Evaluation of plug-in hybrid vehicles in real-world conditions by simulation and their contribution to mitigating greenhouse gas emissions in a battery-constrained environment

Assessing the real-world energy performance and emissions of plug-in hybrid electric vehicles (PHEVs) is complex: it depends on their usage (trip distance, recharging behaviour), and on the different combined uses of their thermal and electric propulsion. This article presents the results of a Concawe study designed to assess the real-world potential for plug-in hybrid vehicles in a battery-constrained environment.

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Introduction

Context

Transport-related greenhouse gas (GHG) emissions represent approximately one quarter of total GHG emissions in the European Union (EU).[1] In the context of targeting carbon neutrality in 2050, as set by the EU Green Deal,[2] reducing transport-related GHG emissions represents both an important stake and challenge. The present study focuses on passenger cars only. When considering each vehicle individually, there are several ways to consider their GHG emissions:

- The tank-to-wheels (TTW) approach focuses only on the tailpipe emissions.
- The well-to-wheels (WTW) approach is more complete and considers the GHG emissions related to the production of the energy carriers.
- The life-cycle assessment (LCA) approach is holistic and also considers the GHG emissions related to the production of capital goods that are necessary for the transport system (e.g. vehicles, energy system infrastructure, etc.).

The LCA approach is the most pertinent one as it presents the most relevant assessment of the impact on the climate. Nevertheless, the TTW and WTW approaches should also be considered because they are currently regulated in Europe (TTW for the vehicles according to the CO_2 standards[3] and WTT with combustion for the fuels according to the EU Renewable Energy Directive (RED II)[4]). For example, a solution that would have a high performance in the LCA scope but a poor performance in the TTW scope would probably face significant barriers to its development in the EU market.

In this context, plug-in hybrid electric vehicles (PHEVs) represent an interesting option as they seem to address the challenges associated with low GHG emissions at each stage (TTW, WTW and LCA).[5] Furthermore, they can relieve some of the (time) pressure on the implementation of fast charging infrastructures for battery electric vehicles (BEVs) so as to make their rollout feasible in a shorter time frame. However, it is believed that the assessments currently available in the literature may need to be updated:

- TTW: As of today, TTW CO_2 emissions are assessed based on the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) which does not necessarily consider the real-world emissions of the vehicle; this could affect PHEV credibility in the future for at least the following three reasons:
  - i) Some PHEVs are purchased due to tax incentives but are rarely plugged in (especially company cars).[6]
  - ii) Some journeys are much longer than the Worldwide harmonized Light-duty Test Cycle (WLTC) over which the CO_2 emissions are assessed. It is therefore possible that, in some cases, the internal combustion engine (ICE) runs for a larger proportion of the total distance travelled than expected in the regulation. According to German statistical studies,[7] only 2% of daily trips are longer than 100 km, but they account for 26% of the mileage driven. These 'rare but long trips' may have a significant impact on the real-world fuel consumption and TTW emissions of PHEVs, which need to be assessed properly.
  - iii) The PHEV has a higher weight than a conventional hybrid electric vehicle (HEV) or pure ICE vehicle — a downside for fuel consumption and CO_2 emissions if they are not charged.

- **WTW and LCA:** Several WTW and LCA studies, such as those led by Ricardo[8] or by IFPEN,[5,9] rank the PHEV among the best solutions in terms of CO_2 emissions. This is especially true if they use renewable fuels. In some favourable cases, PHEVs can even have lower CO_2 emissions than BEVs over their life cycle as their battery is smaller; this will of course be highly dependent on the driver's behaviour in charging the vehicle, as well as on the carbon intensity of the energy sources. While these studies may have encouraging outcomes for PHEVs, they do not address the question of the real ratio of all-electric drive from PHEVs (raised above, also called the 'utility factor', UF), which may be a limiting factor in the applicability of the study conclusions.
- **Systemic aspects:** More recently, Concawe developed a study on optimal electrification scenarios for passenger cars, which aimed to minimise their WTW CO_2 emissions under the constraints of battery availability.[10] It was concluded that, under limited battery availability, PHEVs are the preferred option before BEVs for minimising the WTW CO_2 emissions of new passenger cars, even under conservative UFs ranging between 20% and 50%. This result is explained by the fact that, as long as the overall battery availability is limited, it is more efficient to electrify trips by spreading smaller batteries among many users who use their full capacity than by allocating large batteries to few users who generally use only a small fraction of their full capacity on a daily basis. However, the question remains as to whether the real-world UFs are beyond the 20%–50% threshold identified in this study.

Scope and objectives

If it is understood that PHEVs fuelled by renewable fuels and low-carbon electricity are an interesting option in terms of CO_2 emissions over their life cycle, this technical option also offers the opportunity to reduce the consumption of liquid fuels. This is particularly interesting in the frame of the outcomes of Concawe's work,[11] which mentions that liquid fuels for road transportation could be 100% low-carbon by 2050, but with a consumption of liquid fuels that could be up to approximately one third compared to today's level to be compliant with the GHG emissions trajectory designed by the European Commission in its 1.5 TECH scenario from 'A Clean Planet For All'.[12] Hence, for PHEVs fuelled by renewable fuels to be a viable solution in the long term, they need to prove that they can compete with a third of the consumption of liquid fuels as a first approximation (and still comply with this in real-world operation).

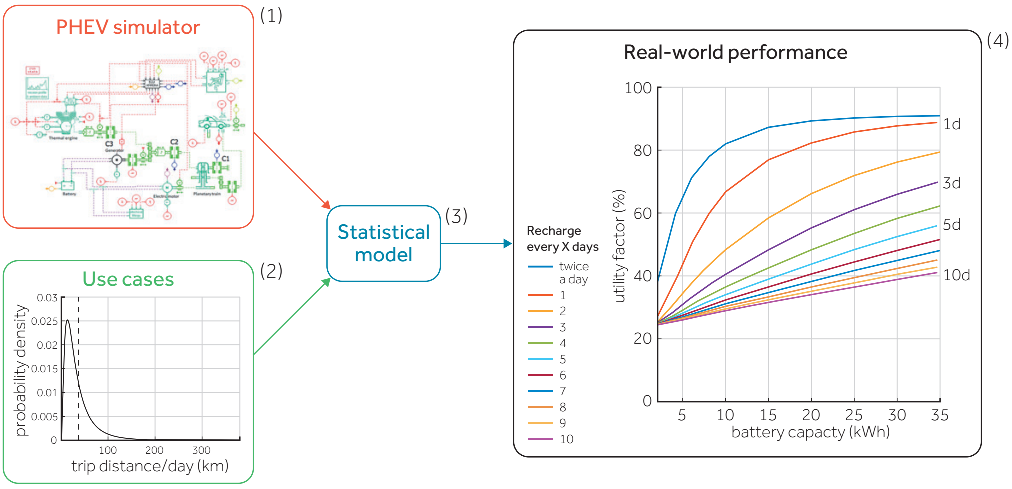
In addition to CO_2 emissions and energy consumption, air quality is also an important factor for road transportation. PHEVs are often seen as an asset for air quality as they allow electric drive in urban areas. However, the intermittent electric drive of PHEVs (and hybrids in general) can present additional challenges for tailpipe emissions control due to multiple exhaust after-treatment heating phases during a drive cycle — which are not necessarily well monitored in the current vehicle homologation process. In this context, the aim of this study was to assess the energy performance and emissions of state-of-the-art PHEVs in real-world conditions.

More specifically, this study intends to assess the life-cycle GHG emissions of PHEVs in real-world conditions, including their sensitivity to the behaviour of the driver regarding recharging, to the battery capacity, to the trip distance, to the fuel used (e.g. fossil fuel vs low-carbon renewable fuel) or to the carbon intensity of the electricity mix. This part of the study was built on experimental results detailed in other articles[13,14] by using simulations. It is the objective of the present article to explain the method used for this part of the study and the results obtained.

The present article provides a detailed description of the following aspects of the study (see also Figure 1):

- The experimental data, used as inputs to the calibration of the vehicle simulator — see *Experimental data* on page 18;
- The calibration of a non-dimensional, physical vehicle simulator and its validation against experimental data (1) — see *Simulation platform set-up* on page 20;
- The projection of the simulation results over a design of experiments (DoE) — see *Simulations over a Design of Experiments (DoE)* on page 22;
- The mathematical methods used to extract patterns from the simulation results database, allowing the energy performance characteristics of PHEVs (CO_2 emissions, fuel and electricity consumptions, and UF) to be obtained from any combination of usage parameters (initial state of charge (SoC) of the battery, trip distance, driving style and profile (urban, extra-urban, highway) and ambient temperature) (3) — see *Analytical model rendering* on page 23;
- The statistical data representative of real-world usage, particularly in terms of vehicle-kilometres travelled (VKT) and outside temperature (2) — see *Statistics of use: Representativeness of each use case* on page 25;
- The forecasted energy performance of PHEVs in real-world usage, as a function of their battery capacity and recharge frequency (4) — see *Weighted average outputs* on page 29;
- Subsequently, the results obtained in this study were able to support the development of a vehicle life-cycle GHG emissions interactive platform — see pages 36–37.

Figure 1: Simulation workflow for PHEV energy performance real-world assessment



Methods and data

Experimental data

Two PHEVs complying with Euro 6d standards were evaluated on a chassis dynamometer (Figure 2) and on-road (Figure 3) using the same road profile, complying with RDE requirements (Figure 4). The two vehicles differ only by their powertrain, one being diesel fuelled, and the other being gasoline fuelled (see Table 1 for the main characteristics of the selected vehicles). The two vehicles, a Mercedes C300de (diesel) and a Mercedes C300e (gasoline), were tested under various conditions, including charge-depleting (CD) and charge-sustaining (CS) modes (i.e. tests starting with a fully charged battery and a discharged battery, respectively), with various fuel compositions including traditional fossil-based fuels (B7, E10), 100% renewable hydrotreated vegetable oil (HVO) and 100% renewable gasoline blended with 20% v/v ethanol (E20). The set of measurements included fuel and electricity consumption, CO_2 and regulated pollutant emissions (NO_x, CO, HC, PN23, PM) as well as non-regulated pollutant emissions such as PN10, CH_4, NH_3 and N_2O.

