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Real-world Fuel Consumption and Utility Factors of Plug-in Hybrid Electric Vehicles in Europe

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Executive Summary

Plug-in hybrid electric vehicles (PHEVs) combine an electric motor with an internal combustion engine and can reduce greenhouse gas emissions from transport if mainly driven on electricity. Some studies indicate only limited electric driving in real world operation due to charging not every day. Here, we show empirical data from over 8,000 individual PHEV in Europe including real-world fuel consumption (FC) and utility factor (UF). We find that the average real-world fuel consumption of PHEVs in Europe is 4.0–4.4 L/100 km for private vehicles and 7.6–8.4 L/100 km for company cars compared to an average of 1.6–1.7 L/100km in WLTP type approval. These values correspond to tailpipe emissions of 90–105 g CO2/km for private and 175–195 g CO2/km for company cars compared to only 37–39 g CO2/km in WLTP type approval. The average real-world electric driving share is about 45%–49% for private cars and about 11%–15% for company cars. The low electric driving share is one of the main reasons for the high deviation between type approval and real-world fuel consumption. Our results demonstrate the importance of real-world vehicle emission measurements and that real-world fuel consumption are much higher than test cycle vales and UF much lower despite recent advances in all-electric ranges.

1 Introduction

Plug-in hybrid electric vehicles (PHEVs) combine an internal combustion engine with an electric motor [1] and offer the potential to reduce greenhouse gas emissions (GHG), when driven on electricity, to contribute to the targets set by the Paris Agreement [2-4]. However, the potential of PHEVs to reduce local pollutants and global GHG emissions strongly depends on their real-world fuel consumption (FC), which is determined by real-world driving behavior and the share of kilometers driven on electricity, the so-called utility factor (UF) [5-7]. Assessing FC 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 and resulting GHG emissions. There has been no large-scale systematic investigation, at least for Europe.

PHEV FC values are commonly assessed in standardized testing procedures, or test cycles. For Europe, the New European Driving Cycle (NEDC) and the Worldwide Harmonized Light-Duty Vehicles Test

Procedure (WLTP) are most relevant [8-9]. These test cycle values are usually considered for determining CO2 emissions of PHEVs. 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 FC and thus emissions of PHEVs [9-10].

The aim of the present paper is to provide an update pervious work [2, 7, 11] on real-world Fuel consumption (FC) and UF with additional more recent data. The focus of the present study is on Europe and the results heavily rely on [12].

2 Data and Methods

2.1 Data

Our work relies on two main data sources. First, we collect technical and test-cycle information on available PHEV models. We analyze all 1,100 PHEV model variants available in Germany (representative for Europe as it is the largest European car market) with various technical properties as available on the model overview of the General German Automobile Club (cf. https://www.adac.de/rund-ums-fahrzeug/autokatalog/marken-modelle/autosuche/?engineTypes=PlugIn-Hybrid).

Second, real world fuel consumption data of N = 5,808 in Europe is obtained from the online source Spritmonitor.de and was provided by the website operator. The data covers more than ten countries in Europe with a focus on west and central Europe (sample size per country are DE 3878, FR 284, CH 129, AT 109, NL 107, HU 96, FI 91, ES 59, IT 57, DK 57, BE 55, SE 50, and more countries with less than 50 vehicles). It covers all major makes with more than 100 vehicles from (makes in alphabetical order) Audi, BMW, Ford, Hyundai, KIA, Opel, Mercedes, Mitsubishi, Skoda, Toyota, Volvo, VW. Additional PHEV usage data and FC was obtained from 3,047 company cars and further private vehicles rom other online sources: honestjohn.co.uk, Carbuyers.co.uk, MILE21.eu, and fishes-auto.fr. We combine this data with mean fuel consumption values of PHEV in a German survey of 1,531 private PHEV kindly provided by [13]. See [12] for further details.

