles, although our WLTP sample is limited. Thus, further refinements of the test cycles should be discussed. The EPA test cycle seems to represent real-world fuel consumption and all-electric range better than the NEDC or the WLTP.

### Incentives need to set minimal electric ranges and favor longer ranges.

Government incentives should encourage long-range PHEVs, making purchase incentives, company car taxation, and special depreciation rules range-dependent, including sufficiently high minimal ranges to obtain incentives. Design options for such policies can also include low conventional fuel use, such as is already the case in China's NEV credit policy (Cui, 2018). Longer ranges increase the proportion of electrified kilometers driven. However, they also require higher battery capacity and an increase in weight and carbon footprint of PHEVs. Consequently, maximum ranges could be specified as well to prevent making PHEVs the heavier alternative to purely battery-electric vehicles because of the dual drivetrains.

### Access to charging points should be improved.

PHEV users should be offered comfortable and affordable home, workplace, and public charging options.

- Because most charging events correspond to **home charging**, the legal and financial barriers to the installation of home charging points should be reduced, especially in multi-family houses. Purchase incentives could be combined with the free installation of a home charging outlet or with charging cards or charging vouchers for users without easy access to home charging. Charging cards and vouchers would increase the social justice of purchase incentives for PHEVs. For company cars, PHEV incentives might further be conditioned on providing a home charging option to be installed either by the company or by the user. Because liability issues for home chargers installed by an employer are difficult to handle and procedures for employees leaving a company are unclear, the user option would be preferred. PHEV incentives might also be handed out as public charging vouchers, especially if home charging is not feasible or available.
- The access to **charging points at the workplace**, the second-most important charging location, could be increased by issuing incentives for PHEV company cars only to companies that provide sufficient workplace charging options. Installing workplace charging infrastructure on preferred parking spots close to a company's facilities would increase the attractiveness of workplace charging even more.
- **Public charging** makes up less than 20% of charging events for electric vehicles in general. PHEV users do not require intermediate charging to reach their destination as they can drive on conventional fuel. They cannot be expected to make additional stops that would reduce the convenience of PHEVs. Accordingly, a significant increase in public charging infrastructure could lead to higher UFs, but the effect

is most likely to be very limited compared with more frequent home charging. At the same time, access to public charging infrastructure is necessary for PHEV users without home or workplace charging. Nondiscriminatory access and a single national charging card could make public charging easier and could expand electric driving of PHEVs. The installation of public or semi-public charging infrastructure could be incentivized for power providers. Registration authorities could provide anonymized heat maps indicating where many PHEV users live.

In terms of upstream $CO_2$ emissions from charged electricity, participation in load management could increase the share of renewables charged and improve the life-cycle emissions of PHEVs.

### Frequent charging should be incentivized.

To ensure high proportions of electric driving in the long term, purchase or tax incentives for private as well as company car users could be linked to achieving a sufficiently high electric driving share. For example, the tax benefit of PHEVs could depend on reaching a significant share of the test-cycle UF in operation.[34]

For company cars, charging at home and work either should be free from taxation on fringe benefits and completely paid by the employer. Fuel cards for company-car users could be limited to a number of liters per year, and PHEV company-car users could be provided similar cards for free charging. Likewise, tax deductibility of conventional fuel use by companies could be reduced to stimulate demand-pull in fleet electrification.

It should be emphasized that companies hold company cars in their possession only between one and four years, and the cars then diffuse into private ownership. A high share of PHEVs as company cars is thus an important enabler for private PHEV ownership. Consequently, for short-term effective impact, policy measures should focus on company cars, also due to the high share of PHEV stock attributed to companies.

In addition, government incentives should be related to annual electric VKT. With increasing mileage, long-distance travel rises, reducing UFs and expanding fuel consumption. Denying incentives to these intense vehicle users, however, would waive a high potential for electrified kilometers driven.

### Conventional-fuel driving should be made less attractive.

Urban access regulations could limit driving on conventional fuel in cities and thus increase electric driving of PHEVs. Yet such rules could be difficult to implement, and compliance checks would be laborious. Technical issues such as ensuring a sufficient battery charge are unresolved. Also, such a measure might lead users to charge the battery via the combustion engine while driving before entering a city to ensure sufficient battery energy. Conventional driving could also be reduced by limiting the power of the combustion engine, such as by requiring the electric power of PHEVs to always be greater than the ICE power.

### Car buyers need to be given realistic electric range and fuel consumption values.

The discrepancy between test-cycle and actual ranges needs to be reduced by using real-world electric-energy consumption values. Car buyers and fleet managers need realistic ranges to choose the right car. Vehicle dealers need to provide useful and realistic information to customers. This could include stating fuel consumption for driving purely on conventional fuel, which gives car buyers a more realistic view of PHEVs. Training programs for vehicle dealers and fleet managers could prove useful, since it is of high importance to select users with an appropriate driving profile for PHEVs.

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[34] Such a policy could be implemented via existing income tax. The owners declare their income tax and state their UF if they apply for PHEV tax discounts. The financial offices could accept the statement as is or ask for proof from a local vehicle repair shop that reads out the on-board diagnostics.

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# APPENDIX A: CASE STUDY

## THE IMPACT OF AMBIENT TEMPERATURE ON PHEV FUEL CONSUMPTION: A CASE STUDY

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Fuel and electricity consumption of both conventional and electric vehicles depend, among other factors, on ambient temperatures and preconditioning of the vehicle. The ambient temperature affects the operation of the combustion engine and the battery and may require the use of auxiliaries such as heating and AC in the vehicle cabin. Preconditioning of the vehicle cabin can mitigate these impacts to a certain extent.

Norway is an interesting test case to investigate the effect of ambient temperature on PHEVs both due to its low winter temperatures and because it is one of the world's leading PHEV markets. The Institute of Transport Economics (Transportøkonomisk institutt, TØI)—an independent institution for multidisciplinary transport research – has conducted comprehensive laboratory measurements of selected vehicles to quantify the impact of ambient temperature and preconditioning on fuel consumption of PHEVs. The measurements were financed by the Norwegian public roads administration and were conducted at the VTT's emission measurement laboratory in Helsinki, Finland.

