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PLUG-IN HYBRID VEHICLE CO_2 EMISSIONS: HOW THEY ARE AFFECTED BY AMBIENT CONDITIONS AND DRIVER MODE SELECTION

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EXECUTIVE SUMMARY

Recent studies show that plug-in hybrid electric vehicles (PHEVs) show a large gap between real-world and official type-approval CO_2 emissions. The gap is to a great extent attributed to less frequent charging than anticipated by the type-approval regulation, but also driving at low and high ambient temperatures while using heating or air-conditioning contributes to a lower share of electric driving.

To assess the effect of ambient temperature and use of air-conditioning in detail, we tested a 2020 model year BMW X1 xDrive25e PHEV. Worldwide harmonized light vehicles test cycles (WLTCs) were performed under type-approval conditions at 23 °C, as well as at -5 °C and 35 °C. At 23 °C, automatic air-conditioning was turned off, while it was set to 22 °C for the tests at high and low temperature. The vehicle was also tested using different plug-in hybrid operating modes to evaluate their effect on the CO_2 emissions.

The electric energy consumed by the air-conditioning compressor and cabin heater reduces the energy available for powering the vehicle and thereby the distance attributed to electric energy (Figure ES-1). While an equivalent of 46 km can be driven using electric energy at 23 °C, the distance is almost halved to 24 km at -5 °C and 41 km (-11%) at 35 °C.

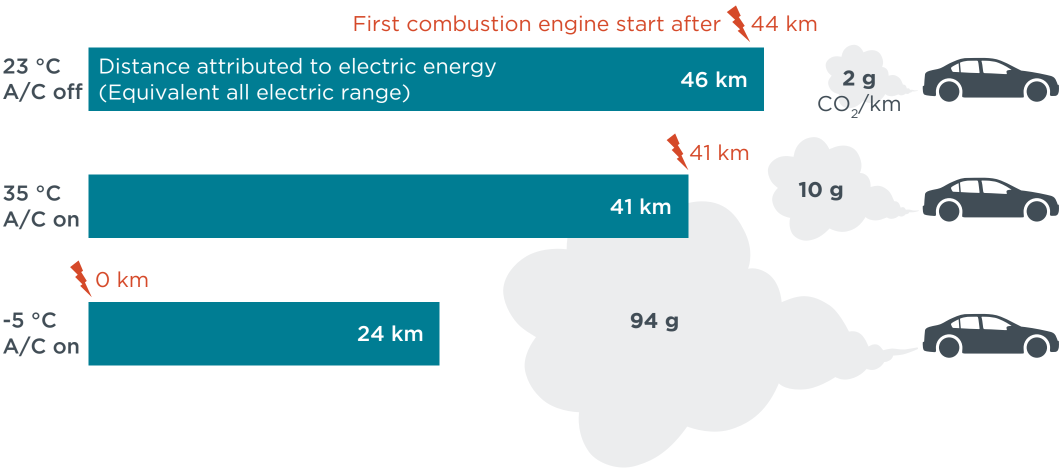

Figure ES 1. Effect of ambient temperature and use of air-conditioning on equivalent all-electric range, charge-depleting WLTC CO_2 emissions and on the range when the combustion engine is turned on for the first time after test start. The results shown are based on two consecutive laboratory WLTCs performed at each ambient temperature, started with a fully charged battery. The battery is depleted during the second WLTC.

When starting with a fully charged battery at 23 °C and 35 °C, the vehicle first operates purely electric until the battery is almost depleted. This results in low charge-depleting CO_2 emissions of 2 and 10 g/km respectively. At -5 °C, however, the combustion engine is used intermittently from the start of the test to warm up the catalyst. In combination with the lower available electric energy for propulsion, this change in operating strategy results in charge-depleting CO_2 emissions at -5 °C of 94 g/km, or more than 40 times higher than at 23 °C.

Together with a 30% increase in charge-sustaining CO_2 emissions from 155 g/km to 201 g/km, the weighted, combined CO_2 value at -5 °C almost triples compared to 23 °C, from 43 g/km to 122 g/km. At 35 °C, the charge-sustaining CO_2 emissions are about 190 g/km and the weighted, combined CO_2 emissions are 57 g/km, which is 34% higher than at 23 °C. These values were all measured under laboratory test conditions. CO_2 emission levels under real-world driving conditions, taking into account the day-to-day recharging behavior of typical drivers, are even higher.

