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LETTER

Country-level differences in the electrified kilometers of plug-in hybrid electric vehicles across Europe

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Abstract

Plug-in hybrid electric vehicles (PHEVs) have been the subject of many debates regarding their role in the electrification of the transport sector for the duality that they can be subsidized due to electric driving, but they can also be driven on fossil fuels. Previous studies focused on the charging and driving behavior of PHEVs to assess their share of electrified kilometers (vehicle kilometers travelled (VKT) with the internal combustion engine off—thus relying only on the electric engine—among all VKT), and to determine their environmental benefits. However, there is limited understanding of how the same vehicle is used in different countries and what that means in terms of the share of electrified kilometers. In this study, we analyze a very large real-world sample (over 32 000 vehicles) of an identical PHEV model to understand how PHEV driving differs in the share of electrified kilometers among 10 European countries and what country-level factors are behind these differences. We find that there is a North–South divide in the share of electrified kilometers within Europe, with a significant decrease southward. Furthermore, at the country-level, a higher share of company cars can be associated with higher shares of electrification contrary to expectations in the literature, highlighting the importance of increased opportunities and incentives for workplace charging and less subsidies for conventional fuel use. We also find that higher electricity prices are associated with lower shares of electrified kilometers at the country-level. Furthermore, PHEVs in our dataset, in all countries have consistently 20% to 40% lower shares of electrified kilometers compared to type-approval values in Europe.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) use both electricity and conventional fuel for propulsion, and their share of electrified kilometers (utility factor) helps us understand their potential to reduce greenhouse gas emissions in the transport sector [1, 2]. PHEVs have been the subject of many debates regarding their role in the electrification of the transport sector for the duality that they can be subsidized due to electric driving, but they can also be driven on fossil fuels. Recently, the European Parliament voting to ban the sale of new vehicles with internal combustion engines (ICEs) brings the role of PHEVs and where they fit into the question once again [3]. An ICCT study found that their fuel consumption and tail-pipe CO_2 emission are two to four times higher than type-approval values [4]. A type-approval proves that a vehicle meets the applicable technical requirements set forth by a national or an international authority, e.g. the European Commission; a type-approval value (e.g. tail-pipe CO_2 emissions) hence refers to values that a vehicle with type-approval would achieve. Previous studies in the literature that look into the real-world usage of PHEVs have one shortcoming in common: lack of available data. Large scale studies [4, 5] usually have to combine multiple datasets together with many differences ranging from sample sizes to collection methods; and given these differences, it is difficult to analyze and compare PHEV usage between countries. Moreover, standards such as the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) that is commonly used in the European Union to label fuel economy and emissions are based on test cycles of 30 minutes [6], which is a very short observation period to make general conclusions on how PHEVs are driven, and this ultimately results in tail-pipe CO_2 emissions of PHEVs being underestimated as shown in several studies [4, 7, 8].

In this study, we analyze a very large real-world sample of the same PHEV model in Europe, collected by a single manufacturer with a worldwide operation. Our PHEV sample contains over 32 000 vehicles in 10 countries. The large size of our dataset provides the opportunity to analyze how the same vehicle is used in different countries, with different electricity and gasoline prices, different charging infrastructure, and different fleet compositions.

We ask the following research questions: (1) are there statistically significant differences in how the same vehicle model is used (with regards to its share of electrified kilometers) in different countries and (2) if so, what country-level factors are associated with these differences? To answer the first question, we use descriptive and inductive statistical methods, and to answer the second one, we enrich our dataset with additional data on country-level factors and then we apply hierarchical linear modeling to analyze if those country-level factors have any impact on the share of electric driving.

Previous studies specifically focused on charging behavior [9–12] and driving behavior [12–15] of PHEV users at the vehicle level. A subset of studies focused on the impact of vehicle factors, either using simulations or real-world data with small sample sizes [7, 16–18]. At the country-level, previous studies focused on consumer adoption and cost effectiveness of PHEVs [19–21].

The unique contribution of our study is that, to the authors' best knowledge, this is the first study that analyzes how the same PHEV is used across different countries in Europe, with a very large real-world sample, and with consistent and single-source data collection that allows country comparisons. The data is further strengthened with a very long mean observation period of vehicles (622 days), contrary to the extremely short test cycles that are prevalent in the literature. This type of analysis, based on a large dataset, further combined with additional data to analyze country-level differences is currently missing in the literature. In this concise article, we aim to address this gap. The outline of the paper is as follows. Data and methods are described in section 2, results are presented in section 3, and we close with discussion and conclusions in section 4.