2.2 Methods

Our data on real-world usage contains real-world fuel consumption. For the NEDC; we derive the real world UF by applying the NEDC definition for the combined fuel consumption and solving the equation for the UF. Specifically, $\mathrm{UF}^{\mathrm{real}} = 1 - \mathrm{FC}^{\mathrm{real}}/\mathrm{FC}^{\mathrm{real}}_{\mathrm{cs}}$. Here, FC^{real}_{cs} is approximated by taking NEDC values with 50% addition for real-world driving, i.e. $\mathrm{FC}^{\mathrm{real}}_{\mathrm{cs}} = 1.5\ \mathrm{FC}^{\mathrm{nedc}}/(1 - \mathrm{UF}^{\mathrm{nedc}})$ with $\mathrm{UF}^{\mathrm{nedc}} = \mathrm{AER}^{\mathrm{nedc}}/(\mathrm{AER}^{\mathrm{nedc}} + 25\mathrm{km})$ (AER = all-electric range). This method is slightly optimistic as a 50% deviation from NEDC is slightly above the fleet mean deviation for conventional combustion engine vehicles and hybrid vehicles [9-11]. The same method is applied to WLTP certified vehicles as the operation can also be divided into a purely electric and combustions engine operation [13].

3 Results

3.1 All-electric ranges of new PHEV models

Since the first PHEVs entered the market about ten years ago, vehicle properties have changed. More recently, mean all electric ranges started to increase (cf. Fig.1). We find that the mean WLTP range of available models has increased from 47 km in 2018 to 58 km in 2021 with a large range of available ranges for individual models.

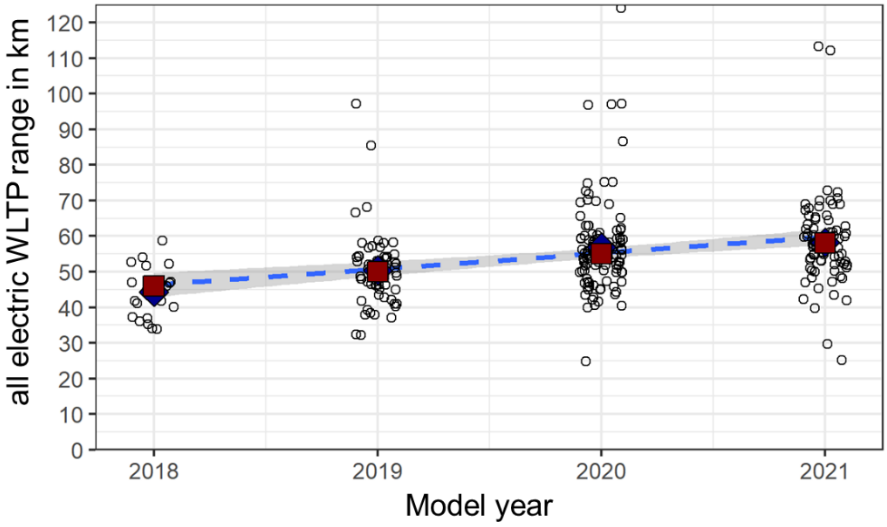

Figure 1: All-electric ranges (AERs) for PHEV models available in Germany by construction year (small circles) with mean (blue diamonds) and median (red squares) values by year together with a line regression (blue dashed line).

3.2 Real-world FC

We analyze the mean real-world FC of private PHEV in Europe according to construction year in Fig. 2 (sample weighted mean values ± two standard error (SE = SD/$\sqrt{N}$), with standard deviation SD and sample size N). We observe an increase in mean FC between 2012 and 2021 with an average FC of 4.65 ± 0.1 L/100 km in the most recent 2021 PHEV. All mean values are significantly higher than WLTP and NEDC test-cycle mean values (thin solid lines in Fig. 2).

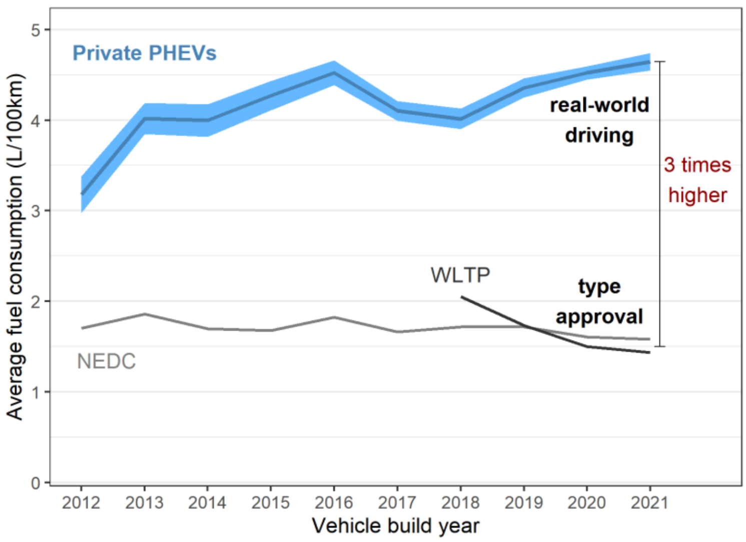

Figure 2: Mean real-world fuel consumption of PHEVs (thick blue) and mean NEDC and WLTP values (thin solid lines) of PHEVs in the sample.