To achieve more realistic PHEV type-approval CO_2 emissions, we recommend **including tests at low and high ambient temperatures with active air-conditioning in the type-approval procedure**. As a short-term solution, we recommend **adapting the PHEV utility factor to better reflect the real-world usage**. **A more representative utility factor can be derived from empirical real-world electric driving share studies and from on-board fuel and energy monitoring (OBFCM) real-world usage data**, compiled by the European Commission for the first time in April 2022 for the calendar year 2021.

The vehicle was further tested in user-selectable charge-increasing PHEV mode, in which the battery charge level is maintained or increased via recuperation only, according to BMW. However, the results of the test indicate that primarily the combustion engine is used to charge the battery until full. The efficiency for generating electricity using the vehicle's combustion engine was calculated to be only 29% to 33%. Consequently, the additional fuel consumed for battery charging increased the WLTC CO_2 emissions by 60%, from 154 g/km to 246 g/km, compared to operation in charge-sustaining mode (Figure ES-2). Compared to charging the vehicle battery with EU grid energy, 2.5 to 2.8 times more CO_2 is emitted when using the charge-increasing mode.

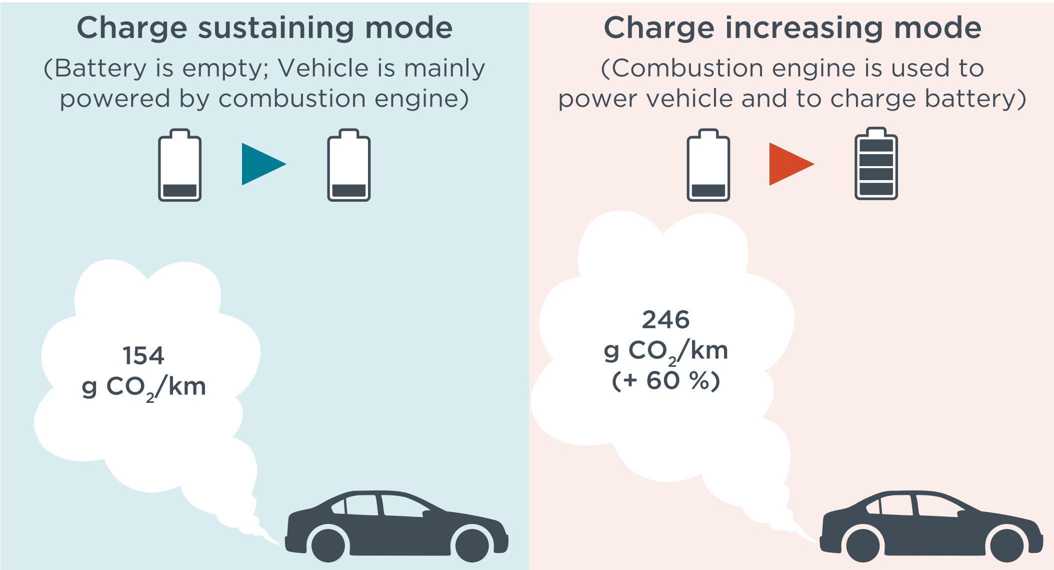

Figure ES 2. Compared to driving in charge-sustaining mode, WLTC CO_2 emissions increase by 60% when using the user-selectable charge-increasing mode.

Offering a charge-increasing mode is allowed by the regulation, but its effect on CO_2 emissions is not assessed during type approval. And while it seems reasonable to implement a mode to maintain the current battery charge level with the intent to save energy for entering zero-emissions zones, there is no compelling reason for charging the battery of a plug-in hybrid vehicle using the combustion engine. As the high CO_2 emissions entailed undermine the intended effect of using plug-in hybrid vehicles to help reduce CO_2 emissions, we recommend **prohibiting user-selectable vehicle modes that increase the battery charge level by using the combustion engine.**