2. Data and methods

2.1. Data

The data we use in this study comes from a single manufacturer with a worldwide operation. Our dataset contains 32 770 vehicles of a single, identical PHEV model in 10 countries in Europe: Belgium, Finland, France, Germany, Italy, Netherlands, Norway, Spain, Sweden, and United Kingdom. The PHEV in question is a 5-seat vehicle, within the compact luxury crossover SUV class. Aggregated data was collected on each vehicle, starting from the date they were handed over to the customer from the manufacturer till a final workshop visit for maintenance when the collection ended. For each vehicle, we have information on the model year, odometer reading at the final workshop visit, observation period (handover date to final workshop visit) and total vehicle kilometers travelled (VKT) with the ICE on, VKT with ICE idle and VKT with ICE off during the observation period. The calculation of the share of electrified kilometers based on these variables are explained in section 2.2.1. The model year, on average, is 2019.1, ranging from 2018 to 2021. Depending on the model year, battery sizes range from 10.4 kWh to 11.6 kWh. In all-electric-ranges (AERs), this corresponds to 35 km to 49 km on average based on the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) values provided by the manufacturer. The mean observation period for all the vehicles in the dataset is 622 days, with the mean vehicle handover date in January 2019 and the mean final workshop visit in October 2020. See table 1 for an overview of the dataset. Detailed descriptive analysis of the data is provided in section 3.1.

The raw data included over 55 000 vehicles, however, we filtered for inconsistencies (e.g. more observation days than the vehicle's model year allows) and only included vehicles with more than 100 observation days and with a total VKT over 1000 km during that period to have a higher degree of confidence in our results. Number of vehicles per country range from 689 for Italy to 8028 for Norway after data cleaning and filtering. The countries in the dataset represent a variety of different regions in Europe, ranging from the Nordics to Western Europe and to Southern Europe.

2.2. Methods

2.2.1. Checking for statistically significant differences in UF between countries

First, we use descriptive and inductive statistical methods and statistical tests; rank-sum test to compare medians and two-sample t-test to compare means of utility factor (UF, i.e. share of electrified kilometers) between selected countries to establish any statistically significant differences in the share of electrification between countries. We calculate the utility factor as the share of VKT with ICE off among all VKT for a single

Table 1. Dataset overview and PHEV features for detailed analysis.

Countries	BE	FI	FR	DE	IT	NL	NO	ES	SE	UK	Overall
Sample size (# of vehicles)	3029	3498	4083	2906	689	1485	8028	879	5537	2636	32 770
Observation period[1] (days)	607	642	592	573	492	656	697	531	602	573	622
Vehicle handover date	January 2019 (overall mean). Overall min–max: May 2017–November 2020										
Final workshop visit date	October 2020 (overall mean). Overall min–max: June 2018–March 2021										
Model years	2019.1 (overall mean). Overall min–max: 2018–2021										
Vehicle size and class	5-seat, compact luxury crossover SUV class										
Battery size	10.4 kWh to 11.6 kWh										
All electric range	35 km to 49 km on average (based on OEM WLTP values)										
Information collected on vehicles (aggregated)	Model year, odometer readings, observation period, vehicle kilometers travelled (VKT) with internal combustion engine (ICE) on, VKT with ICE idle, VKT with ICE off										

Notes: [1]Mean number of aggregated observation days from the vehicle handover date until the final workshop visit. Country abbreviations: Belgium (BE), Finland (FI), France (FR), Germany (DE), Italy (IT), Netherlands (NL), Norway (NO), Spain (ES), Sweden (SE), United Kingdom (UK)

vehicle. This calculation corresponds to pure electric VKT, whereas there is a second method of UF calculation with the addition of VKT when ICE is idle to the share of electrified kilometers, which would correspond to pure (ICE off) plus mixed (ICE idle) electric VKT. VKT with ICE idle refers to when the PHEV makes use of its ICE, without turning it fully on, under certain conditions depending e.g. on the load and operation temperatures [22, 23], while driving on the electric engine. The comparison of the two methods was discussed in [24], where the inclusion of mixed (ICE idle) electric VKT is reported to increase UF estimates by 1% on average and is negligible, having no significant impact on further statistical analysis. For comparison, the difference between the two methods of UF calculation in our dataset is less than 1%, thus we use the pure electric VKT approach.

2.2.2. Data enrichment at the country-level

The dataset contains factors that can cause variation in the share of electrification among users at an individual level, such as the model year and annual total VKT. For example, a high daily and annual VKT can be indicative of more long-distance driving [12] and it is well established that long-distance driving results in lower fuel economy and a lower share of electrification [12, 25]. However, our dataset has limited information at the country-level that can help explain differences between countries. Country-level factors can skew the share of electrification towards a certain direction in a given country. The authors would like to emphasize that the analysis concerning country-level factors is done on an aggregate level; for instance, country-specific policy analyses are out of scope for the present paper. Therefore, data collection at the country-level should reflect the purpose of the paper. The criteria for choosing country-level factors were (1) standardized and publicly available for all 10 countries, (2) can be aggregated, (3) applies country-wide and (4) reflects one of the following aspects of the electrification process in transportation systems: electricity and fuel prices, charging infrastructure, user groups and climate. Based on these criteria, to figure out which country-level factors are behind these differences, we enrich the dataset with the following 7 variables at the country-level: electricity prices, gasoline prices, number of electric vehicles (including both PHEVs and battery electric vehicles (BEVs)) per charging point (with power <22 kW), the share of detached housing, the share of company cars among all new PHEV registrations, precipitation, and surface temperature. See table 2 for a list of all the collected data, their frequency, period, sources and related further information.

