

Realistic Test Cycle Utility Factors for Plug-in Hybrid Electric Vehicles in Europe

Imprint

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Project coordination

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Dienstleistungsauftrag „Wissenschaftliche Unterstützung Klimapolitik und Maßnahmenprogramm 2018“ ELViS-ID E31564581
Federal Ministry

Picture credits

Cover page: Own illustration.

Recommended citation

Plötz, P. and Jöhrens, J. (2021): Realistic Test Cycle Utility Factors for Plug-in Hybrid Electric Vehicles in Europe. Karlsruhe: Fraunhofer Institute for Systems and Innovation Research ISI

Published

April 2021

Notes

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Summary

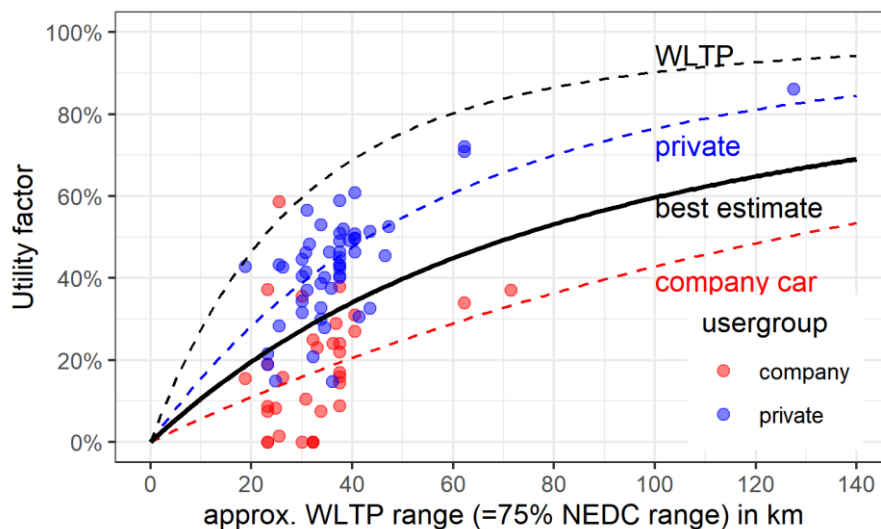
Plug-in hybrid electric vehicles (PHEVs) can use electricity as well as conventional fuel for propulsion (Bradley & Frank, 2009). But, the potential of PHEV to reduce local pollutant and global greenhouse gas emissions (GHG) strongly depends on their real-world usage and the share of kilometres driven on electricity, the so-called utility factor (UF). Generic functions for UF of PHEV are used 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). However, as empirical data on real-world usage of PHEV was scarce until recently, the current WLTP estimates were based on information provided largely by vehicle manufacturers and did not reflect real-world usage of PHEVs.

The aim of this study is to provide UF estimates that are based on empirical PHEV usage data. For this purpose, real-world data on PHEV usage is taken to determine empirical parameters for generic UF functions.

We fitted the existing WLTP UF function to empirical PHEV usage for 1,385 private PHEV from Germany and 10,872 company cars from Germany and the Netherlands. These two markets cover about 40% of PHEV in Europe. We find that the current WLTP UF parameters are too optimistic about real-world UF since long-distance driving was missing in earlier estimates, actual charging is less frequent than commonly assumed and real-world all-electric ranges are lower than WLTP ranges. All three factors lower the actual UF compared to the WLTP UF. We empirically obtain modified UF curves for both user groups and one joint UF curve for both groups assuming equal mileage in both user groups (see the following figure).

Figure: Real-world UF curve for private, company car and both groups combined.

Shown are mean UF for individual PHEV model variants (circles) in private (blue) and company car (red) usage with the WLTP UF curve (black dashed), the best empirical private (blue), company car (red), and joint private and company car UF curve (solid).



Source: Own calculations.

Our best estimate for a realistic UF curve is the WLTP UF curve with the d_n parameter changed from $d_n = 800$ km in WLTP to $d_n = 1540$ km in real-world operation for private cars and to $d_n = 4200$ km for company cars. The best joint estimate with the assumption of 50% private and 50% company car mileage is with $d_n = 2460$ km. Our results show that the existing but unrealistic WLTP UF curve can be easily modified to obtain more realistic UF curves for PHEV in Europe.