We also observed battery charge increase by using the combustion engine when performing a test with user-selectable sports settings for the gearbox and vehicle, even though the charge-increasing mode was not selected. This strategy is presumably applied to ensure that the electric motors can support dynamic driving by boosting the combustion engine. However, it results in increased CO_2 emissions, which are not considered during type approval. To yield more real-world representative plug-in hybrid CO_2 type emission values, we suggest that the **charge-sustaining type-approval test should be performed with those user-selectable vehicle and gearbox settings producing the highest CO_2 emissions.**

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ABBREVIATIONS

A/C	air-conditioning
AC	alternating current
AER	all-electric range
AWD	all-wheel drive
BSG	belt starter generator
CADC	Common Artemis Drive Cycle
CAN	controller area network
CCE	convenience charge electronics
CD	charge depleting
CI	charge increasing
CO_2	carbon dioxide
CoC	certificate of conformity
CS	charge sustaining
DC	direct current
EAER	equivalent all-electric range
EC	grid energy consumption relative to all-electric range
EC_{AC}	grid energy consumption relative to charge-depleting cycle range
EM	electric motor
EME	electric machine electronics
HV	high voltage
HVAC	heating, ventilation, and air-conditioning
HVBM	high-voltage breakout module
ICE	internal combustion engine
OBD	on-board diagnostic
OBFCM	on-board fuel and energy consumption monitoring
PEMS	portable emissions measurement system
PHEV	plug-in hybrid electric vehicle
R_{CDA}	actual charge-depleting cycle range
R_{CDC}	charge-depleting cycle range
REEC	relative electric energy change
SoC	state of charge
UF	utility factor
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure

1. INTRODUCTION

The European Green Deal, the European Commission's strategy to transform the European Union into a sustainable and climate neutral economy by 2050, requires a reduction of greenhouse gas emissions from transport by 90% (European Commission, 2019b; European Commission, 2019c). The CO_2 standards for new passenger cars are one of the key policy instruments to achieve this goal. In 2020, vehicle manufacturers were close to meeting the target of 95 g/km, applicable since January 1, 2020. While most manufacturers increased the share of electric vehicles as part of their CO_2 reduction strategy, manufacturers like BMW and Daimler relied particularly on plug-in hybrid electric vehicles (PHEVs) (Mock et al., 2021).

A recent study on real-world usage of PHEVs reported that CO_2 emissions for privately owned vehicles were two to three times higher than the type-approval values and company cars were even three to four times higher (Plötz et al., 2020). According to the study, the main causes responsible for these large deviations are substantially lower recharge frequencies and more dynamic driving than assumed by the type-approval regulation, as well as the electric energy consumption of air-conditioning, heating, and other auxiliaries, which are not considered in type approval.

Plötz et al. (2020) analyzed real-world usage data from more than 100,000 PHEVs to determine the magnitude and cause of the divergence between real-world and type-approval CO_2 emissions. Complementary, for the study at hand, we tested a 2020 model year BMW X1 eDrive25e PHEV in detail to investigate how ambient temperature and the use of air-conditioning affect the laboratory CO_2 emissions, energy consumption, and electric ranges, which are not accounted for during type approval. As part of the testing, we also assessed the impact of a user-selectable charge-increasing PHEV mode on these parameters. Furthermore, we collected on-board fuel and energy consumption monitoring (OBFCM) data to analyze how OBFCM can help in the future to determine more accurately average real-world consumption and PHEV usage.

In the first part of this paper, we provide an insight in PHEV technology, operating strategies, and the particularities of the type-approval procedure. Then we introduce the test vehicle and give an overview of the performed tests. Based on the test results, we analyze and discuss the vehicle behavior under the different ambient conditions and settings and conclude the paper with recommendations on how to improve the real-world representativeness of PHEV type-approval values.

2. PLUG-IN HYBRID TECHNOLOGY AND HOW IT IS TESTED FOR TYPE APPROVAL

Plug-in hybrid vehicles (PHEVs)[1] combine two power train types: a fuel-powered internal combustion engine (ICE) and an externally chargeable battery-powered electric motor. When recharged regularly, the vehicle can be driven locally pollutant emission free with low CO_2 emissions while allowing use of the ICE for occasional long-distance trips.