Three PHEV models with high sales shares in Europe were tested in different ambient conditions and driving cycles (NEDC, Artemis urban, and Helsinki City). All vehicles where type-approved to NEDC. Although driving cycles do not fully capture real-world usage, they provide useful insights into the order of magnitude of possible effects. See Table A1 for key characteristics of the driving cycles.

**Table A1.** Key parameters of the driving cycles

| Cycle | Focus | Distance (m) | Duration (s) | Average speed (km/h) | Maximum speed (km/h) | Ratio of idling (%) |
|---|---|---|---|---|---|---|
| **NEDC** | type approval | 10,931 | 1,180 | 33 | 120 | 23 |
| **Helsinki** | realistic city driving | 7,807 | 1,380 | 20 | 61 | 30 |
| **Artemis Urban** | realistic city driving | 4,470 | 920 | 18 | 58 | 3 |

The NEDC is known to correspond to lower fuel consumption and $CO_2$ emissions than real-world driving. In the following, we compare the $CO_2$ emissions reported for each vehicle in NEDC with the tailpipe $CO_2$ emissions measured in the other laboratory tests. The NEDC $CO_2$ emission value is calculated from the test results for charge-sustaining and charge-depleting test runs weighted by an electric range-dependent utility factor (EC, 2017). Here, however, we present the results of the individual measurements ($CO_2^{lab}$) of charge-depleting and charge-sustaining runs, compared to the weighted NEDC value ($CO_2^{TA}$): Deviation $CO_2 = CO_2^{lab} / CO_2^{TA}$.

Figure A1 shows the distribution of $CO_2$ emissions in different testing conditions and test cycles in relation to the NEDC value, with a value of one, when the actual fuel consumption equals the reported fuel consumption. The x-axis shows the battery state of charge (SoC) at beginning of the test. The data points have an offset in x-direction in order to indicate the driving cycle: Artemis urban (AU) is shifted to the left, NEDC is "on the line," and the Helsinki City cycle (HEL) is shifted to the right (only 2 data points for the PHEVs, at "as is"). The color of the symbols indicates the ambient temperature: Blue is a test run at -7°C, and red at +23°C. The symbols themselves indicate the driving mode of the vehicle: Circle markers for charge depleting (EV) mode, triangle for charge-sustaining mode, and crosses for hybrid mode. For comparison, diamond markers show the deviation for a diesel ICEV of the same model class. If the vehicle was started with a cold engine, with the engine off for more than three hours or overnight, the data point has an additional black circle. All other data points are "warm starts" of the engine in which the test was driven directly after the previous run. It has to be noted that several data points in the same category, for example the same drive cycle, ambient temperature and driving mode indicate the results of the different vehicles.

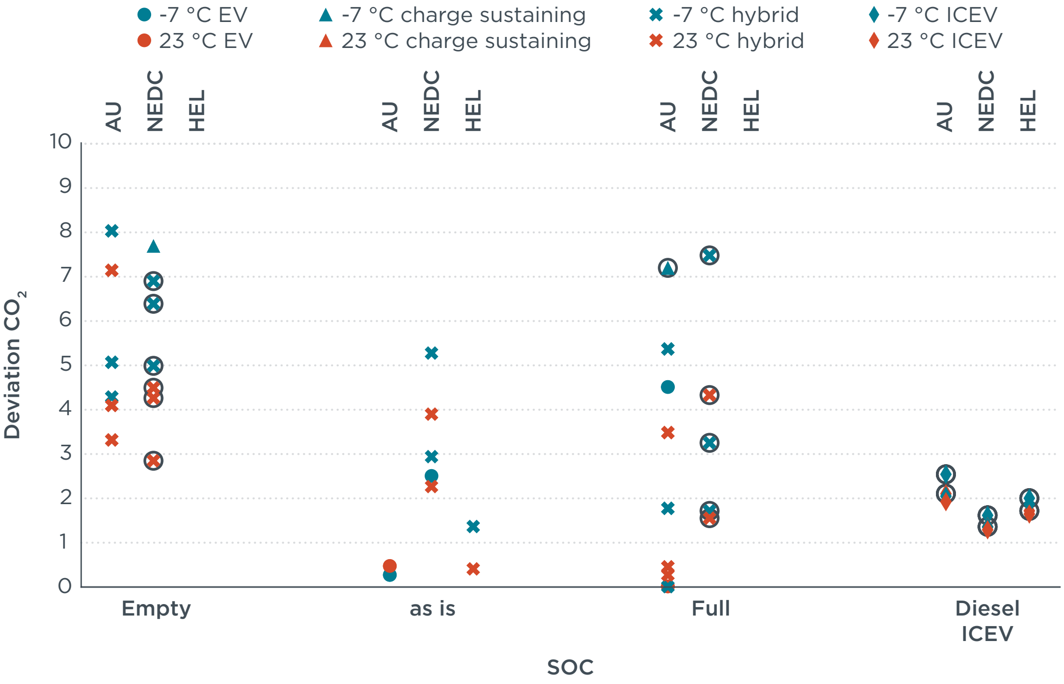

**Figure A1.** Effect of ambient temperature on the $CO_2$ emissions of PHEVs in different testing conditions and drive cycles. Shown is the deviation of $CO_2$ emissions from the NEDC value.

The laboratory measurements confirm the findings of the field data presented earlier in this study: For the diesel ICEV, the deviation factor is clustered around 2 for all start conditions and drive cycles. For low ambient temperatures, we see a tendency to higher deviation.

For the PHEVs, the data shows a wider range in the deviation factor. In some cases, mainly with full battery, the deviation factor is less than 1, meaning that the measured $CO_2$ emissions in the laboratory test are lower than the value reported from type approval. For the majority of runs, however, the deviation is higher, ranging from around 2 up to a factor of 8. Note that even in EV mode (circle markers), the combustion engine was running in some cases.