1 Introduction

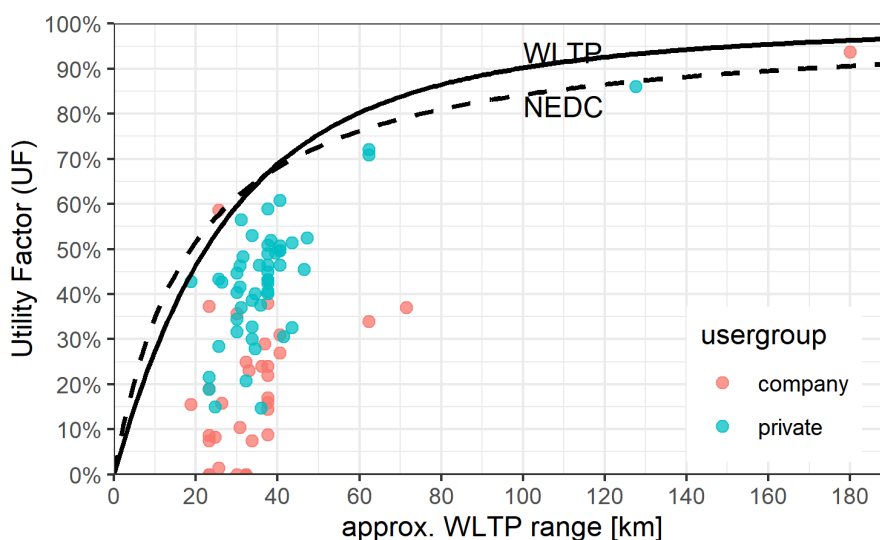
Plug-in hybrid electric vehicles (PHEVs) can use electricity as well as conventional fuel for propulsion (Bradley & Frank, 2009). In 2020, PHEVs accounted for about 3.5% of all new passenger car registrations in Europe.

The potential of PHEV to reduce local pollutant and global greenhouse gas emissions (GHG) strongly depends on their real-world usage and the share of kilometres driven on electricity, the so-called utility factor (UF) (Chan, 2007; Jacobson, 2009; Flath et al., 2013; Plötz et al., 2020).

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). However, as empirical data on real-world usage of PHEV was scarce until recently, the current test cycle estimates were based on information provided largely by vehicle manufacturers and did not reflect real-world usage of PHEVs. Vehicles with long-distance driving were excluded from the analysis and the mean of simulated individual UF was used as basis for the WLTP UF (Eder et al., 2016). A few recent studies provide the first systematic investigation of PHEV usage as well as UF in Europe (Plötz et al., 2020; Plötz et al., 2021). The underlying hypothesis of the present study is a mismatch between empirical and official test cycle UF. To support this hypothesis, Figure 1 shows the empirical UF from the 1,450 PHEV in Germany (aggregated to PHEV model variant mean values) and the official UF curves according to WLTP and NEDC. Despite the still limited sample size for empirical PHEV usage and UF, strong deviations between WLTP UF and actual UF are apparent.

Figure 1: Real-world UF in Germany and test-cycle UF as a function of all-electric range.

Shown is PHEV usage data (mean by PHEV model variant) for Germany for private and company cars. The WLTP UF curve as a solid line and the NEDC UF curve as dashed line. WLTP ranges are assumed 75% NEDC ranges.



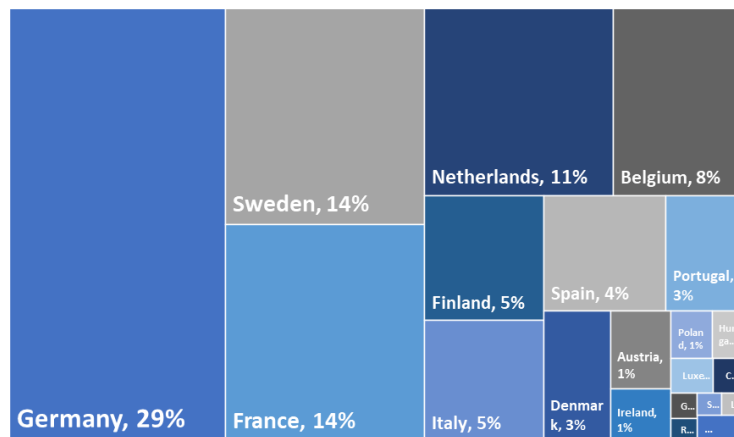
Source: Plötz et al. (2020).

We observe a clear mismatch between official and actual UF. Almost all observations are smaller than WLTP UF and only a few PHEV observations come close to the test-cycle UF. The deviation is larger for company cars than for private vehicles. Accordingly, the apparent systematic deviation between actual and official UF renders the derivation of empirical UF curves meaningful.

The aim of this study is to provide UF estimates that are based on empirical PHEV usage data using least-squares regression analysis. Thus, the present paper aims at filling the gap between simulated UF from conventional vehicles and real-world UF from actual PHEV.