Figure 2: The chassis dynamometer set-up with one of the tested vehicles

Figure 3: Vehicle set-up for on-road tests using a portable emissions measurement system

A significantly higher fuel consumption was observed in the on-road tests than in the chassis dynamometer tests, despite being driven on the same test cycle. This discrepancy is accounted for in the simulation models for an improved fit with real-world data.

Figure 4: Vehicle speed profiles (RDE compliant) measured during chassis dynamometer and on-road tests

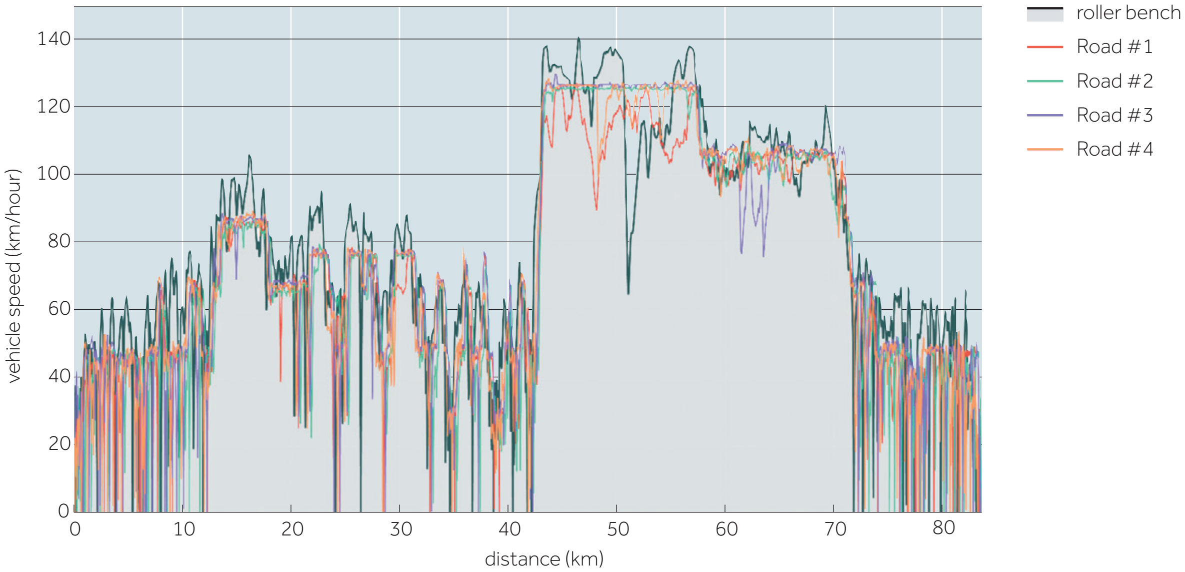


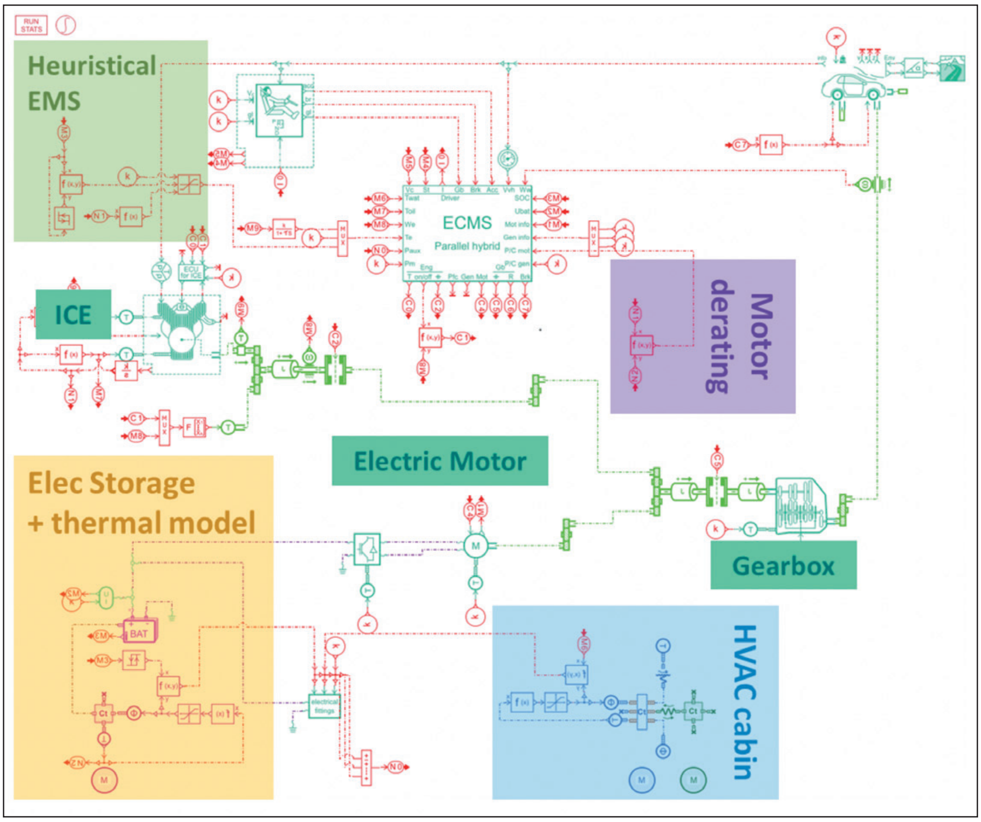
Table 1: Main specifications of selected vehicles, and CO_2 emissions in charge-sustaining mode[a] (i.e. empty battery at start of test) and weighted between CD mode (i.e. full battery at start of test) and CS mode,[b] according to the current regulation

	C300e EQ	C300de EQ
Regulation	Euro 6d-temp	
Fuel type	Gasoline	Diesel
Test mass (kg)	1,885	1,970
WLTP CO_2 (g/km)	CS: 146[a] Weighted: 31[b]	CS: 140[a] Weighted: 30.5[b]
Thermal engine	2.0L 4cyl 155 kW turbo direct injection	2.0L 4cyl 143 kW turbo direct injection
Transmission	9-speed automatic transmission	
Battery	13.5 kWh 365 V	
Electric motor	90 kW	
Hybridisation	P2 parallel hybrid architecture	
Aftertreatment system	2*three-way catalyst close coupled + gasoline particulate filter underfloor	Diesel oxidation catalyst + selective catalytic reduction filter + selective catalytic reductor close coupled
Mileage (km)	4,000	14,000

Simulation platform set-up

The simulations were carried out using Simcenter Amesim™ software. These models transcribe the physics of all devices present in conventional vehicles (combustion engine, transmission, etc.) and electric vehicles (battery, traction engine, power electronics, etc.). The simulation sketch used in this study is provided in Figure 5 for illustration purposes.

Figure 5: Detailed Simcenter Amesim™ sketch of a P2 hybrid powertrain



A component dedicated to hybrid architectures (ECMS: Equivalent Consumption Minimisation Strategy) was used to determine the optimal management strategy for internal combustion and electrical energy to minimise fuel consumption. It was calibrated to fit the experimental behaviour characterised on pages 18 and 19, as illustrated in Figures 6 and 7 on page 21.

Figure 6: RDE test cycle simulation for CD mode (on the left) and CS mode (on the right)

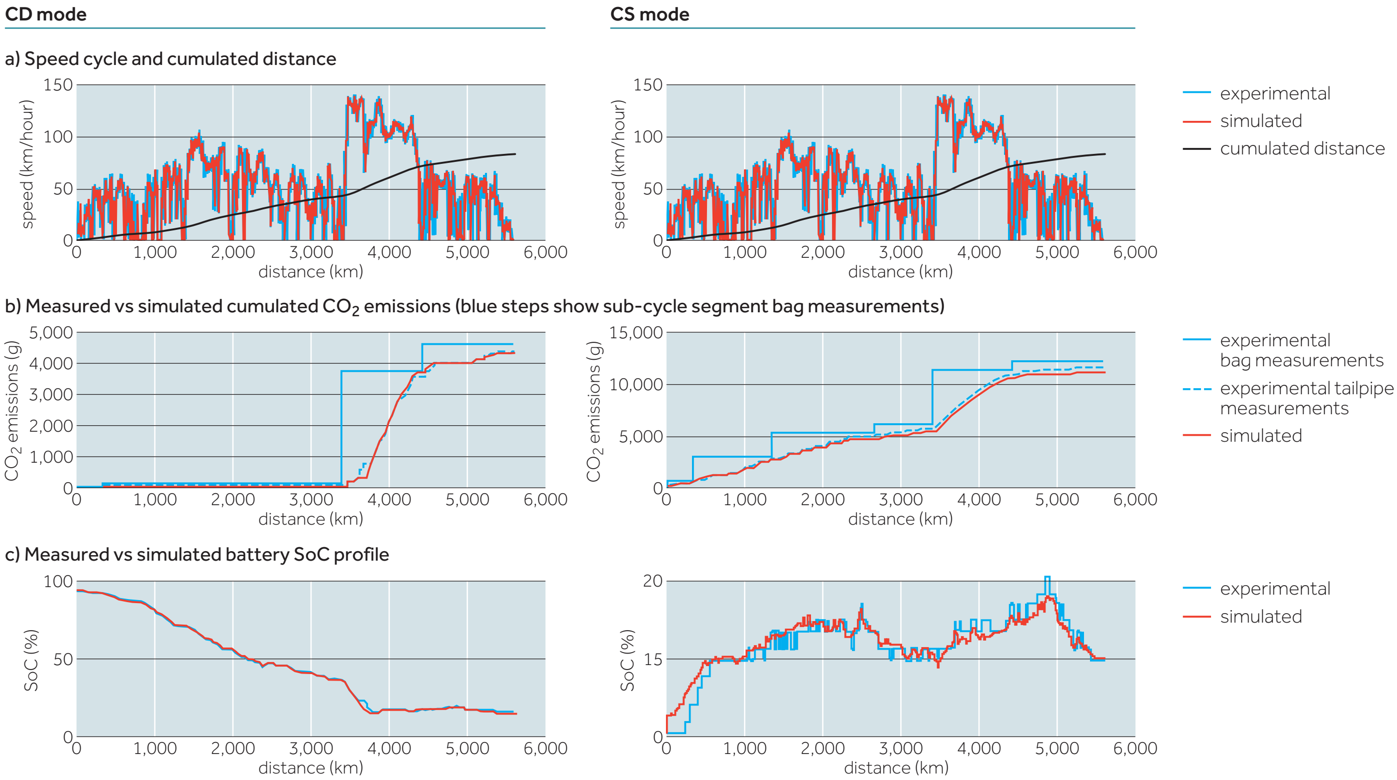
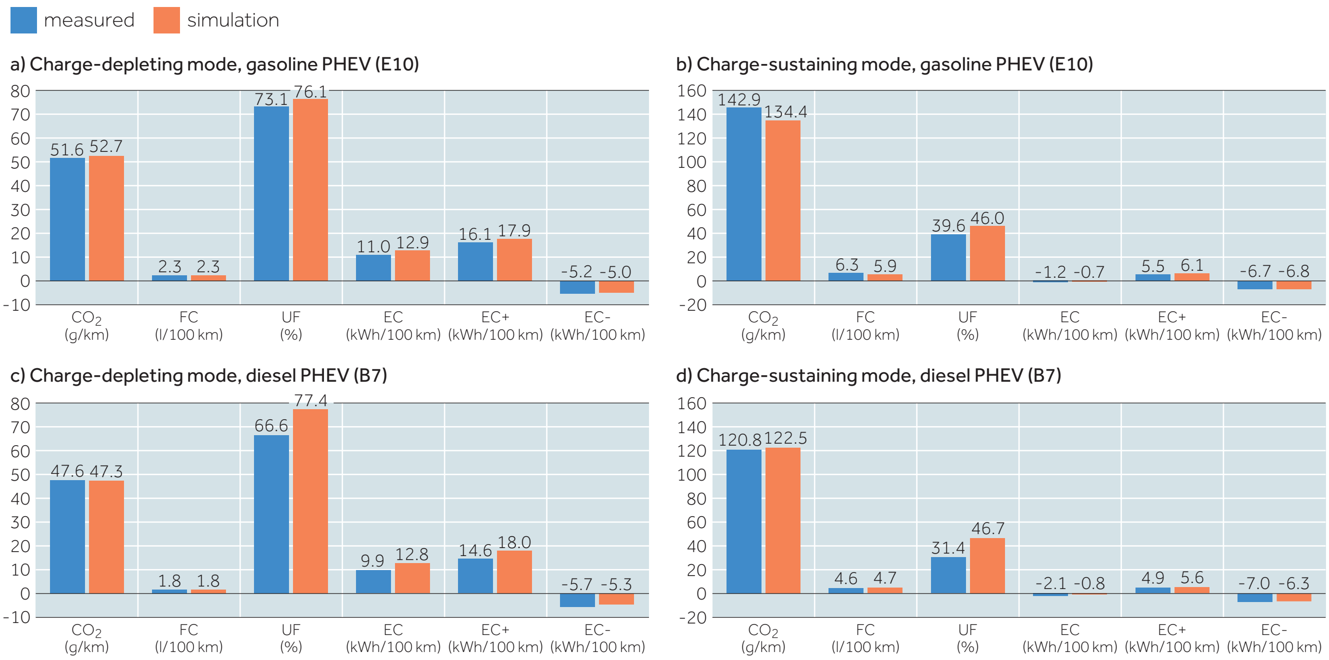