The highest deviation occurs in low ambient temperatures with an empty battery—the results clearly demonstrate the influence of ambient temperatures and the need to frequently charge them to achieve low $CO_2$ emission in real-world conditions. In real life, users would use a mix of drive modes and carry out much of the daily driving starting with a full battery, and driving would occur under variable ambient temperatures and conditions and over variable distances. The average UF for the PHEV fleet in Norway was assessed in table 12, based on data from a user survey, to be 61% in summer and 49% in winter. The $CO_2$ reduction will be lower than the UF as the laboratory tests show that the engine was running in some cases even in EV mode, especially under cold ambient conditions.

# APPENDIX B: DATA AND SUPPLEMENTAL ANALYSIS

## FULL LIST OF FUEL CONSUMPTION VALUES

**Table A2. Mean fuel consumption and UF by PHEV model, country, and user group**. Fuel consumption (FC) in l/100 km, system power in kW, range is NEDC range in km, sample size n, sources/variants is the number of sources or model variants included

| Country | Model | User group | n | Ø FC | NEDC FC | Ø UF | System power | Range | Sources/ Variants |
|---|---|---|---|---|---|---|---|---|---|
| **CN** | Audi A6 40 e-tron | private | 8 | 6.09 | 2.30 | 41% | 180 | 50 | 1 |
| **CN** | BMW 530Le | private | 51 | 5.45 | 1.66 | 38% | 185 | 63 | 5 |
| **CN** | BMW X1 xDrive25Le | private | 29 | 5.38 | 1.80 | 49% | 170 | 77 | 3 |
| **CN** | BYD F3 DM | private | 9 | 7.10 | 2.70 | 48% | 100 | 60 | 1 |
| **CN** | BYD Qin | private | 50 | 4.29 | 1.60 | 53% | 217 | 70 | 1 |
| **CN** | BYD Qin 1.5T | private | 504 | 7.01 | 1.60 | 23% | 220 | 70 | 4 |
| **CN** | BYD Qin 1.5T Plus | private | 209 | 6.70 | 1.60 | 27% | 223 | 70 | 1 |
| **CN** | BYD Qin New Energy 1.5T | private | 279 | 6.22 | 1.40 | 29% | 223 | 80 | 1 |
| **CN** | BYD Qin New Energy 1.5T 101 | private | 47 | 6.36 | 1.20 | 29% | 223 | 100 | 1 |
| **CN** | BYD Qin PHEV 1.5T | private | 61 | 6.15 | 1.40 | 30% | 223 | 80 | 1 |
| **CN** | BYD Qin Pro DM 1.5TI | private | 227 | 6.79 | 1.20 | 0% | 225.5 | 68 | 4 |
| **CN** | BYD Song DM 1.5TID | private | 133 | 7.04 | 1.40 | 20% | 333 | 80 | 1 |
| **CN** | BYD Song MAX DM 1.5T | private | 6 | 7.15 | 1.20 | 6% | 228 | 81 | 1 |
| **CN** | BYD Song Pro DM 1.5T | private | 69 | 7.40 | 1.35 | 14% | 293 | 81 | 2 |
| **CN** | BYD Tang 2.0 TAWD 2015 | private | 69 | 9.81 | 2.00 | 22% | 371 | 80 | 1 |
| **CN** | BYD Tang 2.0T | private | 553 | 9.07 | 2.13 | 27% | 371 | 73 | 3 |
| **CN** | BYD Tang 2.0T 100 | private | 33 | 8.51 | 1.80 | 37% | 371 | 100 | 1 |
| **CN** | BYD Tang DM 2.0T | private | 573 | 9.08 | 1.72 | 22% | 413 | 89 | 5 |
| **CN** | Changan CS75 1.5T PHEV | private | 79 | 6.38 | 1.60 | 22% | 265 | 60 | 1 |
| **CN** | Changan Eado 1.0T PHEV | private | 6 | 7.10 | 1.60 | 13% | 346 | 60 | 1 |
| **CN** | Dongfeng Scenery 580 1.8L PHEV | private | 5 | 7.38 | 1.40 | 8% | 166 | 70 | 1 |
| **CN** | Ford Mondeo 2.0 PHEV | private | 54 | 5.18 | 2.00 | 44% | 197 | 52 | 1 |
| **CN** | GAC Qizhi PHEV 1.5L | private | 61 | 6.28 | 1.70 | 27% | 201 | 59 | 2 |
| **CN** | GAIC GA5 Elite 2015 | private | 10 | 6.24 | 2.40 | 42% | 106 | 50 | 1 |
| **CN** | GAIC GA5 Exclusive 2015 | private | 14 | 5.01 | 2.40 | 54% | 106 | 50 | 1 |
| **CN** | Geely Binyue 260T DCT | private | 9 | 6.46 | 1.40 | 12% | 190 | 62 | 1 |
| **CN** | Geely Binyue 260T DCT Battle | private | 5 | 6.26 | 1.40 | 14% | 190 | 62 | 1 |
| **CN** | Geely Borui GE 1.5T PHEV | private | 550 | 5.80 | 1.57 | 27% | 192 | 60 | 3 |
| **CN** | Geely Emgrand GL 1.5L PHEV | private | 67 | 7.39 | 1.50 | 5% | 190 | 61 | 1 |
| **CN** | Geely Emgrand GL 1.5T DCT | private | 10 | 6.45 | 1.40 | 16% | 190 | 66 | 1 |
| **CN** | Geely Jiaji 1.5TD PHEV | private | 70 | 6.68 | 1.60 | 14% | 190 | 56 | 1 |
| **CN** | Geely Xingyue New Energy 400T | private | 32 | 6.11 | 1.40 | 20% | 320 | 68 | 2 |
| **CN** | Hyundai Sonata 2.0 PHE | private | 5 | 5.03 | 1.30 | 36% | 165 | 75 | 1 |
| **CN** | Hyundai Sonata 2.0 PHS | private | 6 | 5.58 | 1.30 | 28% | 165 | 75 | 1 |
| **CN** | Kia K5 2.0L | private | 72 | 5.09 | 1.30 | 35% | 165 | 75 | 1 |
| **CN** | Lynk 01 1.5T PHEV | private | 6 | 5.86 | 1.70 | 24% | 192 | 51 | 1 |
| **CN** | Lynk 01 1.5T PHEV | private | 23 | 6.54 | 1.70 | 16% | 192 | 51 | 1 |
| **CN** | Lynk 01 1.5T PHEV Pro | private | 173 | 6.50 | 1.70 | 16% | 192 | 51 | 2 |
| **CN** | MG 6 45T E-Drive | private | 47 | 5.70 | 1.50 | 19% | 167.7 | 53 | 1 |
| **CN** | MG 6 45T E-Drive Pilot | private | 46 | 5.11 | 1.50 | 27% | 167.7 | 53 | 1 |
| **CN** | MG 6 50T Pro | private | 7 | 6.01 | 1.50 | 12% | 224 | 51 | 1 |
| **CN** | MG 6 50T Trophy 5 | private | 10 | 6.03 | 1.50 | 12% | 224 | 51 | 1 |
| **CN** | Porsche Cayenne S E-Hybrid 3.0T | private | 6 | 12.37 | 2.90 | 0% | 333 | 36 | 1 |
| **CN** | Roewe 550 Plug-in | private | 57 | 6.11 | 2.30 | 47% | 147 | 58 | 2 |