More details on the country-level variables and related summary statistics are given in appendix A1.

2.2.3. Hierarchical linear modeling to analyze country-level factors

To analyze if any of the country-level factors have an impact on the share of electrification between countries, we apply hierarchical linear modeling (HLM) with UF as the dependent variable. The reason we use a hierarchical linear model is the assumption that country level factors impact the share of electrification at a different rate in each country. Normal linear models violate the independence assumption (standard errors often too small and there are incorrect p-values); and they cannot distinguish between micro and macro levels. Predictor effects can differ under different contexts. A single level model would have error terms that would represent clustered data errors across levels, which would limit the effect of the key predictor. A HLM, therefore, would fit better in understanding the differences between countries (macro level), concerning individual users (micro level). See the following literature on hierarchical linear modeling for a better understanding of the method [64–70].

Table 2. List of collected data at the country-level and sources.

Collected data	Sources, frequency, period (years), other information and references
Electricity prices	Eurostat. Bi-annual. 2019–2020. Euro/kWh. Consumption from 2500 kWh to 4999 kWh—band DC. All taxes and levies included [26].
Gasoline prices	All except Norway: European Commission Weekly Oil Bulletin. Monthly, 2019–2020. Euro-super 95. Euro/l. Prices with taxes [27]. Norway: Statistisk Sentralbyrå (Statistics Norway). Monthly. 2019–2020. Motor gasoline, lead-free 95 octan. NOK/l. Average retail price including taxes and fees [28].
Charging points	European Alternative Fuels Observatory. Annual. 2019–2020. Charging points classified as normal power outing ($P \leqslant 22$ kW) in the specified year, based on the pre-2020 counting methodology [29–38].
PHEV and BEV fleet	European Alternative Fuels Observatory. Annual. 2019–2020. Total number of PHEV and BEV passenger cars in the fleet in that year [39–48].
PHEV and BEV new registrations	European Alternative Fuels Observatory. Annual. 2019–2020. New registrations of PHEV and BEV passenger cars in that year [39–48].
Share of company car registrations	The International Council on Clean Transportation (ICCT). Annual, 2020. Passenger cars [49]
Comparative price levels	Eurostat. Annual. 2019–2020. Annual price level indices. EU27_2020 = 100. Used for levelizing electricity and gasoline prices [50].
Share of detached housing	Eurostat. Annual. 2019–2020. Considering all degrees of urbanization and all income levels. UK values are based on 2018 (no significant changes observed in preceding few years) [51].
Precipitation	Climate Change Knowledge Portal (The World Bank Group). Annual. 2019–2020 [52–61.]
Surface temperature	Copernicus Climate Change Service (through Our World in Data). Annual. 2019–2020. 2 meters above surface [62].
Exchange rates	Eurostat, Monthly. 2019–2020. Used for NOK to Euro exchange regarding gasoline prices [63].

In our modeling, we use annual VKT of individual vehicles in the dataset as a level 1 factor (micro/vehicle level); and the seven variables described in section 2.2.2 and shown in table 6 (in appendix A1) as level 2 factors (macro/country level). See equation (1) for the general HLM. This model is also called the 'adjusted means as outcomes' model where the macro level factors impact the dependent variable at a different rate in each country, but the micro level factor (annual VKT) impacts the dependent variable at the same rate across countries.

$$
\begin{aligned}
&\text{L1} \quad Y_{ij} = \beta_{0j} + \beta_{1j} X_{ij} + \varepsilon_{ij} \\
&\text{L2} \quad \beta_{0j} = \gamma_{00} + \gamma_{01} W_{1j} + \ldots + \gamma_{0n} W_{nj} + \upsilon_{0j} \\
&\qquad \beta_{1j} = \gamma_{10} \\
&\qquad \text{where } Y \text{ is the utility factor, } X \text{ is the annual VKT (level 1 factor)}, \\
&\qquad W_{1\ldots n} \text{ are the level 2 factors, } i \text{ are vehicles and } j \text{ are countries.}
\end{aligned} \tag{1}
$$

We applied forward stepwise selection of country-level factors to estimate the best model fit. Forward stepwise selection works as follows: the iteration starts with the general HLM without any country-level factors ($W_{1\ldots n}$) in equation (1); then at each step, the addition of one country-level factor at a time is tested against the null model given in equation (2) and the change in model fit is recorded. To estimate model fit, we use Akaike information criterion (AIC), log-likelihood and $R^2_{\beta_{0j}}$ which is the proportion of the dependent variable's variance explained at the macro level. Calculations of $R^2_{\beta_{0j}}$ were done using the formula suggested by [71]. At each step, the country-level factor that provides the best increase in model fit in all three estimates without causing any multicollinearity (variance inflation factor <5) is added to the HLM. The iteration continues until the model fit cannot be increased anymore,

$$
\begin{aligned}
&\text{L1} \quad Y_{ij} = \beta_{0j} + \varepsilon_{ij} \\
&\text{L2} \quad \beta_{0j} = \gamma_{00} + \upsilon_{0j}.
\end{aligned} \tag{2}
$$

The application of forward stepwise selection eliminates country-level factors from the model that do not provide any explanatory value regarding their impact on UF or whose impact can be explained by other factors.