In addition to the components of a conventional power train—that is, fuel tank, combustion engine, transmission, and differential gear—PHEVs contain the following additional parts: high-voltage battery, electric motor, inverter to convert direct current (DC) battery voltage to alternating current (AC) motor voltage, on-board charger, and DC-DC convertor to supply the low-voltage electrical system.

A detailed description of the system layout and PHEV components installed in the tested BMW X1 eDrive25e is provided in Section 3.1.

2.1. PLUG-IN HYBRID VEHICLE OPERATING MODES

Depending on the state of charge (SoC) of the propulsion battery, a PHEV can be operated in different modes, which are described below. With a charged battery, the vehicle usually operates in the charge-depleting mode.

Charge-depleting mode (CD). In this mode, the vehicle consumes electric energy from the battery until it is depleted to a target SoC. Depending on the charge level, the current propulsion power demand, and the manufacturer's control strategy, the vehicle can drive purely electric, or the combustion engine can be used to assist the electric motor. The CD mode is often characterized by very low CO_2 emissions. Once the battery is depleted, the vehicle runs in charge-sustaining mode.

Charge-sustaining mode (CS). During CS operation, the battery charge level remains, on average, at a constant SoC, which means that no grid energy is consumed, and the majority of the propulsion energy is generated by the combustion engine consuming fuel. In this mode, the vehicle operates similar to a conventional hybrid vehicle. Its electric motor and battery allow the recuperation of brake energy, the shift of combustion engine operating points, and the ability to drive limited distances using only the generated electric energy. However, the operation and, therefore, the CO_2 emissions remain directly comparable to the type-approval CO_2 emissions of conventional vehicles.

While the CS mode, in principal, reduces CO_2 emissions compared to a nonhybrid vehicle, PHEVs usually have more powerful electric motors and higher capacity batteries and on-board chargers than full-hybrid vehicles, resulting in a substantially increased vehicle mass and, subsequently, CO_2 emissions in charge-sustaining mode similar to comparable ICE-only vehicles, as shown in Table 1 for the tested BMW X1. Despite the lower engine capacity, the 40% smaller fuel tank, and the combustion engine only propelling the front wheels, the PHEV model xDrive25e has a 160 kg higher mass in running order than the higher-performance ICE-only model xDrive25i, resulting in almost identical CO_2 emissions in comparable operating modes. This emphasizes again that PHEVs only contribute to CO_2 emission reduction when operated mostly in charge-depleting mode using grid energy.

1 UN/ECE and EU regulations refer to plug-in hybrid vehicles as OVC-HEVs (off-vehicle charging hybrid electric vehicles).

Table 1. CO_2 emissions of PHEV and comparable internal-combustion-engine-only variants of the BMW X1.

Parameter	xDrive25e (PHEV)	xDrive25i (ICE-only)
Engine type [engine capacity]	Gasoline [1.5 liters] plus electric	Gasoline [2.0 liters]
Fuel tank capacity	36 liters	61 liters
Powered axle	ICE on front axle, electric motor on rear axle	AWD
System power	162 kW	170 kW
Acceleration [0–100 km/h]	6.9 s	6.5 s
Maximum speed	193 km/h	235 km/h
Mass in running order	1,820 kg	1,660 kg
CO_2 emissions WLTP	Charge sustaining: 164–178 g/km[a]	Combined: 164–181 g/km

Note: Data obtained from BMW AG (2021a) with the exception of the charge-sustaining information of the xDrive25e, which was obtained from BMW AG (2020c).
[a] BMW AG (2020c).

Charge-increasing mode (CI) The type-approval regulation allows manufacturers to implement a user-selectable mode where the battery is charged using the electric motor as an ICE-powered generator, meaning that, in addition to powering the vehicle, fuel is consumed to generate electricity. Despite the detrimental effect on CO_2 emissions, the CO_2 emissions in this mode are neither measured during type-approval testing nor are they considered in the determination of the declared CO_2 emission values. This constitutes a regulatory loophole that may result in higher real-world CO_2 emissions than to be expected based on values determined during type approval.