| Country | Model | User group | n | Ø FC | NEDC FC | Ø UF | System power | Range | Sources/ Variants |
|---|---|---|---|---|---|---|---|---|---|
| **CN** | Roewe e550 | private | 153 | 6.46 | 1.60 | 21% | 147 | 60 | 1 |
| **CN** | Roewe e950 1.4T | private | 69 | 6.10 | 1.70 | 30% | 169 | 60 | 2 |
| **CN** | Roewe ei6 45T | private | 101 | 5.62 | 1.50 | 20% | 152 | 53 | 1 |
| **CN** | Roewe i6 45T | private | 216 | 5.61 | 1.50 | 20% | 152 | 53 | 1 |
| **CN** | Roewe i6 Plus 50T | private | 17 | 5.83 | 1.50 | 15% | 224 | 51 | 1 |
| **CN** | Roewe i6 Plus 50T 4G | private | 11 | 5.96 | 1.50 | 13% | 224 | 51 | 1 |
| **CN** | Roewe RX5 eRX5 50T | private | 440 | 5.96 | 1.55 | 24% | 177.5 | 60 | 2 |
| **CN** | Toyota Corolla E+ 1.8L | private | 274 | 4.87 | 1.30 | 22% | 126 | 55 | 3 |
| **CN** | Toyota Levin E+ 1.8PH GS CVT | private | 211 | 4.66 | 1.30 | 25% | 126 | 55 | 3 |
| **CN** | Toyota Prius PHEV | private | 14 | 2.63 | 2.10 | 45% | 100 | 25 | 1 |
| **CN** | Trumpchi GA3S PHEV 1.5L | private | 12 | 6.04 | 1.70 | 38% | 201 | 70 | 1 |
| **CN** | Trumpchi GA5 PHEV | private | 57 | 6.70 | 2.40 | 38% | 139 | 50 | 3 |
| **CN** | Trumpchi GS4 1.5L PHEV | private | 580 | 6.58 | 1.70 | 22% | 201 | 58 | 2 |
| **CN** | Volvo S60L T6 E | private | 10 | 6.13 | 2.10 | 38% | 238 | 53 | 1 |
| **CN** | Volvo XC60 T8 E | private | 8 | 7.16 | 2.30 | 31% | 300 | 50 | 1 |
| **CN** | VW Golf GTE | private | 21 | 4.52 | 1.60 | 37% | 190 | 50 | 1 |
| **CN** | VW Passat 430 PHEV | private | 110 | 4.99 | 1.50 | 37% | 195 | 63 | 2 |
| **CN** | VW Passat Variant GTE | private | 25 | 5.19 | 1.80 | 36% | 200 | 50 | 1 |
| **CN** | VW Tiguan L 430 PHEV | private | 63 | 5.41 | 1.90 | 38% | 195 | 52 | 1 |
| **CN** | WEY P8 2.0T | private | 132 | 8.10 | 2.30 | 22% | 257 | 50 | 1 |
| **CN** | WEY VV7 PHEV 2.0T | private | 6 | 8.26 | 1.60 | 9% | 252 | 70 | 1 |
| **DE** | Audi A3 e-tron | private | 68 | 3.69 | 1.58 | 46% | 150 | 47 | 5 |
| **DE** | Audi A3 e-tron | company | 11 | 6.83 | 1.55 | 8% | 150 | 48 | 2 |
| **DE** | BMW 225xe | private | 109 | 4.34 | 2.05 | 48% | 165 | 44 | 4 |
| **DE** | BMW 225xe | company | 1 | 7.09 | 2.00 | 10% | 165 | 41 | 1 |
| **DE** | BMW 330e | private | 42 | 5.10 | 1.94 | 37% | 191 | 44 | 5 |
| **DE** | BMW 330e | company | 2 | 6.60 | 2.00 | 18% | 185 | 40 | 2 |
| **DE** | BMW 530e | private | 25 | 5.81 | 2.00 | 34% | 185 | 48 | 2 |
| **DE** | BMW 530e | company | 2 | 6.09 | 1.93 | 29% | 185 | 49 | 1 |
| **DE** | BMW i3 REX | private | 17 | 0.98 | 0.60 | 86% | 125 | 170 | 1 |
| **DE** | BMW i3 REX | company | 1 | 0.60 | 0.60 | 94% | 125 | 240 | 1 |
| **DE** | BMW X5 xDrive40e iPerformance | private | 7 | 9.20 | 3.37 | 19% | 230 | 31 | 1 |
| **DE** | BMW X5 xDrive40e iPerformance | company | 2 | 7.10 | 3.37 | 37% | 230 | 31 | 1 |
| **DE** | Chevrolet Volt | private | 5 | 2.17 | 1.20 | 72% | 111 | 83 | 1 |
| **DE** | Hyundai IONIQ | private | 97 | 2.76 | 1.10 | 53% | 104 | 63 | 1 |
| **DE** | Kia Niro PlugIn-Hybrid | private | 100 | 3.15 | 1.30 | 51% | 104 | 58 | 1 |
| **DE** | Kia Optima | private | 11 | 2.97 | 1.60 | 61% | 151 | 54 | 1 |
| **DE** | Kia Optima Sportswagon | private | 33 | 3.99 | 1.40 | 45% | 115 | 62 | 1 |
| **DE** | Mercedes C 350 e | private | 18 | 5.61 | 2.10 | 22% | 205 | 31 | 1 |
| **DE** | Mercedes C 350 e | company | 14 | 7.78 | 2.10 | 4% | 205 | 31 | 2 |
| **DE** | Mercedes C 350 e T-Modell | company | 8 | 7.71 | 2.12 | 4% | 207.5 | 31 | 2 |
| **DE** | Mercedes E 300 de | private | 14 | 4.91 | 1.55 | 27% | 225 | 47 | 2 |
| **DE** | Mercedes E 300 de T-Modell | private | 11 | 5.08 | 1.60 | 28% | 225 | 46 | 1 |
| **DE** | Mercedes E 350 e | private | 5 | 6.30 | 2.10 | 15% | 210 | 33 | 1 |
| **DE** | Mercedes E 350 e | company | 11 | 8.13 | 2.10 | 8% | 210 | 33 | 1 |
| **DE** | Mercedes GLC 350 e | private | 11 | 6.65 | 2.50 | 28% | 235 | 34 | 1 |
| **DE** | Mercedes GLC 350 e | company | 5 | 6.19 | 2.50 | 30% | 235 | 34 | 2 |
| **DE** | Mini Countryman Cooper S E | private | 36 | 4.44 | 2.13 | 48% | 165 | 42 | 3 |
| **DE** | Mitsubishi Outlander PHEV | private | 316 | 4.37 | 1.81 | 49% | 131.25 | 54 | 4 |