Figure 7: Comparison between the experimental and simulation results for the gasoline and diesel PHEVs, in CD and CS modes



After calibration, the simulator was fully capable of reproducing the behaviour of the tested PHEVs, at any temperature between -2°C and +35°C, for a range of driving profiles and trip distances, and under any state of charge of the battery. The simulator also provides an extension to accommodate any battery capacity between 2 kWh and 35 kWh (knowing that the tested vehicles were equipped with a 13.5 kWh battery) as well as a non-plug-in HEV (which is basically 120 kg lighter and working only in CS mode as it cannot be recharged). Although this amounts to a significant range of configurations that can be simulated, the results cannot be extrapolated to any other PHEV having, for example, other engine or electric power, or other energy management strategies.

Projection over a comprehensive range of cases

Simulations over a design of experiments (DoE)

A set of simulation results was generated over all possible vehicle use conditions, aiming at extending the simulation results over a broad range of usage (i.e. not only over a specific RDE cycle). The calibrated simulator referred to above was thus used to provide projections for a wide range of driving conditions and styles, weather temperatures, battery sizing and conditioning, etc.

The simulation matrix has five dimensions, which are summarised in Table 2: ICE type (2 levels); PHEV mode (3 levels); driving cycle (24 levels); battery capacity (3 levels); and outside temperature (3 levels). This results in 1,296 possible combinations, all of which were simulated. In practice, more than 3,000 simulations were performed, and provided detailed results, because several shorter driving cycles required repetition to empty the battery and allow the transition from CD mode to CS mode to be observed.

Table 2: Simulation DoE dimensions and features

Dimensions explored	Number of variations	Values
ICE type	2 combustion modes	Gasoline, diesel
PHEV mode	≥3 initial SoC	CD 95% until 15% depletion + CS hot + CS cold
Driving cycle	5+19 speed profiles	WLTC, ARTEMIS x 4 [Road Type 1–>4] x [Road Conditions 1–>7]
Battery capacity	3 capacities	7 kWh, 13.5 kWh, 25 kWh
Outside temperature	3 initial T°	-2°C, 23°C, 35°C

Notes:
Road Type 1->4 refers to: inner city; outer city; extra urban; and highway.
Road conditions include: jammed circulation; moderate driving; increasingly dynamic patterns, even harsh ones; and finally speeding.

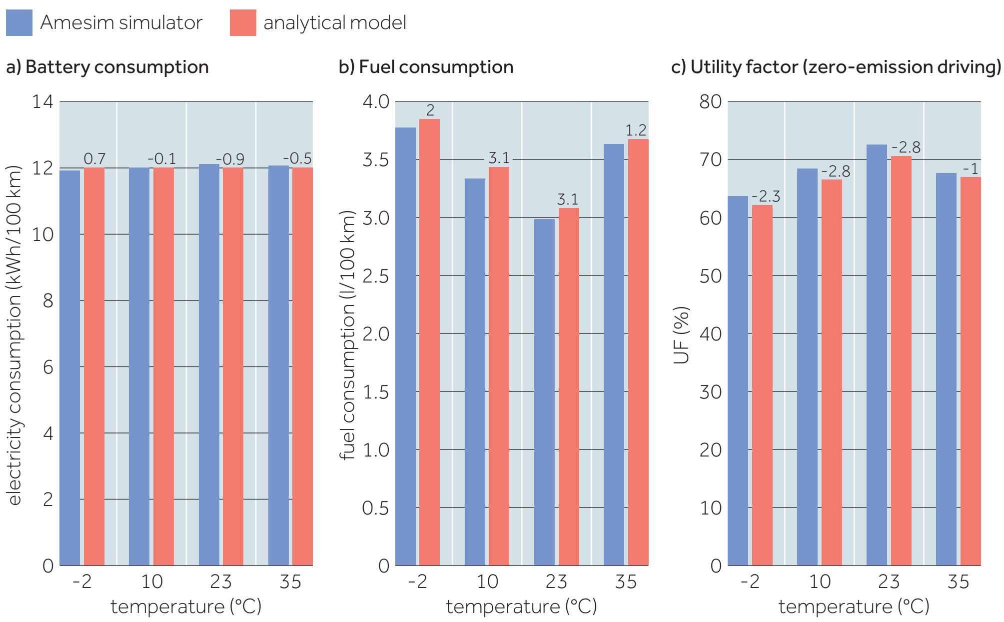
Analytical model rendering

Although simulation can provide any result from any situation once it is properly calibrated, it remains a time-consuming process that cannot be generalised to each practical application. As the study intended to aggregate day-to-day PHEV users' patterns over a whole population, it was necessary to design a simpler analytical method by using the previously generated database. Instead of rerunning simulations, a mathematical post-processing method was developed to bring the results together.

The concept behind the mathematical process developed in this study consists of identifying the asymptotic (lowest) values of energy consumption for each speed profile, to which overconsumptions (i.e. deviations) are then added, knowing that the latter correlate with thermal conditioning. Once consumptions over any clustered cycle can be calculated, they can be summed into a sequence of identified speed profiles, provided as a cycles list and respective mileages, along with the vehicle characteristics and weather conditions. Thereafter, in a loop pattern, a temperature deviation profile and then consumptions can be successively estimated for each segment. Eventually, the addition of all segments indicates the total amounts of electricity and fuel required in this specific use.

To validate the mathematical approach, the same driving cycle was calculated in the physical simulator (Amesim) and with the mathematical equations at -2°C, 10°C, 23°C and 35°C. The results are compared in Figure 8 which shows a good fit between the two sets of results. It can therefore be concluded that the mathematical model is predictive in the range of modelled ambient temperatures [-2°C, 35°C].

Figure 8: Simulation vs mathematically assessed driving sequence for the complete range of ambient temperatures



Note:
The values on top of the bars are the % difference between the results of the two simulation methods.

Results over generalised usage

Due to the degrees of freedom induced by the architecture of PHEVs, they are extremely versatile, being equally capable of operating almost exclusively on electrical or chemical energy depending on the conditions of use. It is therefore necessary to assess the actual behaviour of PHEVs by:

- evaluating the sensitivity of technologies to the conditions of use; and
- assigning a weighting to each condition according to its representativeness.

Thanks to the simulation work, it was proposed to:

- consider the sensitivities of technologies (particularly to ambient temperature);
- consider a wide range of use cases through statistics;
- consider a broad range of recharging frequencies; and
- vary the battery capacity.