For company cars, the mean real-world FC of PHEV in Europe is even higher. Fig. 3 shows sample weighted mean values ± 2 SE. We observe high FC values between 7.5 and 8.5 L/100 km. The average FC of company car PHEVs is 8.0 ± 0.4 L/100 km in Europe. All mean values are significantly higher than WLTP and NEDC test-cycle mean values (thin solid lines in Fig. 3). Table 1 summarizes the mean values.

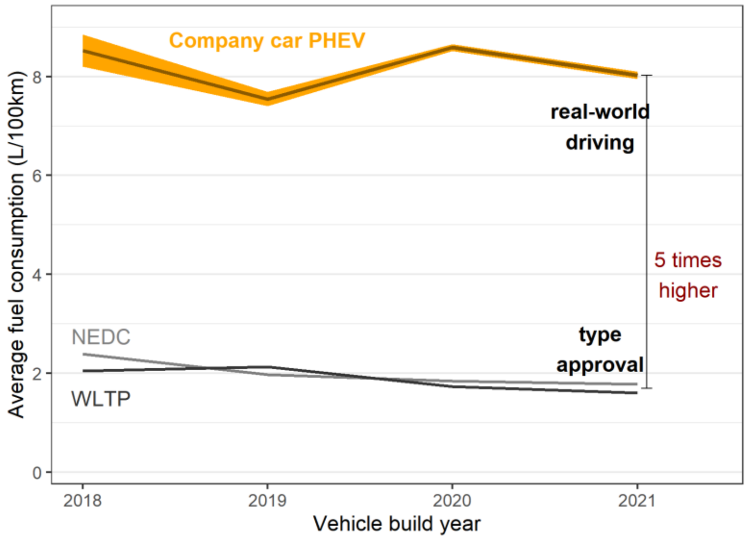

Figure 3: Mean real-world fuel consumption of PHEVs (circles) and mean NEDC values (dashed line) of PHEVs in the sample.

Table 1: Type-approval and real-world fuel consumption of PHEVs in Europe

	NEDC	WLTP	Real-world
Private cars	1.70	1.60	4.2 ± 0.2
Company cars	1.85	1.71	8.0 ± 0.4

3.3 Real-world UF

The deviation between actual and real world FC can have different reasons. An important part of the official FC estimates are the UF. Fig. 4 (Fig. 5) shows the actual UF for the all private (company car) PHEVs in the data base (circles) together with the WLTP type approval values for the CD mode shares. Also shown is a numerical fit to the empirical data.

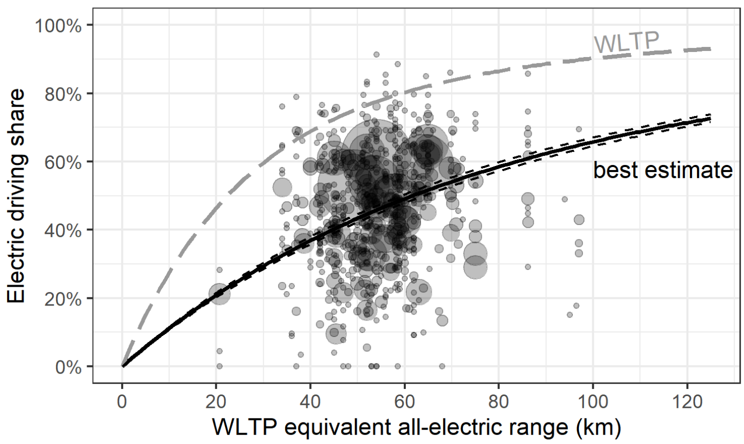

Figure 4: Real-world electric driving shares (circles) with best fit (solid) and type approval (dashed) for private PHEVs.

For the regression, a functional form $UF = 1 - e^{-EAER/L}$ has been chose, with d as fitting parameter. Here, EAER is the WLTP equivalent all-electric range in km and L is a user group specific parameter for scaling. For private vehicles, we obtain L = 80 ± 2.5 km (best fit ± two standard errors) and L = 361 ± 50 km for company cars. Both regression results are obtained from numerical minimization of the sum of squared deviations.