As of the beginning of 2021, there are about 978,000 PHEV in stock in the EU27 (according to www.eafo.eu). The largest markets are Germany (287,000 PHEV in stock), Sweden (132,400), France (132,300), the Netherlands (108,700), Belgium (75,000), Finland (45,600), Italy (44,200), and Spain (43,500). All other markets have less than 30,000 PHEV in stock (as of beginning 2021). The following figure shows the percentage.

Figure 2: PHEV in stock shares in EU27.



Source: Own illustration based on www.eafo.eu.

Here, we cover private and company cars from Germany, the single largest PHEV market in Europe and company cars from the Netherlands. Both market contain about 40% of the PHEV in stock in the EU27.

2 Data and Methods

2.1 PHEV Usage Data

The present study uses PHEV usage data from Germany (private and company cars) and the Netherlands (company cars). All data are taken from Plötz et al. (2020). The individual sources and data cleaning are discussed in detail there and we only give a short summary here (cf. Table 1).

Table 1: Summary of PHEV Usage data sources

Source	Sample size	PHEV model variants	Country
Spritmonitor.de	1,385	51	Germany
German company	72	21	Germany
TNO	10,800	14	Netherlands

Source: Own calculations.

For privately owned vehicles in Germany, we use Spritmonitor.de as source. Spritmonitor.de is a free German web service that allows users to track fuel consumption of their 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. Users provide odometer reading, distance travelled since the last refuelling, and fuel volume added. 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. The UF was calculated according to the methodology explained in section 2.2. After data cleaning, a sample of 1,385 is obtained that represented 1% of the German PHEV stock in 2020.

For company cars in Germany, data from a large private company in Germany with more than 10,000 employees was obtained. 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 sample stems only from one company, but the observed fuel consumption values and impact of all-electric range are in line with the much larger company car sample from the Netherlands (see below). The UF was calculated according to the methodology explained in section 2.2. For this study, a sample of 72 vehicles was available. This sample is quite limited but not far from the original sample of 100 combustion engine vehicles that were used to derive the official WLTP UF curve (Eder et al., 2016).

For the Netherlands, Company car fuel consumption values are available from (Van Gijlswijk & Ligterink, 2018) as well as (Ligterink & Eijk, 2014). The individual values have been taken from these publications. However, one drawback of this data is the lack of sample sizes for individual PHEV models, only the total number of PHEV in the sample is available with $N = 10,800$, and it can be assumed that each PHEV model has a minimum of several hundred observations. On the other hand, an advantage of the data is that the mean UF per PHEV model is already part of the data and does not have to be derived from the observed real-world fuel consumption.

Detailed vehicle specifications such as fuel consumption or all-electric range according were taken from the ADAC-Autokatalog (ADAC, 2020), which contains the required information for PHEV models available on the European market.

Please note that WLTP information was available for a very small sub sample of the data described above. Accordingly, NEDC values have been used throughout for the all-electric range and converted to WLTP as follows. We assume a higher real world electricity consumption for WLTP compared to NEDC (Dornoff et al., 2020). This leads to a lower all-electric range. We assume that the WLTP range is three quarters of the NEDC range. This is the value has been used in the initial UF definition for the WLTP (Eder et al., 2016). This value should be viewed as a conservative estimate; analysis of a small sample of current PHEV models suggests that values of around 85-90% are typical.¹ This means our method will tend to slightly over-estimate empirically derived electric driving shares.

2.2 Methods

The present section explains the UF curves, i.e. the function relating the PHEV's all-electric range to an expected UF, the calculation of the empirical UF, and the regression method to obtain empirical UF curves from PHEV usage data.

WLTP UF Definition

The official WLTP UF curve² in Europe is given by

$$UF(AER, d_n) = 1 - \exp \left[- \sum_{i=1}^{10} c_i \left(\frac{AER}{d_n} \right)^i \right],$$

where AER is the WLTP all-electric range in km and the numerical constants c_i and d_n for Europe are $d_n = 800$ km, $c_1 = 26.25$, $c_2 = -38.94$, $c_3 = -631.05$, $c_4 = 5964.83$, $c_5 = -25095$, $c_6 = 60380.2$, $c_7 = -87517$, $c_8 = 75513.8$, $c_9 = -35749$, $c_{10} = 7154.94$ according to (EC 2017). These official WLTP parameters for the curve have been determined from driving data of conventional vehicles, analysing their daily mileages and assuming a full recharge every night for PHEVs. Furthermore, vehicle profiles with mileages of more than 100 km per day had been eliminated from the driving data, since such profiles were not regarded economically feasible for PHEVs. However, more recent empirical data shows the private vehicles in Germany are – on average – only charged three out of four nights and company cars only every second (Plötz et al., 2020). Furthermore, PHEV show much long distance driving and more than 100 km of daily driving are not exceptional (Plötz et al., 2020). Thus, some of the assumptions in the derivation of the WLTP UF curve are not fulfilled in actual PHEV usage.