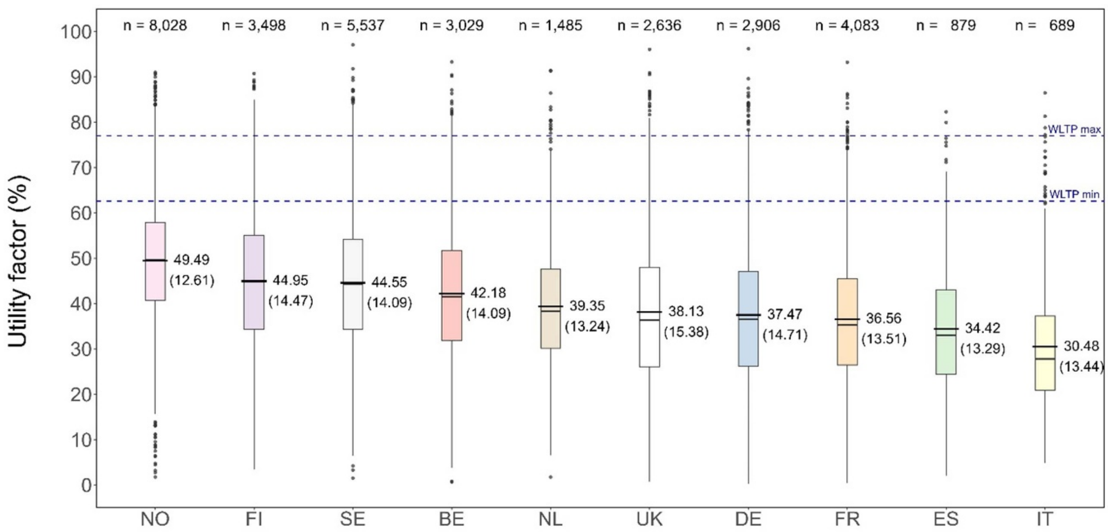

Figure 1. Boxplot of utility factor per country. Means are indicated and the standard deviation is given in parentheses. Min–max WLTP values indicated based on OEM all-electric range. Country abbreviations: Belgium (BE), Finland (FI), France (FR), Germany (DE), Italy (IT), Netherlands (NL), Norway (NO), Spain (ES), Sweden (SE), United Kingdom (UK).

3. Results

3.1. Descriptive analysis

Figure 1 shows the boxplot of UFs per country. We observe significant differences in UF among different countries. Norway has the highest UF (49%) on average with the lowest standard deviation, followed by other Nordic countries Finland (45%) and Sweden (45%). The UF is 42% on average in Belgium. Other Western European countries (Netherlands, United Kingdom, Germany and France) have UFs between 35% and 40% on average. Southern European countries Spain and Italy have the lowest UF on average with 34% and 30%, respectively. We observe regional differences where the Nordics have the highest share of electrification and this share, on average, decreases moving towards southern Europe.

In figure 1, maximum and minimum WLTP UF values, 63% to 77%, are also indicated. WLTP is the standard fuel economy and tail-pipe emissions test procedure for EU countries and is also accepted in other countries such as the United States, China and Japan. In our study, we use the method in [4] as the basis for WLTP utility factor calculation for PHEVs. Minimum and maximum WLTP UF values are based on the minimum and maximum OEM AERs among all model years of that vehicle. We observe that the mean UFs in all countries are, on average, 20%–40% lower in all countries than the WLTP values, meaning that the WLTP overestimates the share of electrified kilometers by a large margin. In Italy, for instance, the mean UF is 33% to 47% lower than the expected WLTP value.

We performed two-sample t-tests to detect statistically significant differences in means, and rank-sum tests to detect statistically significant differences in medians between the UFs in each country. See table 3. We find that there is a statistically significant difference in each comparison of either the mean or median. Where the mean was not significantly different (e.g. Sweden and Finland), the median was, and vice versa. No cases were observed where both the difference in means and medians was insignificant. The statistical tests overall prove the significant differences between these countries that were descriptively visible.

The mean annual and daily VKT, and mean number of aggregated observation days are shown in table 4. We observe that the annual VKT ranges from16 300 km in Italy to 21 700 km in Sweden. We observe the highest annual VKT in Sweden and the Netherlands, both above 21 000 km, which corresponds to approximately 59 km in daily VKT. Italy and Norway have the lowest annual VKT, 16 300 km and 17 000 km respectively, corresponding to approximately 45–47 km in daily VKT.