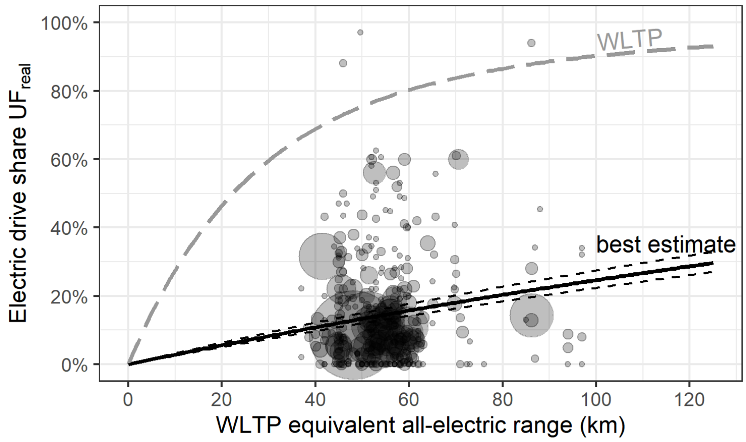

Figure 5: Real-world electric driving shares (circles) with best fit (solid) and type approval (dashed) for company car PHEVs.

We find the actual UFs are much lower than type approval exceptional. The average real-world electric driving share is about 45%–49% for private cars and about 11%–15% for company cars. To understand the time evolution of the deviation in UF, Fig. 6 (Fig. 7) shows the ratio (the difference) between actual and NECD type approval UF.

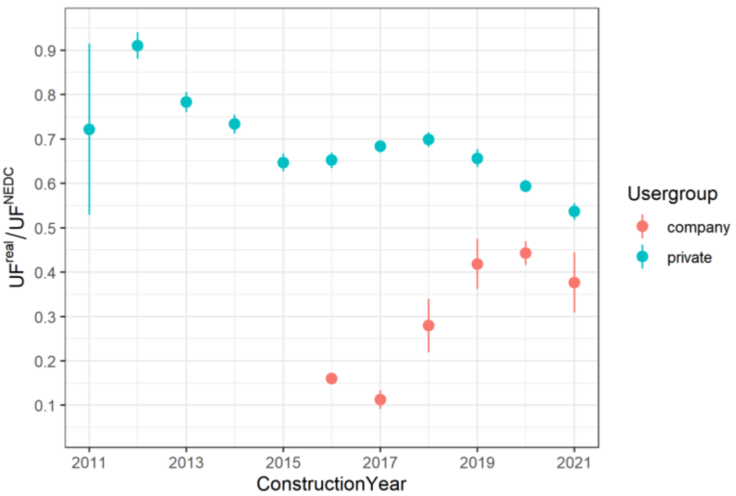

Figure 6: Ratio between real.-world and NEDC UF for private (blue) and company car (red) PHEVs in Europe. Shon are (unweighted) mean values by built year with one standard error.

For private PHEV, we find the actual UF has declined compared to NEDC values over time. It is about 80 – 90 % of the type approval values for private PHEVS of built years 2012 – 2013 and has declined to 50-60 % in more recent years. The ratio has changed similarly (Fig. 7).

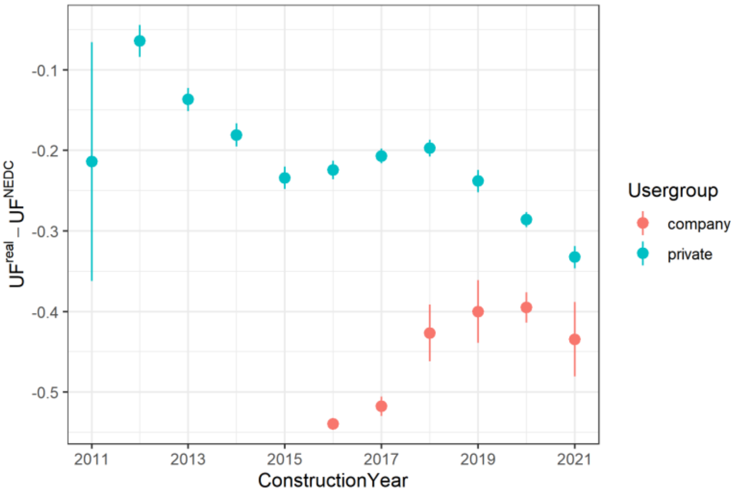

Figure 7: Difference between real.-world and NEDC UF for private (blue) and company car (red) PHEVs in Europe. Shon are (unweighted) mean values by built year with one standard error.