2.2. TYPE APPROVAL PROCEDURE FOR PLUG-IN HYBRID VEHICLES

While the CO_2 emission determination of ICE-only vehicles is fairly straightforward, the procedure for PHEVs is more complex as it requires taking into account the emissions in different operating modes, the relative amount of operation in these modes, and the expected charging behavior of vehicle users. Figure 1 illustrates the procedure. The vehicle is tested in both charge-depleting and charge-sustaining mode. The final type-approval value, which counts toward fulfilling the emission standards, is then calculated by weighting the CO_2 emissions values of both modes using the utility factor (UF). The steps of the procedure and the parameters used are described in more detail below.

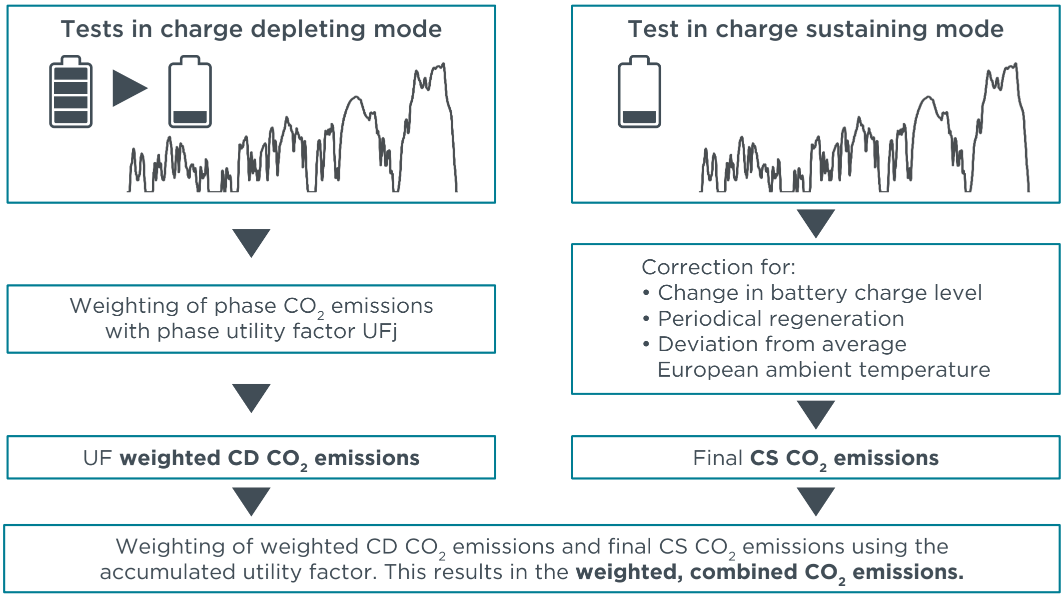


Figure 1. Determination of weighted, combined CO_2 emissions of a plug-in hybrid vehicle.

2.2.1 Test types and how the utility factor is used for weighting the results

Utility factor. As discussed before, driving in charge-depleting and charge-sustaining mode results in quite different CO_2 emission levels. To determine average PHEV CO_2 emissions, it is therefore necessary to make an assumption on how frequently and to which level the battery is recharged with grid energy. The type-approval regulation assumes a recharge frequency of once per day, always resulting in a fully charged battery (GRPE, 2017). Furthermore, the regulation assumes that with increasing available range in charge-depleting mode, it is less likely that the battery is fully drained by the end of each driving day.

These assumptions are reflected in the parameters defined in the EU type-approval regulation to calculate the UF, shown in Appendix 5 of Sub-Annex 8 to Annex XXI of regulation (EU) 2017/1151 (European Commission, 2019a). The UF expresses the distance share of driving in charge-depleting mode relative to the total distance driven, which is expected to increase with higher CD distance.

The UF has two purposes in the type-approval regulation. One is weighting each cycle phase of a charge-depleting test. The latter is applied to account for the assumption that in real-world driving, the battery is not always fully depleted before the next recharge. Therefore, the type-approval regulation assumes that the likelihood of performing a real-world trip with an almost full battery is higher than driving with an almost depleted battery. To reflect this in the type-approval CO_2 emissions, the cycle phases of the charge-depleting test are weighted with phase-specific utility factors UF_i. Considering the findings of Plötz et al. (2020), which state that PHEVs are charged less frequently and a considerable share of trips exceeds the range supported by the battery capacity, this assumption might not hold true in real-world operation. The other purpose of the utility factor is weighting emission and consumption values determined in charge-depleting and charge-sustaining mode; this is calculated from the phase utility factors and only depends on the charge-depleting distance.