| Country | Model | User group | n | Ø FC | NEDC FC | Ø UF | System power | Range | Sources/ Variants |
|---|---|---|---|---|---|---|---|---|---|
| **DE** | Opel Ampera E-REV | private | 39 | 2.26 | 1.20 | 71% | 111 | 83 | 1 |
| **DE** | Toyota Prius PHEV | private | 113 | 2.70 | 1.33 | 48% | 92.5 | 44 | 4 |
| **DE** | Volvo V60 D6 Hybrid | private | 44 | 4.66 | 1.80 | 42% | 206 | 50 | 1 |
| **DE** | Volvo V60 D6 Twin Engine | private | 17 | 4.85 | 1.80 | 40% | 212 | 50 | 1 |
| **DE** | Volvo V60 T8 Twin Engine | private | 13 | 5.27 | 1.90 | 35% | 293 | 46 | 2 |
| **DE** | Volvo XC60 T8 Twin Engine | private | 10 | 5.46 | 2.20 | 36% | 288 | 40 | 2 |
| **DE** | Volvo XC60 T8 Twin Engine | company | 1 | 6.97 | 2.30 | 16% | 288 | 35 | 1 |
| **DE** | Volvo XC90 T8 Twin Engine | private | 8 | 6.80 | 2.10 | 21% | 288 | 43 | 1 |
| **DE** | Volvo XC90 T8 Twin Engine | company | 9 | 10.40 | 2.10 | 0% | 288 | 43 | 3 |
| **DE** | VW Golf GTE | private | 113 | 3.91 | 1.55 | 44% | 150 | 50 | 2 |
| **DE** | VW Golf GTE | company | 1 | 5.77 | 1.50 | 15% | 150 | 50 | 1 |
| **DE** | VW Passat GTE | private | 103 | 4.11 | 1.70 | 46% | 160 | 50 | 1 |
| **DE** | VW Passat GTE | company | 4 | 4.75 | 1.70 | 38% | 160 | 50 | 1 |
| **NL** | Audi A3 e-tron | company | - | 6.90 | 1.57 | 24% | 150 | 48 | 1 |
| **NL** | Chevrolet Volt | company | - | 6.94 | 1.20 | 37% | 111 | 95 | 1 |
| **NL** | Ford C-Max Energi | company | - | 6.58 | - | 23% | 136 | 44 | 1 |
| **NL** | Mercedes C 350 e | company | - | 7.75 | 2.10 | 19% | 205 | 31 | 1 |
| **NL** | Mitsubishi Outlander PHEV | company | - | 7.52 | 1.85 | 29% | 120 | 54 | 2 |
| **NL** | Opel Ampera E-REV | company | - | 6.62 | 1.20 | 34% | 111 | 83 | 1 |
| **NL** | Toyota Prius PHEV | company | - | 4.85 | 2.10 | 16% | 100 | 25 | 2 |
| **NL** | Volvo V60 | company | - | 5.32 | 1.80 | 16% | 206 | 50 | 1 |
| **NL** | Volvo V60 Twin Engine | company | - | 6.41 | 1.80 | 17% | 212 | 50 | 1 |
| **NL** | Volvo XC90 T8 Twin Engine | company | - | 10.00 | 2.10 | 25% | 288 | 43 | 1 |
| **NL** | VW Golf GTE | company | - | 6.85 | 1.50 | 22% | 150 | 50 | 1 |
| **NL** | VW Passat GTE | company | - | 7.04 | 1.70 | 24% | 160 | 50 | 1 |
| **NO** | Audi A3 e-tron | private | 197 | 2.83 | 1.53 | 59% | 150 | 50 | 1 |
| **NO** | Mercedes C 350 e | private | 11 | 4.16 | 2.10 | 41% | 205 | 31 | 1 |
| **NO** | Mitsubishi Outlander PHEV | private | 806 | 3.96 | 1.86 | 55% | 120 | 54 | 1 |
| **NO** | Opel Ampera E-REV | private | 46 | 2.18 | 1.20 | 72% | 111 | 83 | 1 |
| **NO** | Toyota Prius PHEV | private | 67 | 3.91 | 2.10 | 38% | 100 | 25 | 1 |
| **NO** | Volvo V60 | private | 104 | 3.97 | 1.80 | 51% | 206 | 50 | 1 |
| **NO** | VW Golf GTE | private | 283 | 2.90 | 1.50 | 57% | 150 | 50 | 1 |
| **US** | BMW i3 REX | private | 8309 | 0.49 | 0.60 | 93% | 125 | 170 | 1 |
| **US** | Cadillac ELR | private | 5 | 2.43 | - | 66% | 162 | - | 1 |
| **US** | Chevrolet Volt | private | 62616 | 2.00 | 1.09 | 72% | 111 | 96 | 16 |
| **US** | Chrysler Pacifica Hybrid | private | 10 | 5.10 | - | 31% | 194 | - | 2 |
| **US** | Ford C-Max Energi | private | 5455 | 3.35 | - | 41% | 136 | 44 | 5 |
| **US** | Ford Fusion Energi | private | 5872 | 3.14 | - | 44% | 136 | 32 | 7 |
| **US** | Honda Accord | private | 189 | - | - | 22% | 144 | - | 1 |
| **US** | Honda Clarity | private | 14 | 2.35 | - | 58% | 158 | - | 1 |
| **US** | Kia Niro PlugIn-Hybrid | private | 6 | 2.93 | 1.30 | 55% | 104 | 58 | 1 |
| **US** | Mitsubishi Outlander PHEV | private | 8 | 3.59 | 1.70 | 55% | 120 | 54 | 1 |
| **US** | Sonata plug-in hybrid | private | 5 | 3.29 | - | 45% | 153 | - | 1 |
| **US** | Toyota Prius PHEV | private | 1622 | 4.24 | 1.88 | 30% | 98 | 30 | 5 |