Compared to the country average annual VKT, the vehicles in our dataset are in general driven considerably more. For instance, the average annual VKT in Sweden in 2021 was 11 120 km which is close to half of the annual VKT in our dataset [72]. Similarly, the average annual VKT in the European Union in 2019 was 11 300 km, considerably lower than all the countries in our dataset [73]. However, it should be noted that the vehicles in our dataset are new vehicles which on average have higher annual mileage than the fleet average in a given country. For instance, 2–3 years old company cars in Sweden have an average annual VKT of 21 000 km [74], which is much closer to the average annual VKT in our dataset. Yet, some of this difference in annual VKT can be attributed to our dataset containing a single manufacturer and therefore not

Table 3. Two sample t-tests and rank-sum tests for pairwise comparison of country UFs.

	Two sample *t*-test to compare means of UF											Rank-sum test to compare medians of UF									
	BE	FI	FR	DE	IT	NL	NO	ES	SE	UK		BE	FI	FR	DE	IT	NL	NO	ES	SE	UK
BE	—	***	***	***	***	***	***	***	***	***	BE	—	^	**	*	***	***	***	*		***
FI		—	***	***	***	***	***	***		***	FI		—	***		***	***	***	**	^	**
FR			—	**	***	***	***	***	***	***	FR			—	***	*		***		***	***
DE				—	***	***	***	***	***		DE				—	***	***	***	***	*	*
IT					—	***	***	***	***	***	IT					—				***	***
NL						—	***	***	***	**	NL						—	^		***	***
NO							—	***	***	***	NO							—	*	***	***
ES								—	***	***	ES								—	*	***
SE									—	***	SE									—	***
UK										—	UK										—

Confidence levels: ***99.9%, **99%, *95%, ^90%.

Country abbreviations: Belgium (BE), Finland (FI), France (FR), Germany (DE), Italy (IT), Netherlands (NL), Norway (NO), Spain (ES), Sweden (SE), United Kingdom (UK).

Table 4. Means of annual VKT, daily VKT and number of aggregated observation days per country in the dataset.

Country	Mean annual VKT (1000 km)	Mean daily VKT (km)	Mean # of days[1]	*N*
Belgium	20.3	55.6	607	3029
Finland	19.7	54.1	642	3498
France	18.7	51.4	592	4083
Germany	18.4	50.4	573	2906
Italy	16.3	44.8	492	689
Netherlands	21.5	59.1	656	1485
Norway	17.0	46.6	697	8,028
Spain	18.2	49.9	531	879
Sweden	21.7	59.5	602	5537
United Kingdom	17.8	48.8	573	2636
All countries	19.0	52.1	622	32 770

Notes: [1]Mean number of aggregated observation days until workshop visit, *N*: Total number of vehicles.

being fully representative of the entire vehicle fleet and the drivers in a given country. This has no impact on the analyses in this study though, since the focus of our study is to analyze how the same vehicle is used in different countries, thus our dataset inherently cannot be representative of the entire vehicle fleet or all drivers, yet certain conclusions can be drawn for similar type of vehicles in the vehicle fleet.

3.2. Hierarchical linear modelling

Forward stepwise selection results are shown in figure 2. A lower AIC score (part a in figure 2) indicates a better model fit; for log-likelihood (part b) and $R^2_{\beta_{0j}}$ (part c)—which is the proportion of UF variance explained at the country-level—a higher score indicates a better model fit. The cut-off point where each additional variable results in a better model fit in all three estimates is marked with a vertical dashed line. We observe that the inclusion of (1) surface temperature, (2) share of company cars among all new PHEV registrations, (3) electricity price and (4) precipitation results in the best model, increasing the model fit in all three estimates; hence they are included in the hierarchical linear model. The model with these four variables explains 90% of the UF variance at the country-level. Further addition of EVs per charging point and the share of detached housing results in worse AIC scores, hence, are excluded from the model even though they provide higher log-likelihood and $R^2_{\beta_{0j}}$ estimates. The dashed red line indicates the addition of gasoline price into the model at each step. We observe that, for all three model estimates in figure 2, the addition of the gasoline price results in a worse model fit at each step than the best possible fit, meaning that there is at least one variable that increases the model fit more than the gasoline price. Furthermore, the addition of the gasoline price into the model as the seventh (final) variable results in high multicollinearity with several other variables, hence, it is not shown in figure 2.