Capturing the sensitivity of technologies: assessment of results on a large matrix

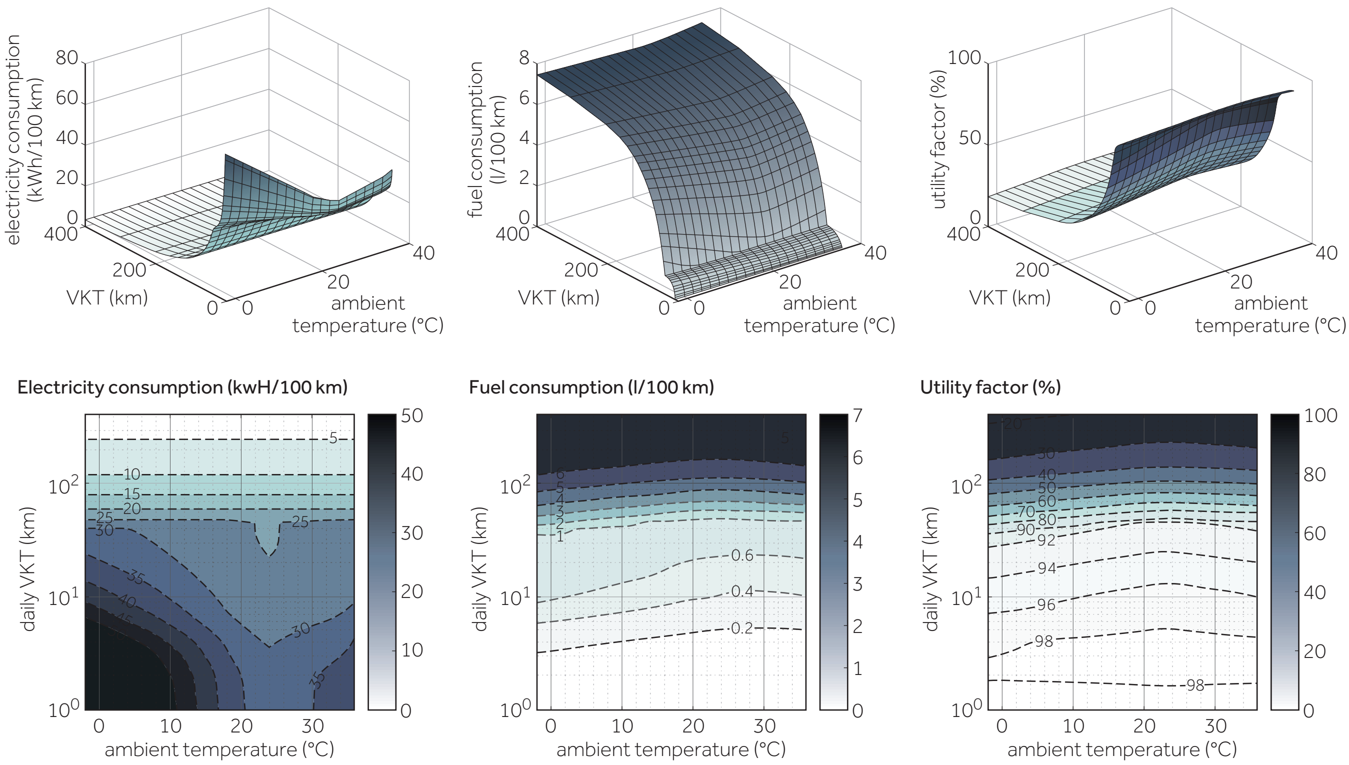
Based on the analytical model described above, each individual use case was simulated as a combination of:

- **v** conditions of daily VKT and associated driving patterns, 24 cases [4:400 km]
- **t** conditions of ambient temperature, 20 cases [-2:36°C]
- **r** conditions of recharge interval, 11 cases [0.5:10 days]
- **b** conditions of battery sizing, 10 cases [2:35 kWh]

Figure 9 on page 25 shows the results of simulations made for one given value of battery capacity (15 kWh) and recharge frequency (every day) for the gasoline PHEV. A total of 480 combinations of temperature/daily mileage were considered.

The simplified mathematical model reproduces the behaviour of the physical model, and therefore also of the vehicles evaluated experimentally. A plateau of high UF values (>95%) is observed for short distance trips (<20 km) as a PHEV recharged every day is able to handle these distances almost completely in all-electric mode. In such cases, a low fuel consumption is consistently observed and a high electrical consumption is stated. A sharp increase in power consumption in cold ambient conditions is observed as a consequence of battery and cabin conditioning. As trips become longer, the battery SoC decreases, resulting in a sharp decrease in the UF. Consequently, the average electrical consumption decreases and the average fuel consumption increases sharply with trip distance, and even more at low temperature due to the decrease in the electric range caused by the battery and cabin heating.

Figure 9: Example of results for one given battery capacity and recharge frequency (gasoline PHEV with a 15 kWh battery recharged every driving day)



The same simulations were performed for every battery size (2 to 35 kWh) and recharge interval (0.5 to 10 days), for both diesel and gasoline vehicles, leading to around 53,000 use cases simulated, including variations in technology sizing, and in environmental and driving conditions.

Statistics of use: representativeness of each use case

As seen above, the most influential parameter on the behaviour of a PHEV for a given charging interval is the daily distance travelled. Furthermore, as is the case for highly electrified vehicles in general, the electrical consumption of PHEVs is particularly sensitive to ambient temperature conditions.

This following text focuses on the statistical distributions of use observed for these two influencing parameters, extracted from the literature. These statistical distributions are then used to weight the different use cases according to their probability.

Ambient temperature

Through the Geco air application, IFPEN has collected daily mobility data from thousands of non-professional drivers. The frequency of temperature recorded during each trip (weighted by distance) is shown in Figure 10. This distribution is approximated by a gamma distribution law (equation (1)), as illustrated in Figure 11:

$$P(t;k,\theta) = \frac{(t-t_0)^{k-1} e^{-\frac{t-t_0}{\theta}}}{\Gamma(k)\theta^k} \quad (1)$$

To study the climatic sensitivity, this same distribution is shifted by an offset of +10°C and -10°C to arbitrarily represent warmer and colder climate conditions. The average temperatures thus reproduced are close to the average Australian (22°C) and Swedish (2°C) temperatures, respectively.

Figure 10: Distribution of the ambient temperature while driving (weighted by distance travelled)

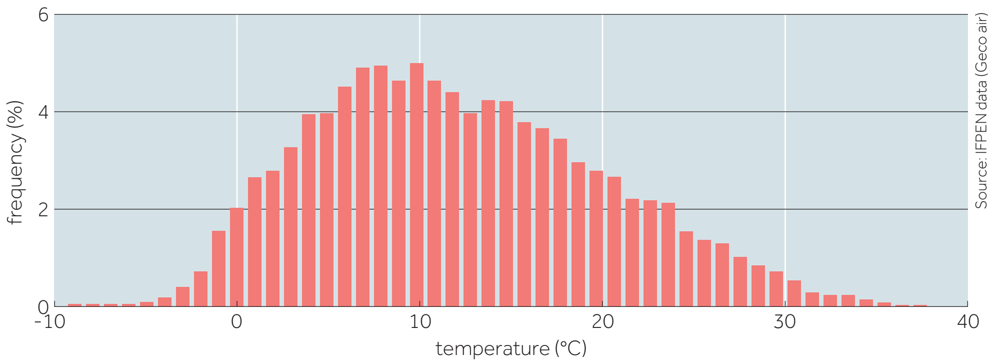
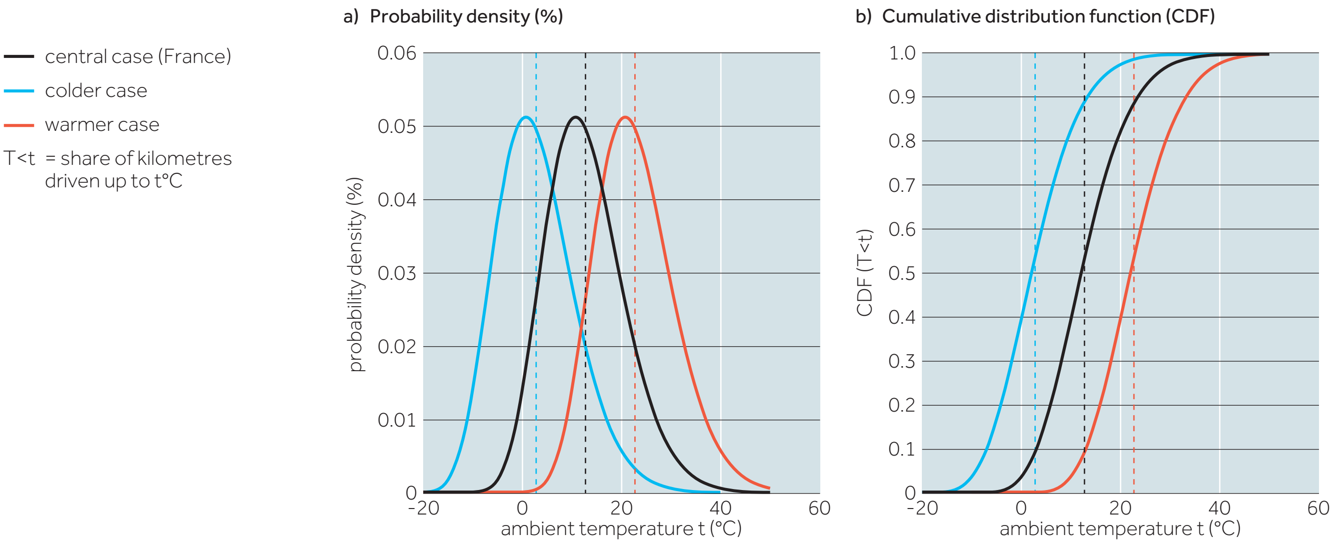