The official WLTP curve with its exponential form provokes the general question of matching functional forms for UF curves and their dependence on all-electric range. Quite generally, four fundamental conditions appear required for any UF curve: (1) Its range should be limited to the interval from zero to one,³ (2) it should be zero at zero all-electric range, (3) it should converge to one as the all-electric range approaches infinity, and (4) it should be monotonically increasing with all-electric range. An infinite number of mathematical functions fulfil these criteria. However, practical aspects make simple forms with only a few parameters preferable. The form $UF(x) = 1 - \exp(-f(x))$ with a monotonically increasing

¹ This value is consistent with the deviation between WLTP and NEDC range in a small sample of PHEV from the ADAC autokatalog, where we included the BMW 225 XE iPerformance, BMW x5 xDrive 45e, Mercedes A 250 e, Hyundai IONIQ Plug In-Hybrid, Volvo XC60 T8 Twin Engine, Opel Grandland X 1.6 DI Turbo Hybrid4, and Opel Grandland X 1.6 DI.

² Strictly speaking, the UF in the WLTP definition measures the share of km driven in charge depleting mode which allows for intermittent deployment of the internal combustion engine (ICE). In contrast, we derive our empirically estimated UFs based on a tacit estimate of the driving share in pure electric mode with zero fuel consumption. Depending on powertrain characteristics and operating strategy, some vehicles may not foresee any ICE deployment in charge depleting mode, i.e. there is no difference between pure electric mode and charge depleting mode. Other vehicles tend to increasingly make use of their ICE under higher load conditions and with decreasing battery state of charge. In such cases, the share of km driven in charge depleting mode with non-zero fuel consumption is higher than the share in pure electric mode with zero fuel consumption. At the same time, the charge depleting range is higher than pure electric range. Overall, we expect our method of estimating the relationship between pure electric range and the share of km driven in pure electric mode to result in a very similar UF-curve compared to estimates based on the relationship between charge depleting range and share of km driven in charge depleting mode. However, more research on the relation between pure-electric UF and CD-mode UF is required.

³ and need only be defined for non-negative all-electric ranges.

function $f(x)$ and $x = AER/d$ being the all-electric range divided by a scale parameter d requires already the first three criteria. Accordingly, the WLTP UF curve fulfils the general criteria that a UF curve should meet. The complexity of the function form, i.e. a polynomial of degree ten in the case of the UF curve, should be large enough to follow empirical data, but not more complex. Thus, the general form of the official UF curve is acceptable. However, one or several of the parameters should be chosen such that the curve follows actual real world UF data.

The parameter d_n in the official UF curve is an effective driving distance that rescales the all-electric range. Higher d_n means that the same all-electric range leads to a lower UF. For the present study we use the official WLTP UF curve but treat the scaling parameter d_n as a free parameter. This has the advantage that we keep the functional form of the UF curve which has the right asymptotic behaviour (zero UF for zero km range, 100% UF for infinite range and strong monotonically increasing) and would be simple to change in legislation as only one parameter needs to be changed. In the results part below, we will obtain d_n values that lead to UF curves following the empirical UF data.

UF Calculation from Fuel Consumption Data

For the Dutch dataset, UFs are explicitly given and can be used as input values for the regression analysis. For the other datasets, where the actual UF is missing, we estimate the real-world UF from the real-world fuel consumption

$$UF^{\text{real}} = 1 - FC^{\text{real}}/FC_{\text{cs}}^{\text{real}}$$

with "CS" indicating "charge sustaining mode". Here, $FC_{\text{cs}}^{\text{real}}$ is approximated by taking NEDC values with 50% addition for real-world driving, similar to the deviation between NEDC and real-world fuel consumption of HEV (Plötz et al., 2020; Dornoff et al., 2020, Tietge et al., 2019):

$$FC_{\text{cs}}^{\text{real}} = 1.5 FC_{\text{cs}}^{\text{NEDC}} = 1.5 \frac{FC^{\text{NEDC}}}{1 - UF^{\text{NEDC}}}.$$

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: $FC_{\text{cs}}^{\text{real}} = FC_{\text{cs}}^{\text{EPA}}$. Likewise, when the real UF is known, the real-world consumption can be estimated by inverting the above equations:

$$FC^{\text{real}} = FC_{\text{cs}}^{\text{real}}(1 - UF^{\text{real}}) = 1.5 FC_{\text{cs}}^{\text{NEDC}} (1 - UF^{\text{real}}).$$

For all WLTP cases with UF missing, NEDC fuel consumption values were available and the UF derived as explained above. A further discussion of the applied method for UF calculation can be found in (Plötz et al., 2020).