The exclusion of the gasoline price, EVs per charging point and the share of detached housing from the hierarchical linear model cannot be interpreted as if these factors do not have significant impacts on the UF. However, in our modeling, at the macro-level, it should be interpreted as such that there are other factors

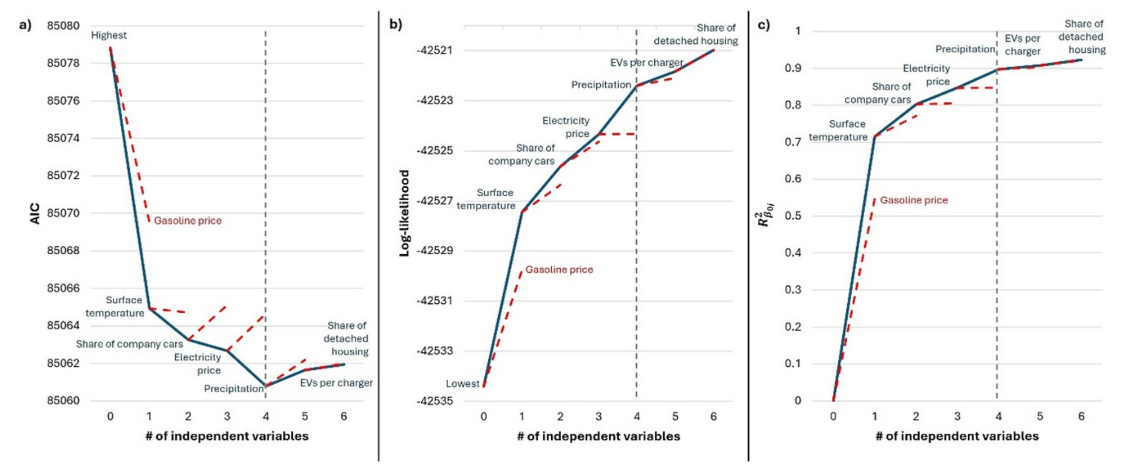

Figure 2. Forward stepwise selection of variables for the hierarchical linear model.

Table 5. Hierarchical linear modeling results.

Dependent: Utility factor (%)			
Fixed effects	**Estimate**	**Std. err.**	**Sig.**
Intercept	60.68	3.77	***
Annual VKT (1000 km)	−0.53	0.01	***
Electricity price (€ cents/kWh)	−0.44	0.16	*
Share of company cars (%)	0.20	0.05	**
Precipitation (in 100 mm)	−0.60	0.27	
Surface temperature (°C)	−1.07	0.16	***
Random effects	**Variance**	**Std. dev.**	
Country (intercept)	2.83	1.68	
Residual	170.27	13.05	

$N = 32\,770$
Groups: 10 (country)
Confidence levels: ***99.9%, **99%, *95%

that have much larger impacts on the UF when comparing any two countries, therefore the impacts of the gasoline price, EVs per charging point and the share of detached housing are overshadowed at the country-level. In figure 2, we observe that the surface temperature has the highest impact on the model fit in all three estimates, and it explains more than 70% of the UF variance at the country-level.

Results of the HLM are given in table 5. We observe that annual VKT (level 1 factor) has a statistically significant impact on the UF of individual users with a confidence level of 99.9%. Every 1000 km increase in annual VKT (or approximately 3 km increase in daily VKT) is associated with a half percentage point decrease in the UF of individual users. This is in line with previous findings in the literature [24].

In table 5, our results indicate that electricity price (level 2 factor) has a statistically significant impact on the UF at the country-level with a confidence level of 95%. We would like to note here that the interpretation of level 2 factors requires caution; meaning that the effect of the variable is for differences between countries and not for individual vehicles within the same country. Countries with a 0.1 €/kWh increase in electricity price are associated with a 4% lower UF at the country-level.

The share of company cars among all new PHEV registrations (level 2 factor) also has a statistically significant impact on the UF at the country-level with a confidence level of 99%. Countries with a 10% increase in the share of company cars among all new PHEV registrations are associated with a 2% higher UF at the country-level. This result is counterintuitive to the expected negative impact of company cars on electrification in the literature [4, 75]. This might indicate that policies regarding PHEVs at the workplace (such as incentivizing workplace charging and providing a gasoline card) can impact driving and charging behavior (and thus share of electrified kilometers) in a country; and the negative impacts reported in the literature can be country-specific rather than universal.

Our results in table 5 also indicate that countries with a 1 °C higher surface temperature (level 2 factor) are associated with a one percentage point lower UF at the country-level, with a confidence level of 99.9%. Surface temperature was initially chosen as a factor to account for the impact of ambient temperature. For instance, compared to driving at 23 °C, the UF is halved at −5 °C due to cold starts and cabin heating; and it decreases on average by 10% at 35 °C due to air conditioning [22], meaning cold temperatures have a bigger impact on UF. Therefore, the model expectation was to observe a lower UF at the country-level with decreasing average surface temperatures. However, our results show that surface temperature instead works as a geographical location (latitude) indicator (average surface temperature is directly correlated with latitude), highlighting the difference in UF between northern (high UF) and southern (low UF) Europe; and this characteristic overshadows any impact related to cold starts, cabin heating and air conditioning. Finally, our results indicate that precipitation does not have a statistically significantly impact on UF at the country-level.