## ANNUAL ELECTRIC MILEAGE BY NEDC RANGE FOR PHEVS AND RANGE-EXTENDED ELECTRIC VEHICLES

The main text showed the effect of NEDC range on annual electric kilometers driven for all PHEVs. The following figure distinguishes between PHEVs and range-extended electric vehicles, the Chevrolet Volt, Opel Ampera, and BMW i3 REX. The depedence of annual electric kilometers driven on range and the mean values of annual electric kilometers driven for fixed given ranges are the same as in the main text.

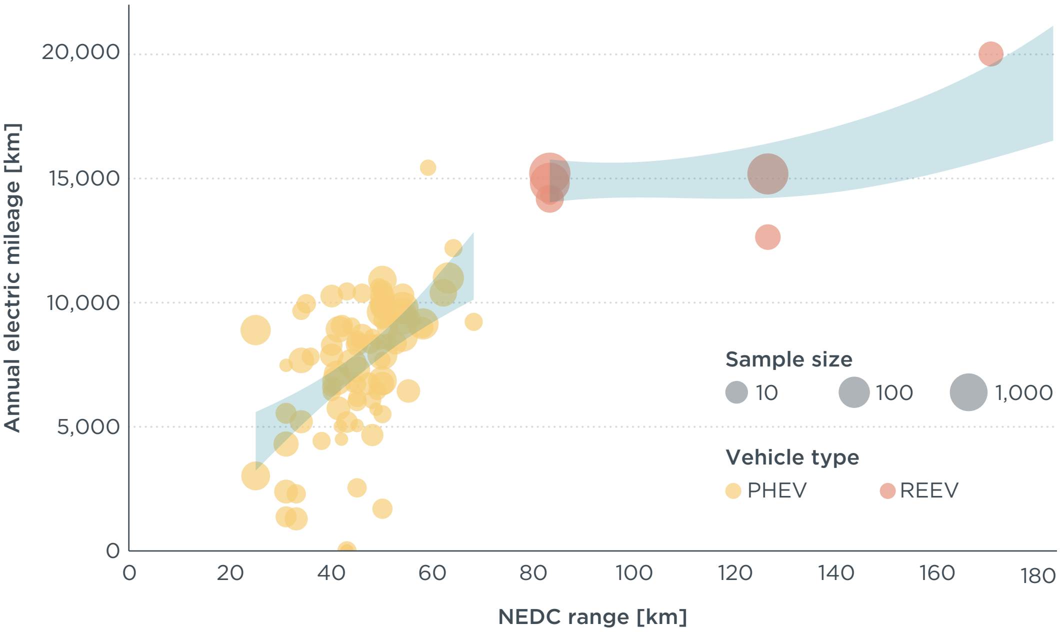

**Figure A2. Annual electric mileage by NEDC range**. Mean annual electric mileage by PHEV model variant for the range-extended electric vehicles (REEVs) (squares) and PHEVs (circles). Every data point corresponds to a model mean with different sample sizes (indicated by the size of the symbol). The shaded area is a sample size-weighted local smoother (95% confidence bands of generalized additive model).