The bottom graph of Figure 2 shows, for two consecutive worldwide harmonized light vehicles test cycles (WLTCs), the accumulated utility factor versus the charge-depleting distance on the right axis and the phase-specific UF values on the left axis.

Charge-depleting test. Figure 2 illustrates the procedure to determine the CD CO_2 emissions, which is explained in more detail in the following section.

Before test start, the vehicle battery is fully charged by connecting it to the mains, and the vehicle is soaked at the test temperature of 23 °C. Starting with a cold engine at the beginning of the first cycle, consecutive WLTCs are then performed. The measured speed profile of three WLTCs is shown in the top graph of Figure 2. While driving, the electric energy flow to and from the propulsion battery is measured and accumulated (left side of third graph from top).

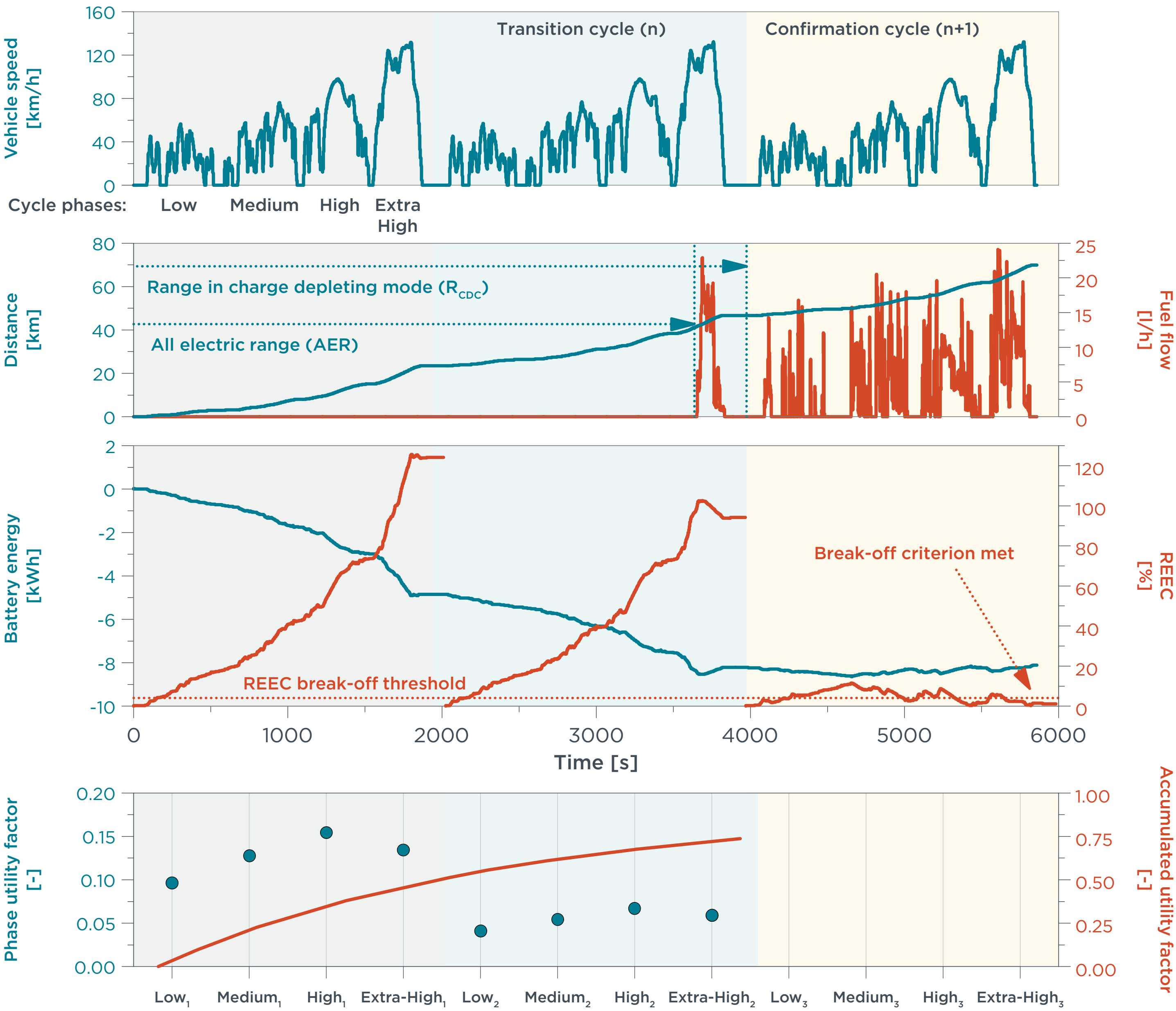


Figure 2. Principal of charge-depleting CO_2 emission determination. The top graph shows the speed profile of three WLTCs. Each cycle consists of phases low, medium, high, and extra-high. At the end of each test, the relative electric energy change (REEC) of the traction battery is calculated (right side of third graph from top). When the REEC drops below the break-off criterion of 4% at the end of a WLTC, charge-sustaining mode has been reached. This cycle is called the confirmation cycle and the preceding one the transition cycle. Only the cycles up to and including the transition cycle are considered being driven in charge-depleting mode. The left side of the bottom graph shows the utility factor used to weight each cycle phase until the end of the transition cycle. The accumulated utility factor (bottom graph, right side) is used to calculate the PHEV weighted, combined type-approval CO_2 emissions.

At the end of each WLTC, the absolute value of accumulated energy flow to and from the battery is divided by the vehicle WLTC cycle energy demand. The latter is the energy demand at the wheels required to propel the vehicle along the speed profile calculated using the vehicle test mass and road-load parameters. The type-approval regulation refers to the ratio of absolute electric energy and cycle energy demand as the relative electric energy change (REEC), expressed as a percentage and shown on the right axis of the third graph in Figure 2. When the REEC at the end of a WLTC is below 4%, meaning the energy change of the