Regression Analysis

We used standard statistical methods to find the value for the parameter d_n that best matches the empirical data. "Best" is defined as smallest sum of squared deviations. More specifically, we use non-linear weighted least squares to adjust for differences in sample size in regression. To correct for the different sample sizes in the observations for mean UF, each observation is weighted.⁴ As the UF function depends non-linearly on the d_n parameter, we perform a non-linear fit.

⁴ by the inverse of its standard error which is proportional to the square roots of sample sizes, cf. (Plötz et al., 2020)

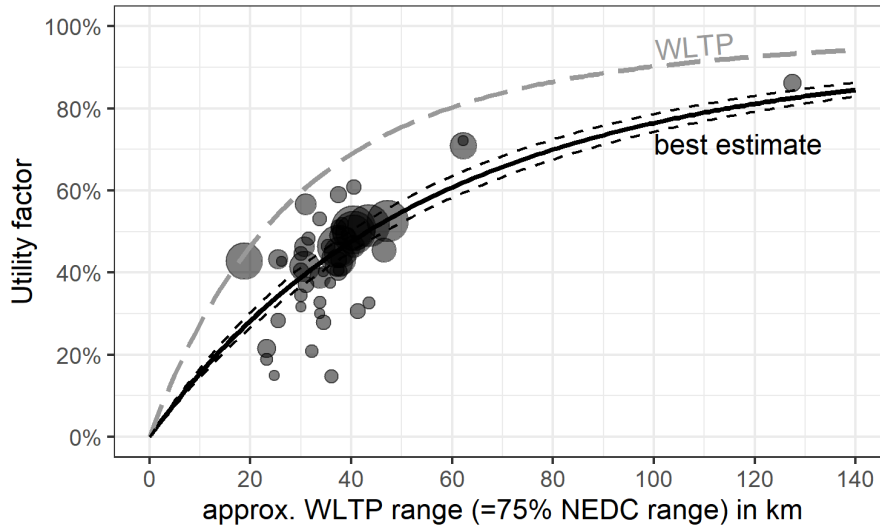
3 Results

3.1 UF Curve for Private Cars

We first derive an empirical UF curve for private vehicles in Germany, following the methodology outlined in the previous section. We use the UF curve from WLTP but treat the scaling parameter d_n as free parameter and find the d_n which best fits the empirical data by sample size weighted non-linear least squares. The resulting best estimate from the non-linear sample size weighted regression is $d_n = 1544 \pm 124$ km (with \pm two standard errors) and $d_n = 1750 \pm 140$ km if WLTP range is assumed 85% NEDC range. Thus the empirical d_n is around twice the official WLTP value of $d_n = 800$ km. This is effectively rescaling the daily driving distance by a factor of two, i.e. real world vehicles need about twice the range to reach the official WLTP UF than expected from WLTP. The data and best empirical UF curve are shown in Figure 2.

Figure 2: Utility factor as a function of all-electric range for private cars in Germany.

Shown is PHEV usage data (mean by PHEV model variant) for private cars in Germany (circles by sample size with larger circles for larger samples). The WLTP UF curve is shown as dashed grey line, the best empirical UF curve as black solid line (with \pm two standard errors as this dashed lines). WLTP ranges are assumed 75% NEDC ranges.



Source: Own illustration.

The figure also shows the empirical UF curve when the statistical uncertainty of the parameter d_n is taken into account as thin dashed lines. It shows that the deviation from the official UF curve is much larger than the statistical inaccuracy.