## REGRESSION ANALYSIS – AGGREGATED VEHICLE DATA

Since the direct emissions are strictly non-negative, we use an exponential for the effect of all-electric range (AER) $FC^{real} = \exp(\beta_0 + \beta_1 \text{Power} + \beta_2 \text{AER} + \beta_3 \text{usergroup} + \beta_4 \text{country}) + \varepsilon$. Here, the system power (Power), i.e. combustion engine power plus electric motor power measured in 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 fuel consumption approaches a finite value (i.e. the emissions in the charge-sustaining mode) and is decreasing to zero for AER→∞ (i.e. a negative $\beta_2$). Likewise, the fuel consumption approaches zero for Power→0and grows with increasing power (i.e. positive $\beta_1$). The inclusion of weight as an additional covariate does not alter the results shown below. The regression is performed after taking logarithms of the above equation $\ln (FC^{real)} = \beta_0 + \beta_1 \text{Power} + \beta_2 \text{AER} + \beta_3 \text{usergroup} + \beta_4 \text{country} + \varepsilon$ by ordinary least squares. The model itself and all coefficients are significant ($p < 0.05$) and the coefficients have the expected signs ($\beta_1 > 0$ and $\beta_2 > 0$) for AER→0 and are significantly different from zero. In the regression for aggregated values, we compare averages of subsamples with different sample sizes. We use weighted least squares to adjust for these differences in sample size. More specifically, the uncertainty of the individual sample averages has nonconstant variance (heteroskedasticity). To correct for the different variances in the observations, each observation is weighted by the inverse of its standard error. In our case of mean values, the weights are thus proportional to the reciprocal of $1/\sqrt{N} = \sqrt{N}$. We thus use the square roots of sample sizes as weights.

**Table A3. Factors impacting average real-world fuel consumption**. Dependent variable: (log of) real-world fuel consumption in l/100 km. Standard errors in parentheses. Source: Own calculations. *p<0.05; **p<0.01; ***p<0.001.

| | **Sample-size weighted** | **Not sample-size weighted** |
|---|---|---|
| | **Change in real-world average fuel consumption** | |
| **All-electric range [10 km]** | –13%*** (0.5%) | –9% *** (0.6%) |
| **System power [10 kW]** | +3.1% (0.3%) | +2.8%*** (0.2%) |
| **Company cars** | +31%*** (11%) | +32%*** (5.5%) |
| **Country: China** | +44%*** (5%) | 40%*** (4%) |
| **Country: NL** | | +20%*** (7.4%) |
| **Country: NO** | –12% (7.7%) | –17%* (8.6%) |
| **Country: US** | –12% (5.4%) | –19%* (5.2%) |
| *Observations* | 211 | 225 |
| *$R^2$* | 0.913 | 0.812 |
| *Adjusted $R^2$* | 0.910 | 0.806 |
| *F-Statistics* | 355*** (df = 6; 204) | 134*** (df = 7; 217) |

**Table A4. Regression results for UF real**. Quasi-binomial regression model with robust standard errors in parentheses. Source: Own calculations. *p<0.05; **p<0.01; ***p<0.001.

| | **Dependent variable: UF** | | |
|---|---|---|---|
| | **Sample-size weighted** | **Not sample-size weighted** | **Without Chevrolet Volt** |
| **All-electric range [10 km]** | 0.232***<br>(0.033) | 0.175***<br>(0.016) | 0.222***<br>(0.019) |
| **System power [10 kW]** | -0.037***<br>(0.006) | -0.042***<br>(0.006) | -0.033***<br>(0.005) |
| **Company cars** | -1.333***<br>(0264) | -1.186***<br>(0.287) | -1.354***<br>(0.261) |
| **Country: China** | -0.991***<br>(0.088) | -0.836***<br>(0.089) | -0.995***<br>(0.082) |
| **Country: Netherlands** | | 0.163<br>(0.290) | |
| **Country: NO** | 0.324***<br>(0.082) | 0.335***<br>(0.089) | 0.332***<br>(0.078) |
| **Country: US** | 0.013<br>(0.140) | 0.034<br>(0.102) | -0.255*<br>(0.126) |
| **Constant** | -0.781***<br>(0.159) | -0.426***<br>(0.131) | -0.790***<br>(0.116) |
| *Sample size weighted* | Yes | No | Yes |
| *Chevrolet Volt included* | Yes | Yes | No |
| *Observations* | 214 | 228 | 197 |
| *Null Deviance* | 507.5 | 44.0 | 279.5 |
| *Residual Deviance* | 93.4 | 16.7 | 68.3 |

### Regression Analysis – Individual Vehicle Level Data

We performed regression analysis of the individual UFs on annual mileage, all-electric range, system power, and other control variables (user group and country). We ran regression models with and without the Chevrolet Volt and with and without an interaction between annual mileage and all-electric range, as an increase in range could be expected to decrease with annual mileage.

**Table A5. Fractional logit regression on UF for individual vehicle data**. Quasi-binomial regression model with robust standard errors in parentheses. Source: Own calculations. *** p<0.001, ** p<0.01, * p<0.05.

| | Dependent Variable: UF | | | |
|---|---|---|---|---|
| | (1) | (2) | (3) | (4) |
| **Annual mileage [1000 km]** | -0.029***<br>(0.001) | -0.026***<br>(0.002) | -0.040***<br>(0.003) | -0.036***<br>(0.009) |
| **All-electric range [10 km]** | -0.002<br>(0.005) | 0.175***<br>(0.013) | -0.029***<br>(0.009) | 0.128***<br>(0.038) |
| **System power [10 kW]** | -0.049***<br>(0.005) | -0.031***<br>(0.004) | -0.048***<br>(0.005) | -0.031***<br>(0.004) |
| **Private users** | 1.245***<br>(0.224) | 1.219***<br>(0.220) | 1.200***<br>(0.225) | 1.200***<br>(0.221) |
| **Country US** | 0.938***<br>(0.037) | -0.554***<br>(0.140) | 0.954***<br>(0.038) | -0.554***<br>(0.140) |
| **Interaction annual VKT & all-electric range** | | | -0.001***<br>(0.0003) | 0.002<br>(0.002) |
| **Intercept** | -0.044<br>(0.241) | -1.265***<br>(0.252) | 0.230<br>(0.255) | -1.004***<br>(0.330) |
| *Chevy Volt data included?* | Yes | No | Yes | No |
| *Sample N* | 11,759 | 1,602 | 11,759 | 1,602 |
| *Null deviance* | 2383.4 | 352.06 | 2383.4 | 352.06 |
| *Residual deviance* | 1679.7 | 242.32 | 1677.3 | 242.08 |

The regression results on the effect of annual mileage, system power, and user group are fairly robust against exclusion of the Volt data and the inclusion of an interaction term.