battery over the cycle is less than 4% of the required cycle energy, the battery is considered depleted and hence the vehicle has reached charge-sustaining mode. The cycle in which this break-off criterion is fulfilled for the first time is called the confirmation cycle, labeled with index n+1. In the example shown, the break-off criterion is reached in cycle number 3. The preceding WLTC, indexed with n, is called the transition cycle and is considered the last cycle being driven in charge-depleting mode.

For each cycle phase Low_i, $Medium_i$, $High_i$, and $Extra\text{-}High_i$ of each charge-depleting $WLTC_i$ up until the end of the transition cycle n, a phase-specific utility factor UF_j is calculated, as shown on the left axis of the bottom graph of Figure 2. The phase UFs consider both the distance driven in this phase as well as the total UF of all previous phases and are used to weight the measurement results of each phase according to the following equation, exemplary shown for calculating the weighted charge-depleting CO_2 emissions:

$$M_{CO_2,CD,weighted} = \frac{\sum_{j=1}^{k}(M_{CO_2,CD,j} \times UF_j)}{\sum_{j=1}^{k} UF_j} \qquad \textit{Equation 1}$$

With j being the phase number, k being the number of phases up until the end of the transition cycle, $M_{CO_2,CD,j}$ the phase CO_2 emissions in g/km, and UF_j as the phase-specific utility factor.

Charge-sustaining test. In addition to the CD test, a cold-started charge-sustaining test is performed. This CS test is identical to the type-approval test used for non-PHEVs. As a PHEV in charge-sustaining mode can be considered a not-chargeable hybrid electric vehicle, only one CS test is performed and, similar to ICE-only vehicles, a subsequent correction for a change in the battery state of charge is performed to take into account any related CO_2 benefit or penalty, as shown in Figure 1. Furthermore, a correction is applied to account for the difference in the test ambient temperature of 23 °C compared to the average ambient temperature in the EU, assumed by the type-approval regulation to be 14 °C[2].

2.2.2 Parameters determined during type-approval testing

Table 2 outlines the key parameters determined for plug-in hybrid vehicles during type-approval testing. These are described in more detail below.

2 The correction factor applied is called the ambient temperature correction test (ATCT) factor and is shared among vehicles belonging to the same ATCT family.