Figure 11: Ambient temperature distributions retained for the current work



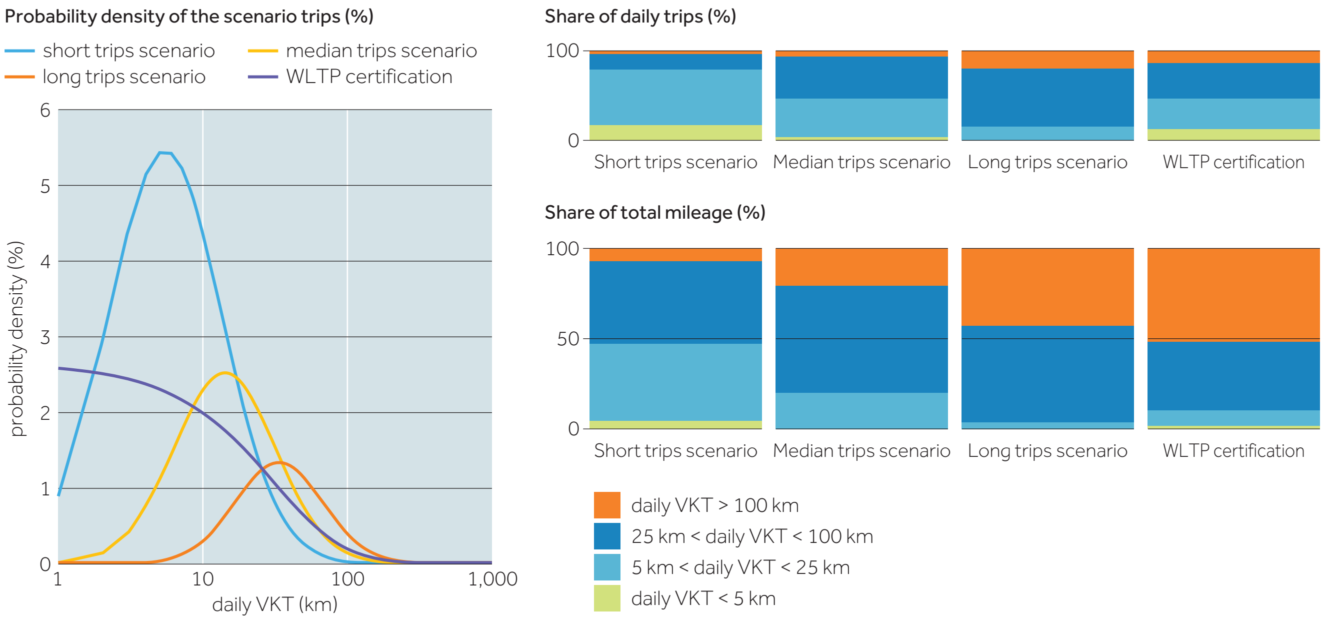
Daily vehicle mileage travelled

The UFs defined by the WLTP protocol for the type approval of PHEVs come from mobility studies determining the daily distances operated. Assuming daily charging, they represent the possible percentage of the distance covered in all-electric mode by a fleet according to the vehicle's electric range.

Other data are available in the literature, in particular from mobility surveys in Germany.[15] Figure 12 represents the log-normal distribution (see equation (2)) from the German mobility survey by Plötz *et al.*[15] for the 'medium' vehicle class (yellow curve in the left graph, 'Median trips scenario'). From there, two other scenarios were designed, corresponding to shorter and longer trips (blue and orange curves). The bar graphs on the right hand side allow the reader to visualise the corresponding share of trips (top) and the share of mileage driven (bottom) according to the trip distance.

$$Prob(d;\mu,\sigma) = \frac{1}{d\sigma\sqrt{2\pi}}\exp\left(-\frac{\ln(d)-\mu}{2\sigma^2}\right) \qquad (2)$$

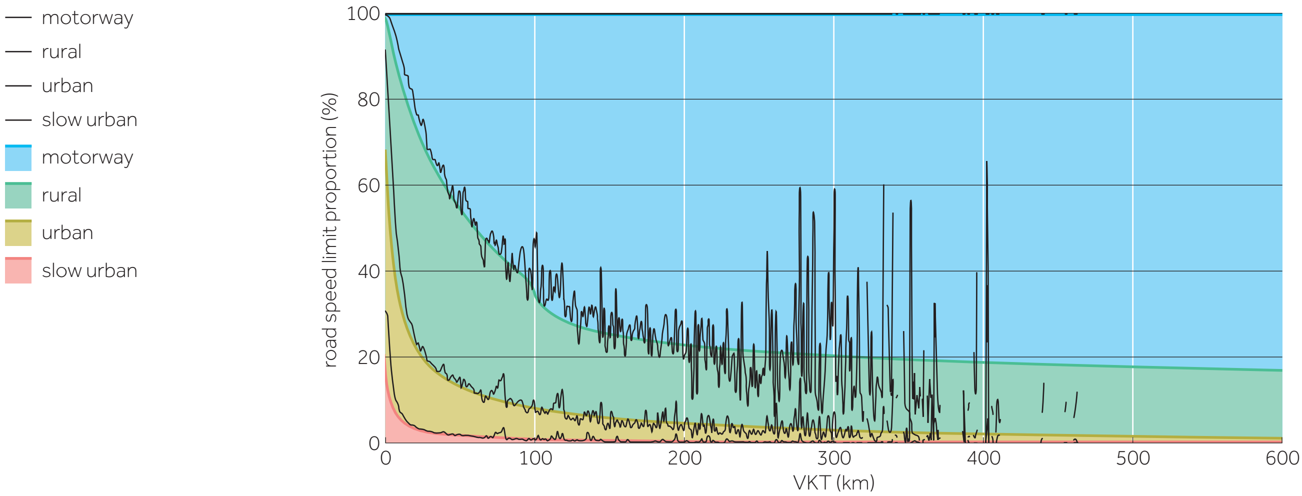
Figure 12: VKT distribution retained for the current work



Driving pattern (a function of VKT)

The type of route also has an impact on energy (electricity and fuel) consumption levels and UF. In the IFPEN database, as illustrated in Figure 13, the share of kilometres travelled in slow urban, urban, rural and motorway conditions is determined as a function of VKT. For the sake of simplification, the driving order adopted was always from the slowest (slow urban) to the fastest (motorway).

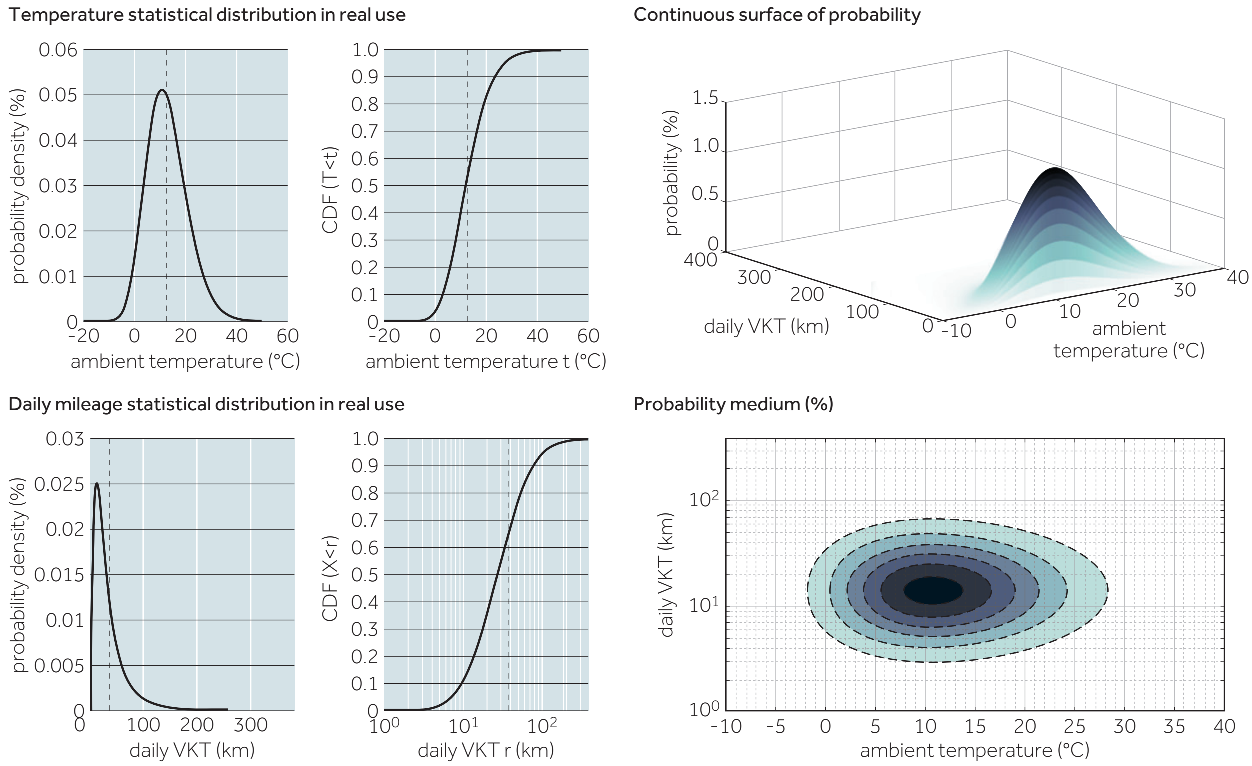
Figure 13: Typology of roads as a function of daily mileage



Resulting probability matrix

Assuming that temperature and trip distance are independent, the probability of a pair (VKT-ambient temperature) is obtained by the multiplication of the laws previously established for the VKT and the ambient temperature. Therefore, considering the driving temperature distribution in France and the daily vehicle mileage from literature (German mobility survey in this instance), a probability matrix is determined which makes it possible to ascertain the probability of each situation in real-world conditions (see Figure 14 on page 29).

Figure 14: Matrix of use cases, probability function of ambient temperature and daily mileage