**Table A6. Typical change in UF by changing variables**. Marginal effects at means (MEM) with standard errors in parentheses. Source: Own calculations. *** p<0.001, ** p<0.01, * p<0.05.

| | Marginal effect on UF | |
|---|---|---|
| | (1) | (2) |
| **+1,000 km annual mileage** | -0.63%***<br>(0.04) | -0.63%***<br>(0.01) |
| **+10 km all-electric range** | -0.04%<br>(0.21) | +4.3%***<br>(0.95) |
| **+10 kW system power** | -1.04%***<br>(0.24) | -0.76%**<br>(0.28) |
| **Private user instead of company car** | +30.0%***<br>(8.5) | +25.5%***<br>(5.9) |
| **Country: U.S. instead of Germany** | +22.0%***<br>(2.0) | -12.9%<br>(7.2) |
| *Chevy Volt data included?* | Yes | No |
| *Sample size N* | 11,759 | 1,602 |

We also analyzed more complex regression models including interaction terms between range and annual mileage, but the total effect of mileage and range remained the same.

**Table A7. Regression of fuel consumption on impact factors in Germany and the United States**. Dependent Variable: (log of) real fuel consumption in l/100 km. Standard errors in parentheses. Source: Own calculations. *** p<0.001, ** p<0.01, * p<0.05.

| | Change in real-world average fuel consumption | |
|---|---|---|
| | **(1)** | **(2)** |
| **+1,000 km annual mileage** | +2.1%***<br>(0.1%) | +1.0%***<br>(0.1%) |
| **+10 km NEDC all-electric range** | −1.5%***<br>(0.3%) | −11.4%***<br>(0.6%) |
| **+10 kW system power** | +3.8%***<br>(0.4%) | +3.1%***<br>(0.2%) |
| **User group: private** | −20.4%***<br>(8.5%) | −23.4%***<br>(5.2%) |
| **Country: U.S.** | −68.3%***<br>(2.7%) | +1.2%<br>(6.3%) |
| *Chevrolet Volt included?* | Yes | No |
| *Observations* | 11,759 | 1,602 |
| *$R^2$* | 0.246 | 0.379 |
| *Adjusted $R^2$* | 0.246 | 0.377 |
| *F-Statistics* | 766.6*** | 194.9 |

## Effect of Observation Period on Simulated UF

To measure the effect of short observation periods on simulated UF, we simulate the same driving data with increasing observation period. To this end, we use the daily VKT of the large Chevrolet Volt driving dataset from the Voltstats.net sample. We use only vehicles with at least 100 days of observation and no more than 25% missing values. Each vehicle's daily driving is simulated as PHEVs with 20, 40, 60, 80, and 100 km real-world range. The mean UF over the sample is calculated.

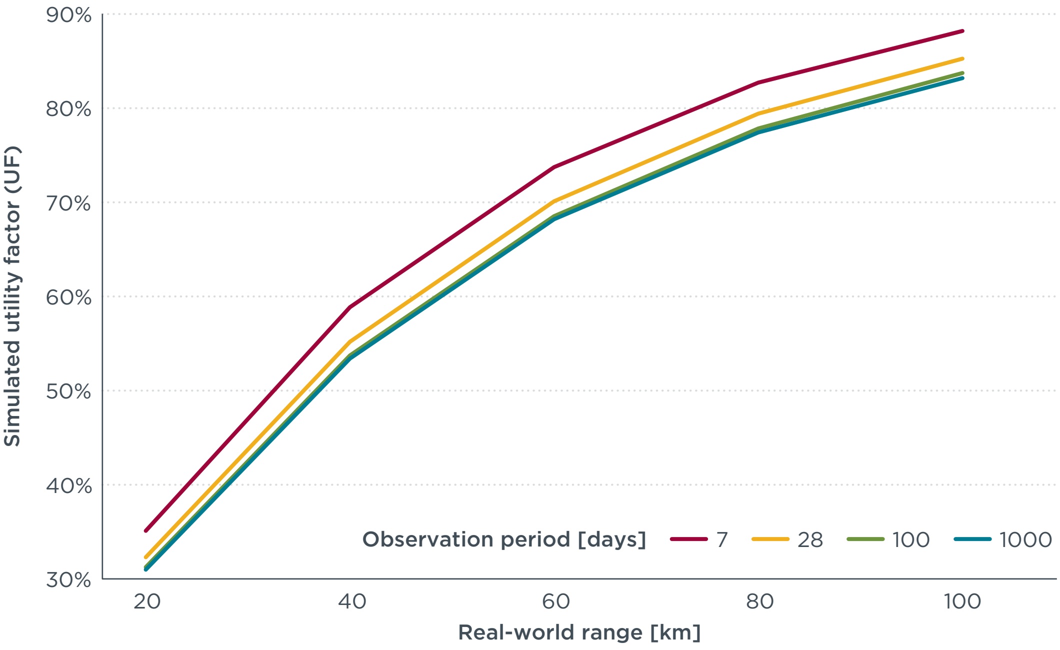

**Figure A3. Effect of observation periods on simulated UF**. The simulated UF is shown as a function of real-world range in km for different observation periods of the driving data in the simulation: 7 days (red), 28 days (orange), 100 days (light green), and 1,000 days (blue). The simulated UF for given range decreases with observation period as long-distance trips are rare and appear only in long observation periods.

The simulation with increasing observation period clearly shows a decrease in simulated UF by about 5 percentage points as the observation period increases. The difference is particularly strong from 7 to 28 days, but still clearly visible from 28 to 100 days.