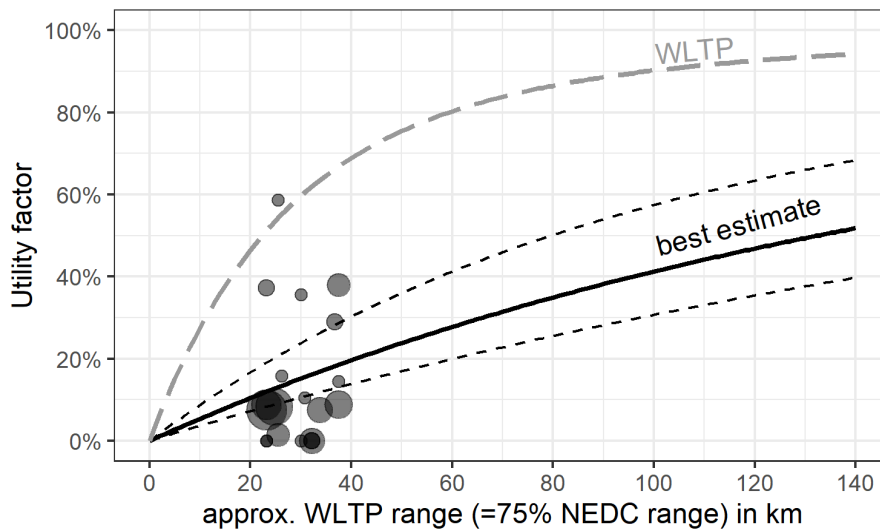
3.2 UF Curve for Company Cars

We now turn to real-world UF of company cars. In a first step, only company cars from Germany are analysed. We perform sample size weights non-linear regression and obtain the best estimate as $d_n = 4740 \pm 2250$ km (and $d_n = 5400 \pm 2500$ km if WLTP range is assumed 85% NEDC range). Thus the empirical d_n is around six times the official WLTP value of $d_n = 800$ km. This is effectively rescaling by a factor of six, i.e. real world vehicles need about six times the range to reach the official WLTP UF than expected from WLTP. The data and best empirical UF curve are shown in Figure 3. The figure also shows

the empirical UF curve when the statistical uncertainty of the parameter d_n is taken into account as thin dashed lines, but the deviation between official UF curves is much larger than the statistical inaccuracy.

Figure 3: UF versus all-electric range for company cars in Germany.

Shown is PHEV usage data (mean by PHEV model variant) for company cars in Germany (circles by sample size). The WLTP UF curve is shown as dashed grey line, the best empirical UF curve as black solid line (with \pm two standard errors as this dashed lines). WLTP ranges are assumed 75% NEDC ranges.

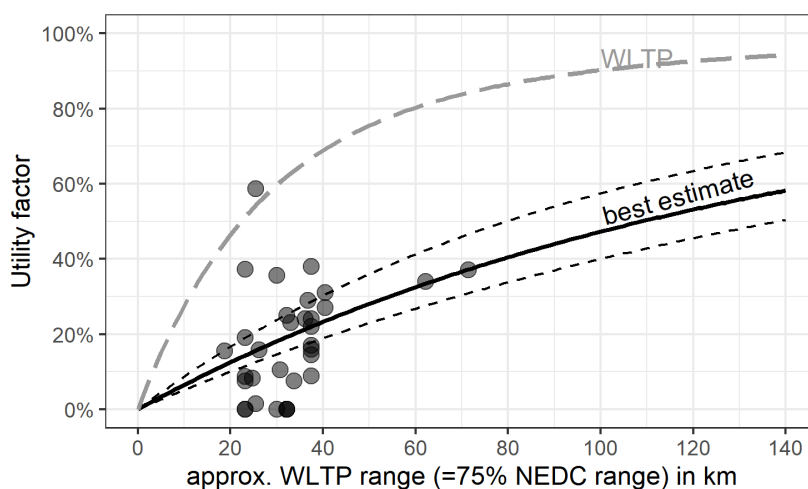


Source: Own illustration.

As the company car sample from Germany has a very limited sample size, we combine the larger data set from the Netherlands (N = 10,800) with the German data. However, as no information is available on the individual sample sizes for PHEV model variants in the Dutch data, we can only perform non-weighted least squares regression. Figure 4 shows the resulting UF curve.

Figure 4: UF versus all-electric range for company cars in Germany and the Netherlands.

Shown is PHEV usage data (mean by PHEV model variant) for company cars in Germany and the Netherlands (circles). WLTP UF curve as dashed grey line, best empirical UF curve solid line (\pm two SE dashed).



Source: Own illustration.

We obtain as best estimate for company cars in Germany and the Netherlands as $d_n = 3900 \pm 1050$ km (and $d_n = 4400 \pm 1200$ km if WLTP range is assumed 85% NEDC range). Thus the empirical d_n is almost six times the official WLTP value of $d_n = 800$ km. This is effectively rescaling by a factor of six, i.e. real world vehicles need about five times the range to reach the official WLTP UF than expected from WLTP. Figure 4 also shows the empirical UF curve when the statistical uncertainty of the parameter d_n is taken into account as thin dashed lines, but the deviation between official UF curves is much larger than the statistical inaccuracy.

Taking both results together, i.e. the sample size weighted regression for Germany and the non-weighted regression for Germany and the Netherlands, we obtain approximately $d_n = 4500$ km as best empirical estimate for a UF curve for company cars in Europe.