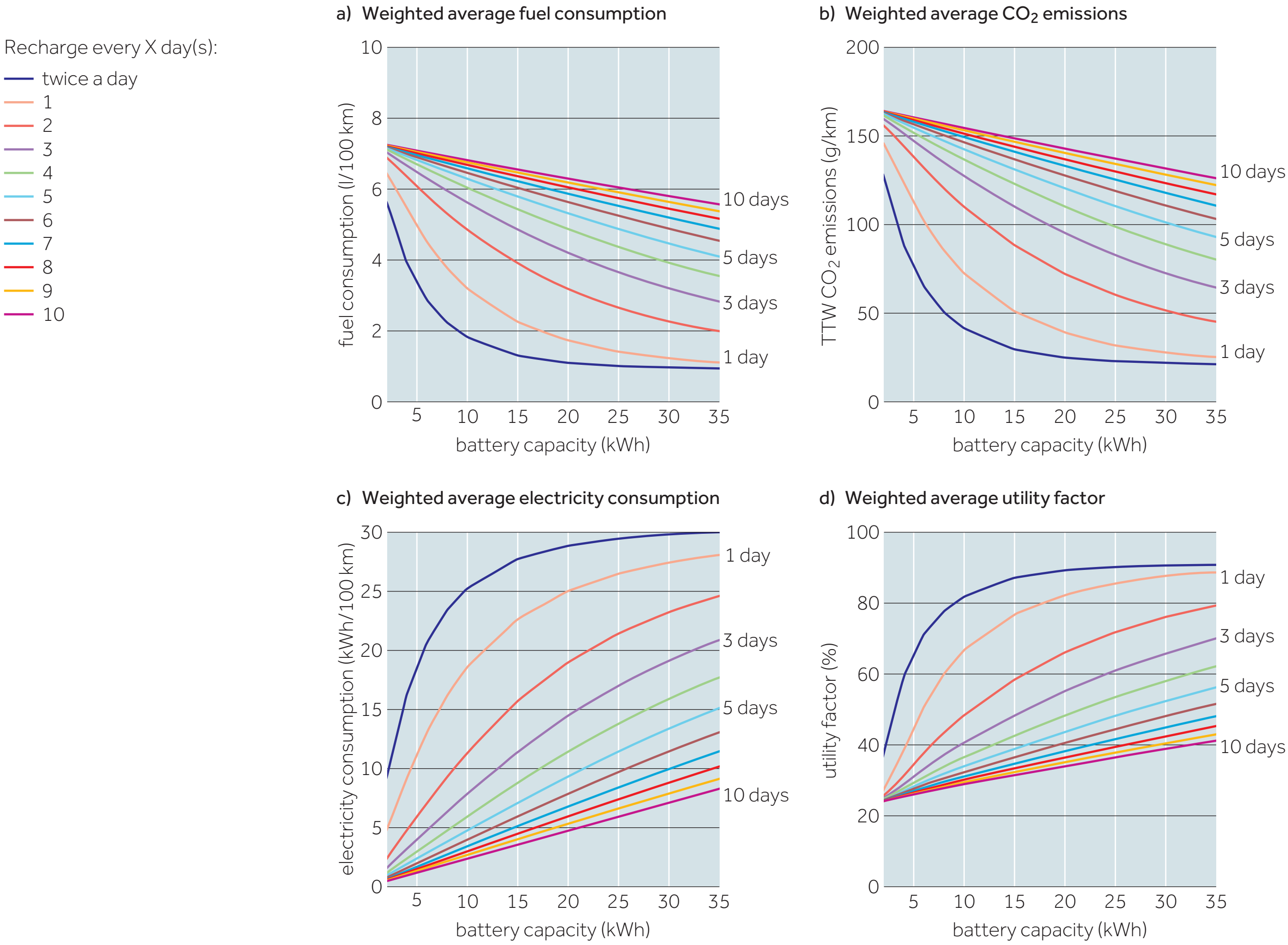


Weighted average outputs

For each combination of battery capacity and recharge frequency, weighted average values are calculated taking into account each individual use case over the whole range of VKT and ambient temperature, and its representativity.

Thus, for a given battery capacity and charging interval combination, mean scores representative of the actual use are obtained, resulting from the weighting of the energy performance in each use case, weighted by its representativeness and its distance. This was done for each combination of battery capacity and recharge interval, so that the evolution of energy performance parameters in real-world conditions as a function of these two key parameters could be obtained. Figure 15 on page 30 shows the weighted average outputs over the full range of variations for recharge interval and battery capacity. This figure is key to understanding the sensitivity of real-world average energy performance (fuel and electrical consumptions and UF) of PHEVs to both the technological sizing and the final user behaviour.

Figure 15: Weighted average fuel consumption, CO_2 emissions, electricity consumption and UF over the full range of variations for battery capacity (from 2 kWh to 35 kWh) and recharge frequency (from twice a day to every 10 days) — gasoline PHEV



Discussion

Impact of battery capacity and recharge interval on PHEVs — key results

Figure 15 illustrates the influence of the dimensioning of the battery according to the frequency of recharging:

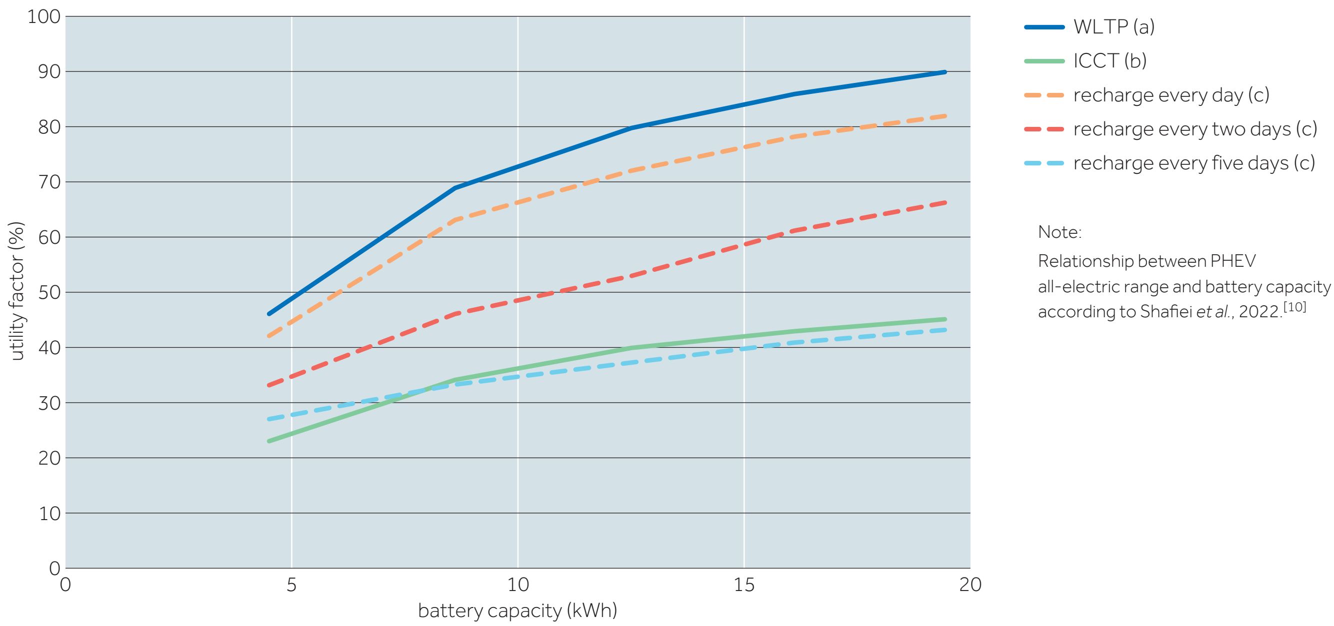
- Frequent recharging of PHEVs is a necessary condition for a high electrification rate: recharging every day enables the potential to reach an average weighted fuel consumption of 2.25 l/100 km and a UF of around 77% with a gasoline PHEV equipped with a 15 kWh battery. Recharging every three days induces a fuel consumption of 4.85 l/100 km (+116%) and a UF of around 48% (-29 points).

- A weighted average UF of 50% is reached at around 6 kWh of battery capacity, and 80% is reached at around 18 kWh of battery for an every-driving-day recharge.
- The first few kWh of battery capacity are the most effective in reducing the weighted average fuel consumption: considering 1 recharge/day, the gain in increasing the battery capacity above 20 kWh is low. For instance, adding another 15 kWh to the vehicle, leading to a 30 kWh PHEV, would increase the UF by only 10 points, from 77% to 87%, if recharged every day; in contrast, the same 15 kWh battery could electrify 77% of the mileage of another PHEV, which is more efficient if the total amount of available batteries is constrained.[10]

Shifting from an individual vehicle evaluation to a systemic perspective

To shift from the individual vehicle evaluation performed in this work to a systemic perspective, it is necessary to link this work to the conclusions drawn by Shafiei *et al.* (2022).[10] In their study, Shafiei *et al.* could not evaluate the UF of PHEVs by themselves and had to draw from the literature based on data from UNECE (2017)[16] and ICCT (2020),[6] as shown in Figure 16. It is interesting to compare these UFs with those obtained in this work, shown here in the case of the gasoline PHEV (Figure 16). It can be observed that the UF calculated for a recharge frequency every day is 4 to 8 points lower than the one given by the WLTP. It can also be seen that the UF calculated for a recharge every five days follows closely the UF suggested by the ICCT.

Figure 16: Utility factors according to (a) UNECE, 2017,[16] (b) ICCT, 2020[6] and (c) this work for a recharge frequency every day, every two days and every five days, as a function of battery capacity



Note:
Relationship between PHEV all-electric range and battery capacity according to Shafiei *et al.*, 2022.[10]

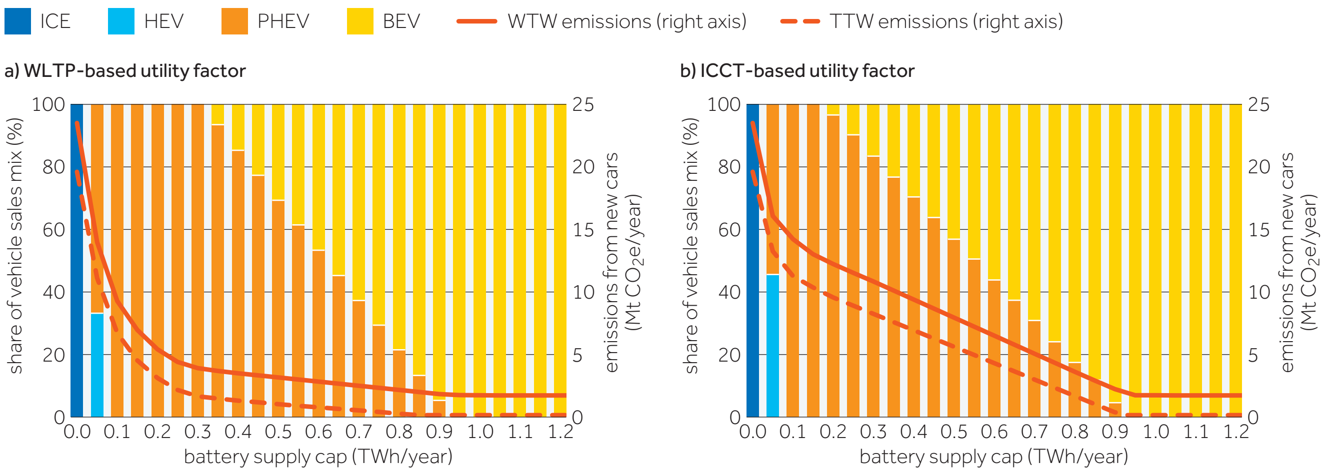
Based on the UFs extracted in UNECE (2017)[16] and ICCT (2020),[6] Shafiei *et al.* (2022)[10] calculated the optimal allocation of batteries to passenger cars that would minimise their WTW GHG emissions, under various levels of battery supply to Europe ranging between 0 to 1.2 TWh/year. Figure 17 on page 33 shows one of the major findings of their work: under a constrained supply of batteries, it is better to allocate batteries to PHEVs first to minimise WTW GHG emissions; and only once the battery supply is less constrained do BEVs start to be part of the optimal solution, firstly along with PHEVs, and eventually alone. This conclusion reflects the fact that (i) in the frame of a highly decarbonised electricity grid (assumed for 2030 in their work), electrifying the driven mileage leads to reduced WTW GHG emissions, and (ii) to maximise the electrification of the driven mileage, it is more efficient to share smaller batteries used at their full capacity in all vehicles (enabled by PHEVs under a constrained supply of batteries) rather than to allocate underutilised bigger batteries to a few vehicles (which would occur if a BEV strategy is adopted too early).