4. Discussion and conclusions

We find that the shares of electrified kilometers are 20%–40% lower than the expected values based on WLTP standards in all countries, confirming the findings of Plötz *et al* [4], Tansini *et al* [7] and Chatzipanagi *et al* [8] where they state that WLTP values underestimate CO_2 emissions and fuel economy of PHEVs. This indicates that the WLTP standard we use today for labeling fuel economy and tail-pipe emissions need to be revised. In line with our findings, the European Parliament adopted a revision of WLTP UF curves used in fuel consumption estimates from 2025 onwards, to better reflect real-world data [76].

Company cars are associated with a lower utility factor in the literature [4, 75]. Yet, we find that countries with a higher share of company cars are associated with a higher share of electrified kilometers in our study. This can happen due to several reasons. First, the negative impact of company cars in the literature are reflective of smaller sample sizes than ours, which means that the driving behavior represents either one country as in [75] or is dominated by one, as in [4]. Second, the assessment of company cars has been done only at the individual level in the literature and never at the country-level. Therefore, the literature on company cars can reflect country-specific circumstances (e.g. users being less incentivized to charge due to companies commonly paying for gasoline consumption in that country) and focuses on the individual level. Our study instead focuses on the country-level. This can be interpreted as such that, while at the individual level, company policies regarding fuel payment can negatively impact UF in certain countries; at the country-level, larger scale policies such as increased opportunities and incentives for workplace charging can have a positive impact on the share of electrified kilometers as shown in [77], and our findings support this positive impact.

While electricity prices and fleet compositions explain some of the differences in the share of electrified kilometers between countries in Europe, the greatest explanatory variable in our modeling was the surface temperature which acted as a latitude indicator. Nordic countries are known to lead the electrification process in the transportation sector in Europe. However, it is unknown if this directly translates into more efficient driving of PHEVs. Our finding statistically solidifies the North–South divide in the share of electrification within Europe, which is presented in figure 3 for the broader audience; yet it brings up more questions than answers. Future extensions of our work could focus on what creates the North–South divide in Europe, with detailed analysis on (1) quantifying the impact of country-specific policies surrounding PHEVs on the share of electrification and (2) how this impact differs across Europe.

The vehicle dataset we used in this study has its strength in its large sample size, long observation period and single-source collection, which allows for an aggregate analysis of the same vehicle across ten European countries, yet it is still limited. For example, there is an uneven distribution of sample sizes in different countries. The number of vehicles observed is higher in Northern European countries compared to Southern European countries, e.g. there are over 8000 vehicles observed in Norway, whereas there are less than 2000 vehicles observed in Spain and Italy combined. This difference might have arisen due to the market penetration of the manufacturer of the examined PHEV in those countries. Although the difference in sample sizes is large at first glance, this can only be said in relation to the large size of the overall dataset itself; meaning that a sample size of e.g. 879 for Spain occupies a small portion within this dataset, however it is in fact a quite large sample within the broader literature. For comparison, a 2022 ICCT study that looks at the real-world usage of PHEVs in Europe has a sample size of only 48 in Spain [4]. Strengthened further with a very long observation period (e.g. 531 days on average for Spain, 622 days on average for the whole dataset), we expect the utility factors estimated in each country to be significantly representative for the specific PHEV model, and expect no impact on our results due to the differences in sample sizes in different countries. Other limitations of the vehicle dataset regarding lack of information at the country-level were countered by additional data collection explained in section 2.2.2.