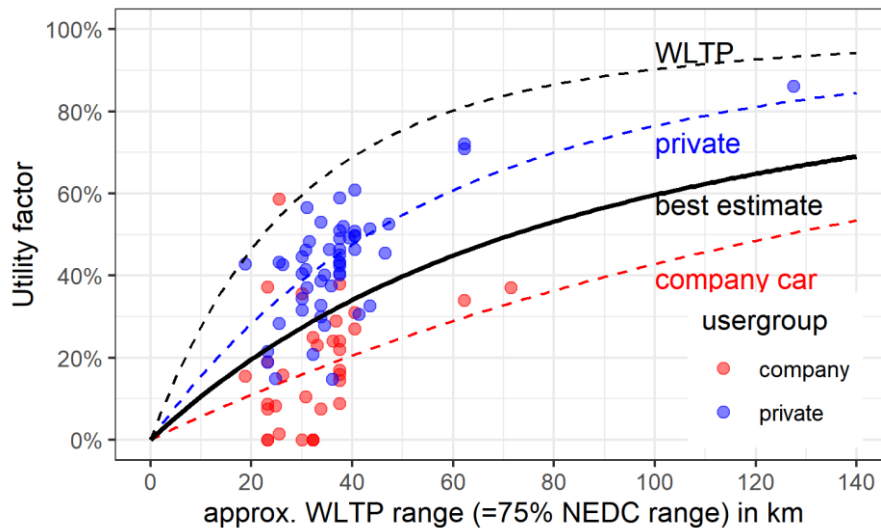
3.3 PHEV Stock UF Curve

As the actual PHEV stock consists of both private and company cars, we combine the estimate into a joint best-estimate UF curve as an evenly weighted average of the above curves. Currently, the share of company cars in PHEV stock in Germany is slightly above 50% (cf. Jöhrens et al. 2020). It is conceivable that the share of private PHEV stock will increase over time as company cars are sold off to the private market after 3-4 years. However, the average annual mileage driven for company cars is significantly higher than for private cars. We expect the impact of slightly higher private ownership versus lower mileage under private ownership to approximately cancel each other out. It therefore appears appropriate to weigh company cars and private cars evenly.

We obtain the weighted sum of the two UF curves is $0.5 \text{ UF(AER, } d_n = 1544) + 0.5 \text{ UF(AER, } d_n = 3900)$. Please note that the weighted sum of this functions with two parameters is not equal to the function of the weighted sum of parameters as the UF function is non-linear in the d_n parameter. However, the weighted sum has a form similar to the original UF function and we can find a parameter value that closely matches the weighted sum. We obtain a UF curve with $d_n = 2460$ km as good estimate for the joint private and company car UF curve. In this case the mean absolute percentage deviation from the weighted sum is 3.7%. All UF curves are shown in Figure 5.

Figure 5: UF versus all-electric range for private and company cars.

Shown are mean UF for individual PHEV model variants (circles) in private (blue) and company car (red) usage with the WLTP UF curve (black dashed), the best empirical private (blue), company car (red), and joint private and company car UF curve (solid).



Source: Own illustration.

In summary, we obtain an empirical UF curve that takes the functional form of WLTP curve but is derived from empirical data.

4 Discussion

The aim of this study was to derive a best estimate of the current EU real-world utility factor given the empirical data currently available. The resulting curve comes with some uncertainty. The key issue is that currently available data is limited and cannot be considered a truly random sample of the EU PHEV fleet. Inter alia, our sample covers only two European countries. However, these two countries alone currently cover 40% of the PHEV stock in Europe. Furthermore, similarly low UF are observed in other major markets. For example, Plötz et al. (2020) collected a small sample of fuel consumption values from PHEV user reports in the UK, most likely private vehicles. For the 43 PHEV under consideration the mean real-world fuel consumption was much higher than test-cycle values implying similarly low UF. These numbers deviation observed in the small UK sample are consistent with the findings for Germany. The deviation between test cycle and actual UF is less pronounced but still present for Norway acc. to. (Plötz et al., 2020). Yet, Norway has some of the most beneficial economic conditions for high electric driving shares, as it has some of the highest fuel prices and lowest electricity prices in Europe. On the other hand, Germany has some of the highest private electricity prices in Europe and comparatively low fuel prices. In conclusion, the PHEV UF results presented here appear realistic for major markets in Europe but the deviation could be less pronounced in markets with very favourable energy prices.

For company cars, the data is from countries where incentives for owning company cars were quite pronounced while incentives for electric driving are generally limited. Often, company car drivers own a fuel card from the employer to refuel for free and therefore have little financial incentive to plug in. Yet, the obtained curves solely rely on empirical usage data and appear realistic for markets with these economic conditions. However, it is conceivable that average company car utility factors could improve (in the direction of private utility factors) in future, if company policies and Member State policies to support electric driving were improved accordingly.