The question remains as to whether Europe will actually experience a constrained battery supply in 2030. Regarding the demand aspects, according to Shafiei *et al.*,[10] supplying 0.95 TWh/year of batteries for passenger cars in Europe would enable all of them to be electrified, providing that their individual battery capacity is lower than 60 kWh. According to Strat Anticipation (2022),[17] the demand for batteries in the EU for electrified light vehicles would be 0.894 TWh/year in 2030 (for BEVs equipped with a 78 kWh battery and sales which are not fully electrified), starting from 0.123 TWh/year in 2022, and through 0.365 TWh/year in 2025. Regarding the supply aspects, there have been significant differences in announced, revised and realistic output forecasts for battery production facilities ('Gigafactories') in the EU. For example, according to Strat Anticipation,[17] the EU's planned output for battery production in 2025 went down from 0.45 TWh/year (evaluated Q4 2021), through 0.392 TWh/year (evaluated February 2022) to 0.224 TWh/year, therefore requiring 0.141 TWh/year of imports; for 2030, the EU's planned output was 0.80 TWh/year in Q4 2021, rose to 1.037 TWh/year in February 2022, and dropped to 0.609 TWh/year, therefore requiring 0.285 TWh/year of imports. It is unclear where the imports would come from, but they are unlikely to come from North America as its planned production output is also lower than its demand, resulting in an import balance; and forecasts of China's planned production output indicate that China will barely meet its internal demand.

In brief, it appears highly likely that the battery supply for passenger cars in Europe will be constrained for the next 10 years (i.e. not sufficient to enable 100% of passenger car sales to be BEVs) and, under these conditions, Shafiei *et al.*[10] concluded that a vehicle sales mix oriented towards PHEVs would be optimal in minimising WTW GHG emissions.

Figure 17: Optimal vehicle sales mix minimising WTW GHG emissions subject to a constrained battery supply in 2030

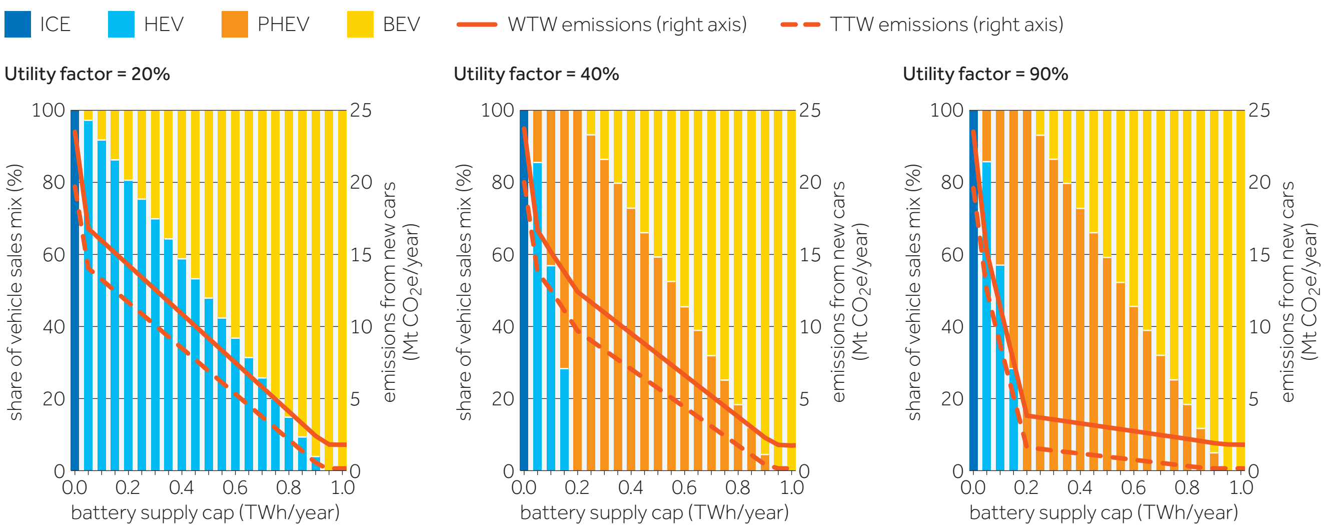
Results assume battery capacities of 1.54 kWh (HEV), and 58.4 kWh (BEV). PHEV battery capacities are optimised to minimise WTW GHG emissions, and their utility factors follow the WLTP and ICCT curves on Figure 16. (Source: adapted from Shafiei *et al.*, 2022[10])



Additionally, Shafiei *et al.*[10] looked further into the influence of the UF on the results of their optimisations. They found that, below a certain UF, called the 'break-even utility factor', PHEVs were no longer efficient in minimising WTW GHG emissions, and therefore the structure of the passenger car sales mix shifted directly from HEVs to BEVs without going through PHEVs (Figure 18, left). Conversely, above the break-even utility factor, PHEVs play an important role in the transition between HEVs and BEVs to minimise WTW GHG emissions, and the structure of the passenger car sales mix remains mostly unaffected whatever the utility factor above the break-even point (Figure 18, centre and right).

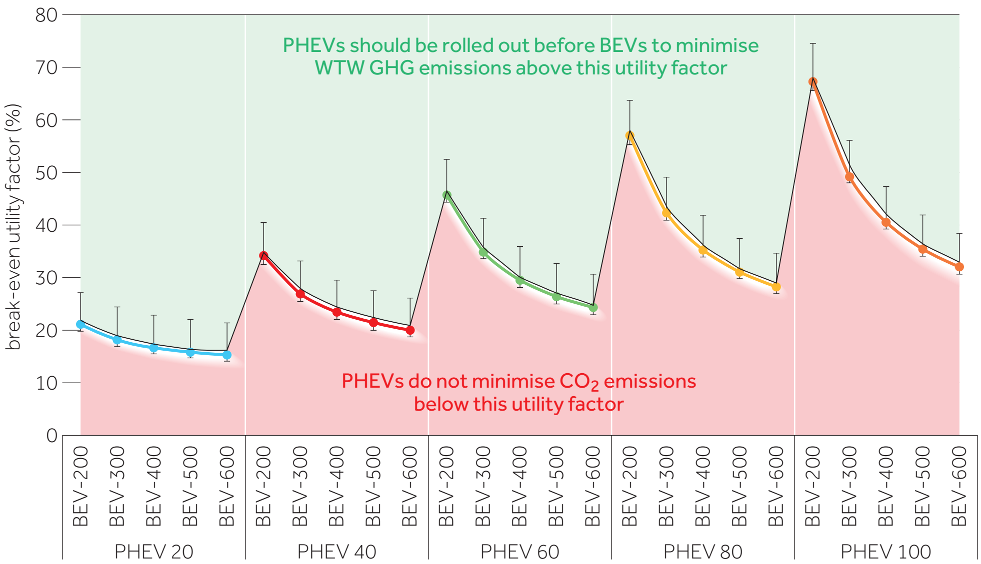
Figure 18: Optimal vehicle sales mix minimising WTW GHG emissions as a function of battery supply to Europe in 2030 for three levels of UF (20%, 40% and 90%), with the break-even point being 30%

Results assume fixed battery sizes of 1.54 kWh (HEV), 12.5 kWh (PHEV) and 58.4 kWh (BEV). (Source: adapted from Shafiei *et al.*, 2022[10])



Shafiei *et al.*[10] generalised this approach and calculated the break-even utility factor for a variety of combinations of battery capacities for PHEVs and BEVs (shown as a function of their all-electric driving range in Figure 19). It can be seen that PHEVs with smaller batteries (e.g. PHEV 20) have a lower break-even utility factor: this is because smaller batteries can be shared with more vehicles that are more likely to use them at their full capacity, resulting in an efficient electrification of the overall mileage. For the same reasons, BEVs with smaller batteries (e.g. BEV-200) require PHEVs to have a bigger break-even utility factor.

Figure 19: Break-even utility factor of PHEVs for various combinations of battery capacities for PHEVs and BEVs

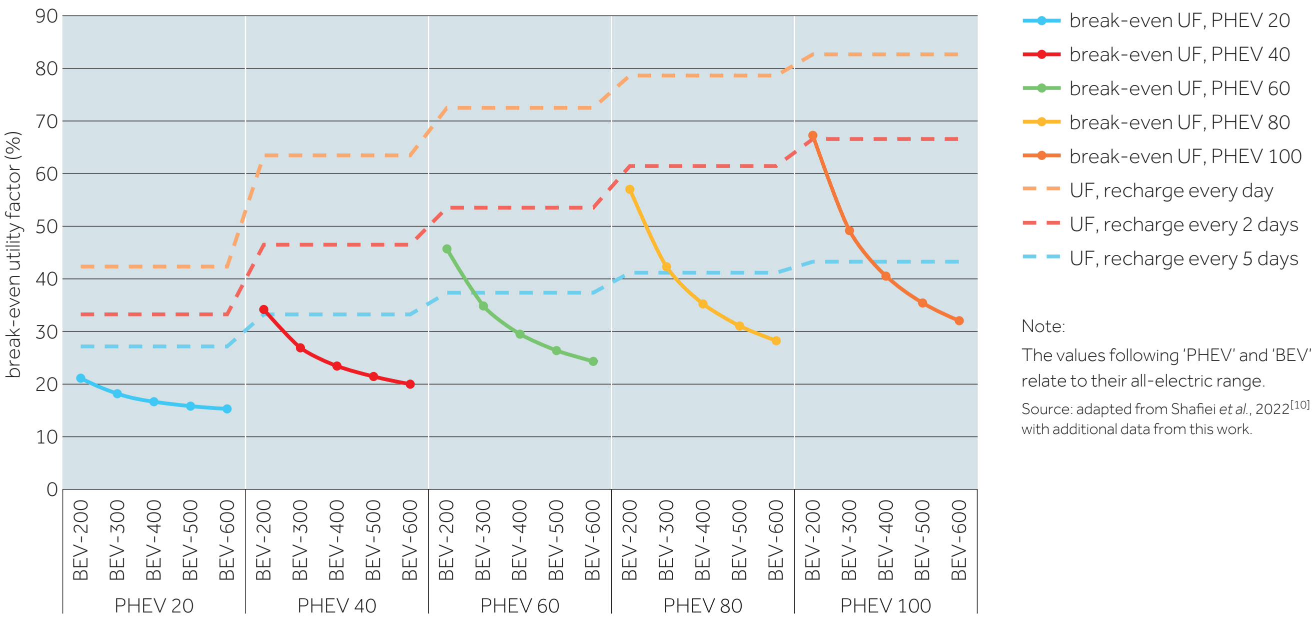


Notes:
The values following 'PHEV' and 'BEV' relate to their all-electric driving range.
Error bars show the sensitivities with respect to the carbon intensity of the electricity supply mix ranging from 0 to 76.4 gCO_2e/MJ.
Source: adapted from Shafiei *et al.*, 2022[10]