4 Discussion

Our sample includes over 6,000 WLTP-certified and a total of nearly 9,000 PHEVs, covering 28 European countries and two user groups. While PHEVs in Germany dominate our sample, we also cover ten other countries with at least 50 vehicles – including essential major current PHEV markets. Data for Eastern European countries is lacking which reflects the low PHEV stock shares in those countries. Even though varying and partly small sample sizes for individual countries barely allow any statistically significant comparison between the countries, we find similar tendencies in all European countries, indicating cross-national consistency and robustness of our findings. Data on company cars was available only for Germany and Austria, with a minor share for Austria. However, the overall trend is consistent for both countries and similar to earlier company car data from the Netherlands. Thus, we presume certain resilience and consistency for our latest WLTP-focused results, yet single numerical values may change. For the private users in the Spritmonitor.de data, we draw on voluntarily self-reported fuel consumption. It could therefore to be biased towards users with an above-average interest in their vehicle's energy consumption and thus the reported fuel consumption could be lower than in the full fleet of private PHEVs.

Overall, latest results are consistent with findings from a previous study [11]. For private PHEVs, an increased deviation of the real-world from type-approval fuel consumption values is noticeable. The (sample size weighted) deviation for private, NEDC type-approved vehicles reported in 2020 was 135%–235% and has increased to 240%–260% for NEDC and 270%–310% for WLTP certified PHEVs. The deviation was 340%–410% for NEDC type-approved company cars in the 2020 study is now 420%–460% for NEDC and 455%-520% for WLTP certified vehicles. This increase may result from larger ICEs, higher combustion engine power, larger and heavier vehicles, as well as newly attained customer groups during the progressive PHEV market diffusion. The latter may be supported by fiscal incentives, including PHEV purchase subsidies and reduced tax rates, and feature minor environmental concern than early adopters that might be, for instance, associated with less charging or any other behavioural changes. Overall, we observe an increase of the deviation but cannot attribute it to specific reasons.

5 Conclusion

PHEVs can reduce greenhouse gas emissions from transport if mainly driven on electricity. Here, we show empirical data from over 8,000 individual PHEV in Europe including real-world fuel consumption (FC) and utility factor (UF). We find that the average real-world fuel consumption of PHEVs in Europe is 4.0–4.4 L/100 km for private vehicles and 7.6–8.4 L/100 km for company cars compared to an average of 1.6–1.7 L/100km in WLTP type approval. These values correspond to tailpipe emissions of 90–105 g CO_2/km for private and 175–195 g CO_2/km for company cars compared to only 37–39 g CO_2/km in WLTP type approval. The average real-world electric driving share is about 45%–49% for private cars and about 11%–15% for company cars. The low electric driving share is one of the main reasons for the high deviation between type approval and real-world fuel consumption. Our results demonstrate the importance of real-world vehicle emission measurements and that real-world fuel consumption are much higher than test cycle vales and UF much lower despite recent advances in all-electric ranges.

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Biographies

Patrick Plötz studied Physics in Greifswald, St. Petersburg and Göttingen. Doctorate degree in Theoretical Physics from the University of Heidelberg. Since 2011 researcher in the Competence Center Energy Technology and Energy Systems at the Fraunhofer Institute for Systems and Innovation Research ISI. Since March 2020 Coordinator of Business Unit Energy Economy. Since 2020 private lecturer at the Karlsruhe Institute of Technology (KIT).

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Georg Bieker is a researcher on the ICCT Europe team and co-cluster coordinator for the batteries and EV cost parity cluster. His current work focuses on the life-cycle climate and other environmental impacts of electric and combustion engine passenger vehicles, including the fuel and electricity consumption of plug-in hybrid and battery electric vehicles in real-world usage conditions. With a background in battery research, he further supports the ICCT's expertise on current and future battery technologies. Georg holds M.Sc. and Ph.D. degrees in Chemistry from the University of Muenster (Germany).

Peter Mock is Director of ICCT Europe. Prior to joining the ICCT, Peter was a staff member of the Daimler Global Environmental Protection department and completed a dissertation assessing future market potentials of different vehicle technologies and fuels at the Institute of Vehicle Concepts of the German Aerospace Center (DLR). He holds a diploma degree in Chemistry and Economics (Dipl.-Chem. oec.) from the University of Ulm (Germany) and a doctor's degree in engineering (Dr.-Ing.) from the University of Stuttgart (Germany).