At present, however, we believe that our “best estimate” is more likely to over-estimate than to under-estimate the true current average electric driving share in the EU: First, we used the assumption that the WLTP range is about 75% of the NEDC range while the true value is probably closer to 85%. (A systematic comparison between WLTP and NEDC ranges would be required but is beyond the scope of the present short paper.) Second, we estimated real world electric driving shares based on conservative estimates of real world fuel consumption (details described above) which in turn leads to optimistic electric driving shares. Third, the sample of private users draws on voluntarily self-reported fuel consumption. It is therefore likely to be biased towards users with an above-average interest in their vehicle’s energy consumption. This is likely to coincide with more regular charging behaviour. Fourth, our sample only includes two vehicle models with high electric range: the Chevrolet Volt/Opel Ampera and the BMW i3 REX. Compared to other plug-in hybrids, those two models resemble pure electric vehicles and are generally referred to as “range-extended electric vehicles”; moreover the i3 REX’s fuel tank only holds 9 litres. Due to these vehicle characteristics, their electric driving share is likely to exceed that of other PHEVs with similar range. Data on spritmonitor.de of three recent PHEV models with WLTP ranges between 68 and 98 km (not included in our slightly older data set) suggest significantly lower electric driving shares compared to the Volt/Ampera and the i3 REX.

Despite the very limited data on long range PHEVs, our estimate of about 60 % mean UF for PHEV with 100 km all-electric WLTP range is consistent with an OEM’s expectation on future UFs of around 50%-60% with a 100 km range⁵.

We therefore believe our study will be helpful in informing policy debates around a revision of the WLTP utility factor. There is a possibility that the true UF-curve will generally improve over time as infrastructure and incentives for electric driving are improved across the EU. Moreover, as more empirical data becomes available, future UF-curves will describe the true (and evolving) relationship between electric ranges and electric driving shares more accurately than our current best estimate. Therefore, the UF-curve should be revised regularly.

5 Conclusion

Recent empirical studies provide evidence that the current WLTP utility factor (UF) function is too optimistic compared to empirical observations of real world electric driving shares of plug-in hybrids. Reasons include long-distance driving being excluded in the development of the WLTP function, actual charging being less frequent than commonly assumed and real-world all-electric ranges being lower than WLTP ranges. All three factors lower the actual UF compared to the WLTP UF. The aim of this study was to provide UF estimates based on empirical PHEV usage data. We believe our “best estimate” offers an approximation of the current “real world”-UF in the EU, more likely over-estimating than under-estimating it. Our study therefore provides a starting point for a potential revision of the WLTP UF. The true UF-curve may generally improve over time as infrastructure and incentives for electric driving are improved across the EU. Moreover, as more empirical data becomes available, future UF-curves will describe the true (and evolving) relationship between electric ranges and electric driving shares more accurately than our current best estimate. Therefore, the UF-curve should be reviewed regularly and, where necessary, revised.

⁵ Cf. <https://www.auto-motor-und-sport.de/tech-zukunft/alternative-antriebe/interview-bmw-entwicklungsvorstand-frank-weber-elektroauto-wasserstoff-phaev-zukunft/>

Table 2: Summary of parameter estimates for UF curve

Shown are the WLTP and the best empirical values for the parameter of a modified WLTP UF curve $UF(AER, d_n) = 1 - \exp[-\sum_{i=1}^{10} c_i (AER/d_n)^i]$, where AER is the WLTP all-electric range in km and $c_1 \dots c_{10}$ are the numerical constants in the current WLTP regulation (EC 2017).

Data	d_n parameter
WLTP	800 km
Private only	1544 ± 124 km
Company car only	4500 ± 1500 km
Best estimate	2600 ± 800 km

Source: Own calculations.

We fitted the existing WLTP UF function to empirical PHEV usage for 1,385 private PHEV from Germany and 10,872 company cars from Germany and the Netherlands. These two markets cover about 40% of PHEV in Europe. We empirically obtain modified UF curves for both user groups and one joint UF curve for both groups assuming 50% stock share for each.

Our best estimate for a realistic UF curve is the WLTP UF curve with the d_n parameter changed from $d_n = 800$ km in WLTP to $d_n = 1540$ km in real-world operation for private cars and to $d_n = 4500$ km for company cars. The best joint estimate with the assumption of 50% private and 50% company cars in PHEV stock is with $d_n = 2600$ km. Our results show that the existing but unrealistic WLTP UF curve can be easily modified to obtain more realistic UF curves for PHEV in Europe.

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