The results published by Shafiei *et al.*[10] can be bridged with the work undertaken in this study: as the models developed here give the real-world utility factors as a function of the PHEV battery capacity and their recharge frequency, they can be compared to the break-even utility factor. In Figure 20 on page 35 it can be observed that a PHEV recharged every driving day or every two driving days always has a utility factor above the break-even point, whatever the battery capacities of the PHEVs and the BEVs. This means that, under limited supply of batteries to Europe, it is always preferable to roll out PHEVs first (before BEVs) providing that they are recharged at least every two driving days. If the PHEVs are recharged only every five driving days, the conclusion is somewhat different: for the PHEVs having a smaller battery (PHEV 20 and PHEV 40), the real-world utility factors are still above the break-even point.

This means that 'small PHEVs' (with a battery capacity lower than 8.6 kWh) are a no-regret option: even if they cannot be recharged very often (notwithstanding that the more often they are recharged, the better), they will always manage a deeper cut in WTW GHG emissions compared to a 'BEV-only' strategy. For the PHEVs having a bigger battery (PHEV 60 to PHEV 100), the results are more contrasted if they are recharged every five driving days as they depend on the BEVs against which they 'compete': if the BEVs have a smaller battery (less than 60 kWh or 400 km driving range), these become more efficient in minimising WTW GHG than those PHEVs; but if the BEVs batteries are bigger than 60 kWh, then the PHEVs become more efficient again, whatever their battery capacity.

Figure 20: Break-even utility factor of PHEVs compared to real-world utility factors for various combinations of battery capacities for PHEVs and BEVs



Note:
The values following 'PHEV' and 'BEV' relate to their all-electric range.

Source: adapted from Shafiei *et al.*, 2022[10] with additional data from this work.

Conclusions

Two Euro 6d PHEVs were selected to allow a relevant comparison between gasoline and diesel internal combustion engines. These vehicles were tested on a chassis dynamometer and on-road, both with standard and renewable fuels, in CD and CS modes.

Two simulators for the gasoline and diesel PHEVs were set up, calibrated and validated. A DoE was performed under various conditions (temperature, driving cycles, initial battery SoC, battery capacity) to extend the energy performance findings of these two vehicles, i.e. the CO_2 emissions, UF, and fuel and electricity consumption. Finally, a simplified mathematical model was established and validated, allowing the energy performance parameters to be estimated for any combination of use. This work established that the energy performance of PHEVs is heavily dependent on the conditions of use (temperature, trip distance, recharging frequency and battery sizing), as the ratio of use of each of the two energy sources available on board is extremely variable.

A weighting methodology based on available real-world statistics was implemented on the parameters of ambient temperature and daily distance travelled. Furthermore, the recharging frequency and battery capacity factors, which depend on end users and manufacturers, respectively, were also varied (but not weighted as too few statistics are available) so as to provide insights via a sensitivity analysis. The study shows that frequent recharging of PHEVs is a necessary condition for a high electric drive rate: for a gasoline PHEV with a battery of 15 kWh, recharging every day leads to an average fuel consumption of 2.25 l/100 km and a utility factor of 77%, whilst recharging every three days leads to a fuel consumption of 4.85 l/100 km (+116 %) and a utility factor of 48% (-29 points). By comparison, the non-rechargeable gasoline HEV with a 2 kWh battery evaluated under the same conditions shows an average fuel consumption of 7.3 l/100 km and a utility factor of 24%. Compared to this reference HEV, the gasoline 15 kWh PHEV allows a consumption reduction of 69% if it is recharged every day and a reduction of 34% if it is recharged every three days. Furthermore, it is observed that the first kilowatt-hours of battery capacity are the most effective in electrifying the PHEVs: for instance, adding another 15 kWh of battery capacity to the vehicle, leading to a 30 kWh PHEV, would increase the UF by only 10 points, from 77% to 87%, if recharged every day; alternatively, the same 15 kWh battery capacity could have electrified 77% of the mileage of another PHEV, which is more efficient if the total amount of available batteries is constrained.

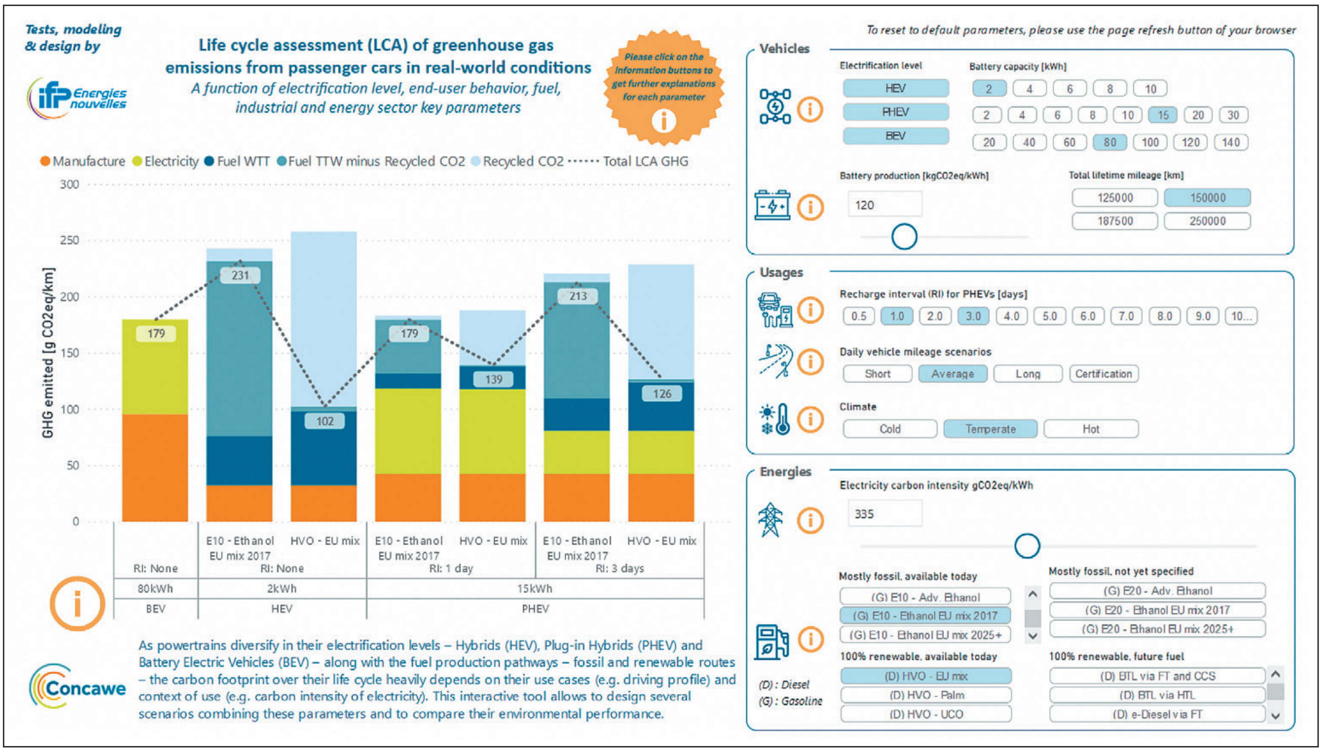
Shafiei *et al.*[10] concluded that, as long as the PHEVs' UFs are above their break-even points, they are part of the optimal vehicles sales mix minimising WTW GHG emissions in a scenario where the supply of batteries to the EU is constrained. The real-world assessment performed here confirms that, for a typical driving profile, the PHEVs' UFs are always above the break-even point when recharged every driving day or every two driving days. In addition, 'smaller' PHEVs with an all-electric driving range of 40 km or less are always above their break-even UF even if recharged down to every five driving days.

Outlook: from tank-to-wheel to life-cycle emissions — a vehicle LCA interactive tool

The TTW CO_2 emissions evaluated in this work do not offer a complete picture of the GHG emissions emitted during the life of a vehicle. To achieve this, a broader analysis of the vehicle's life cycle needs to be determined by considering not only the TTW emissions of the vehicle during its use, but also the WTT emissions related to the energy sources (electricity and fuel production) and, finally, the production and end of life of the vehicle itself, including the battery. Such an assessment is based on many parameters, for example: the CO_2 intensity of electricity production; the CO_2 WTT emissions and associated recycled CO_2 from different fuel production pathways; the CO_2 emissions related to the production of the vehicles, particularly the battery; the lifetime of the vehicles; etc. Given the quantity of possible pathways, assumptions and their variability, it is impossible to have a consensus on the definition of a baseline (around which sensitivities can then be run).

For this reason, a dynamic LCA GHG tool has been developed, allowing users to configure any possible combination of parameters and to compare the life-cycle emissions of PHEVs with those of other types of vehicle electrification, i.e. HEVs and BEVs (Figure 21). This tool is supported by the energy performance model developed in this article (which provides the TTW CO_2 emissions, the energy consumption and the UFs), which also integrates the WTT and life-cycle emissions as a function of the selected configurations.

Figure 21: Screenshot of the on-line vehicle LCA simulator
(accessible at https://www.carsCO2comparator.eu)



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