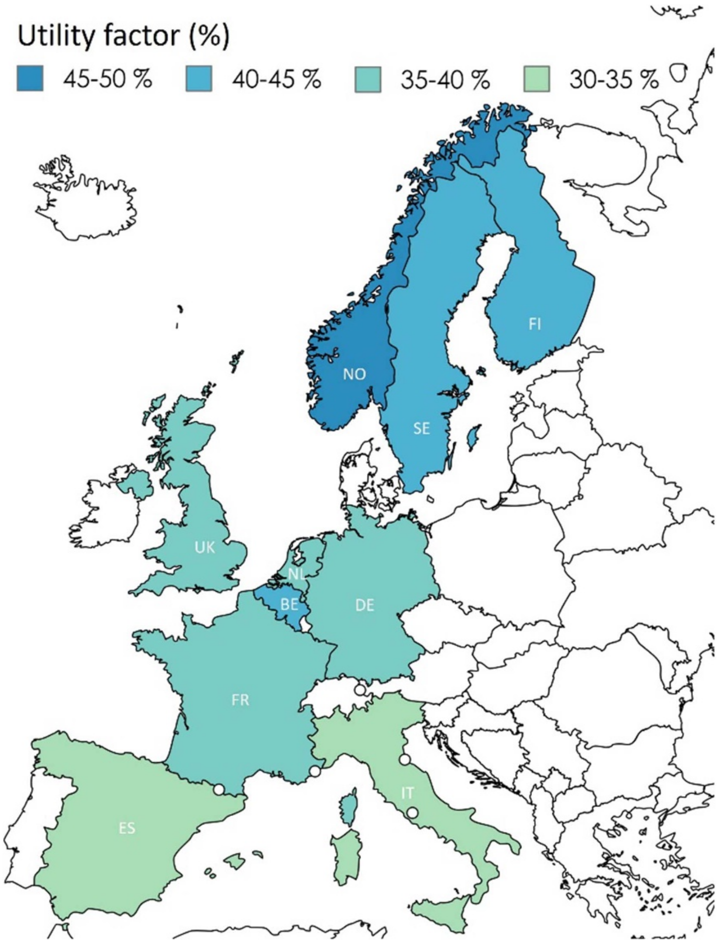

Figure 3. Utility factors in analyzed countries, presented on a European map. Country abbreviations: Belgium (BE), Finland (FI), France (FR), Germany (DE), Italy (IT), Netherlands (NL), Norway (NO), Spain (ES), Sweden (SE), United Kingdom (UK).

In conclusion, in this paper, we used a very large real-world sample of an identical PHEV model in Europe, enriched with country-level data, to analyze the share of electrified vehicle kilometers and understand how the same vehicle is used in different countries. For our specific PHEV model, results indicate that (1) there is a North–South divide in the share of electrification within Europe where UF decreases southwards, (2) at the country-level, higher share of company cars can be associated with higher shares of electrified kilometers, highlighting the importance of increased opportunities and incentives for workplace charging and less subsidies for conventional fuel use, (3) higher electricity prices are associated with lower shares of electrified kilometers at the country-level, and (4) PHEVs in all countries have consistently 20%–40% lower shares of electrified kilometers compared to WLTP standards.

Data availability statement

The data cannot be made publicly available upon publication due to legal restrictions preventing unrestricted public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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Author contributions

(CRediT): Ahmet Mandev (Conceptualization, Methodology, Formal analysis, Writing—original draft, Writing—review & editing, Visualization). Frances Sprei (Funding acquisition, Conceptualization, Writing—review & editing).

Table 6. Summary statistics of the collected data at the country-level.

	2-year average (2019–2020)						2020
Country	Electricity prices levelized (€/kWh)	Gasoline prices levelized (€/litre)	EVs (PHEV + BEV fleet) per charging point ($P \leqslant 22$ kW)	Share of detached housing (%)	Precipitation (mm)	Surface temperature (°C)	Share of company cars among all new PHEV registrations (%)
Belgium	0.24	1.17	10.9	36.0	858	11.2	90.1
Finland	0.14	1.16	16.7	46.4	647	3.9	39.1
France	0.17	1.26	13.2	44.2	827	14.3	60.2
Germany	0.28	1.26	11.6	27.0	669	10.5	61.4
Italy	0.22	1.48	6.6	24.3	834	13.7	52.3
Netherlands	0.15	1.38	4.1	17.2	793	11.4	57.1
Norway	0.11	1.06	36.5	57.2	1238	1.5	57.3
Spain	0.24	1.28	13.6	13.7	599	14.6	73.5
Sweden	0.16	1.14	22.8	44.5	675	4.7	69.6
United Kingdom	0.18	1.12	14.3	24.0	1281	9.8	68.0

Appendix

A1. Country-level variables and summary statistics

The present PHEV model uses gasoline, thus, to reflect fuel prices, only gasoline prices were considered, excluding diesel. The charging infrastructure is reflected by (1) the number of electric vehicles (EVs—including both PHEVs and BEVs) per charging point, which indicates the availability of public charging (only charging points with power <22 kW were considered based on the charging capability of the present PHEV model) and (2) the share of detached housing, which increases the availability of home charging. The user group is reflected by the share of company cars among all new PHEV registrations, for which we have combined sources from ICCT [49] (report on company shares of all EV registrations and how much of this is divided between PHEVs and BEVs) and European Alternative Fuels Observatory [78] (data on newly registered PHEVs and BEVs in a given year). Company car users are known to have different usage patterns and differ significantly from the private fleet [4]. Finally, the climate is reflected by precipitation (rainfall) and surface temperature (2 meters above surface level) which is known to impact fuel efficiency of PHEVs [22, 79]. It is worth mentioning that although country-specific policies are excluded from the analysis, the impacts of such policies can reflect themselves in, e.g., EVs per charging point.

Country-level data was collected for the years 2019 and 2020, and after calculating annual averages, the consequent 2 year averages were used for further analysis in section 2.2.3. The reasoning behind is that the country-level comparisons are performed on an aggregate level and a time series analysis is not viable due to the lack of high-resolution data, therefore a time frame has to be chosen that would reflect the observation period seen in the vehicle dataset. The observation period on average is from January 2019 to October 2020 and the same period holds for each country ± 1 month; therefore a 2 year average of 2019 and 2020 for each collected country-level variable is sufficiently reflective for the present purpose. The only exception is for the share of company cars among all new PHEV registrations, where the data was only publicly available for 2020. The electricity and gasoline prices were levelized based on the average comparative price levels (purchasing power parities) for the 2019–2020 period. Summary statistics of the collected data at the country-level are given in table 6.

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