Table 2. Key parameters determined for plug-in hybrid vehicles during type approval.

	Parameter name	Notation	Description
Range	Charge-depleting cycle range	R_{CDC}	Distance driven in charge-depleting test sequence until the end of the transition cycle
	Actual charge-depleting range	R_{CDA}	Distance driven in charge-depleting mode, that is, until the battery is depleted and the vehicle switches to charge-sustaining mode
	All-electric range	AER	Distance driven in charge-depleting mode until the combustion engine consumes fuel first time
	Equivalent all-electric range	EAER	The distance driven attributed to the recharged electric energy
Emissions	Charge-sustaining	$CO_{2,CS}$	Emissions determined in cold-start WLTP with depleted battery
	UF-weighted, charge-depleting	$CO_{2,CD,weighted}$	Phase emissions of CD test, weighted with phase specific UFs
	UF-weighted, combined	$CO_{2,weighted,combined}$	Emissions of charge-sustaining and charge-depleting tests, weighted with utility factor
Energy	UF-weighted, charge-depleting	$EC_{AC,CD}$*	Grid energy consumption in CD tests, weighted with phase-specific UFs
	UF-weighted	$EC_{AC,weighted}$	Grid energy consumption weighted between charge-depleting and charge-sustaining tests using the cycle UF
	Electric energy consumption	EC	Grid energy consumption per kilometer driven attributed only to the electric energy, that is, relative to the equivalent all-electric range

* For battery energy instead of grid energy, index AC is replaced by DC.

Weighted, combined emissions. As shown in Figure 1, determining a value representative for the average CO_2 emissions of a PHEV requires weighting the emissions determined in both charge-sustaining and charge-depleting mode. The resulting value is called the weighted, combined CO_2 emissions, which is the official type-approval CO_2 value of a PHEV and is used to determine a manufacturer's compliance with the CO_2 targets, to determine electric vehicle subsidy eligibility and taxes, and to provide consumer information. The weighted, combined CO_2 emissions are calculated using the following formula:

$$M_{CO_2,weighted,combined} = M_{CO_2,CD,weighted} \times \sum_{j=1}^{n} UF_j + M_{CO_2,CS} \times \left(1 - \sum_{j=1}^{n} UF_j\right) \qquad \textit{Equation 2}$$

With j being the phase number, n being the number of phases up until the end of the transition cycle, $M_{CO_2,CD,weighted}$ as the UF-weighted CD CO_2 emissions defined in Equation 1, $M_{CO_2,CS}$ as the corrected CS CO_2 emissions, and UF_j as the utility factor of phase j.

For the example shown in Figure 2, the sum of the phase-specific UFs until the end of the transition cycle is approximately 0.73, meaning the vehicle is expected to be operated approximately 73% of its total distance in CD mode.

Ranges. A number of ranges to characterize a PHEV are derived from the charge-depleting test results. The distance driven until the end of the transition cycle is called the charge-depleting cycle range (R_{CDC}), often referred to as the charge-depleting range, which is, per definition, always a multiple of the WLTC distance.

The all-electric range (AER) is determined during the charge-depleting test. This is the distance driven until the combustion engine consumes fuel for the first time.

The AER and the R_{CDC} can be taken directly from the charge-depleting test results, whereas two other PHEV relevant ranges, the equivalent all-electric range (EAER) and the actual charge-depleting range (R_{CDA}), can only be derived indirectly.

The R_{CDA} is the distance in charge-depleting mode until the battery state of charge stabilizes; that is, it only considers that part of the transition cycle where battery depletion is still occurring. The R_{CDA} is therefore usually shorter than the R_{CDC}; the latter containing the entire transition cycle distance, regardless of when battery charge sustaining is reached during this cycle.

The EAER is the range in charge-depleting mode that is attributed to electric energy. If a vehicle operates purely electric until the vehicle reaches charge-sustaining mode, the EAER equals the R_{CDA} and the AER. However, if the electric motor and combustion engine are used simultaneously, only part of the driven distance can be attributed to using electricity. The EAER determination therefore requires the subtraction of the ICE-attributed distance from the R_{CDC}. Considering that the charge-depleting CO_2 emissions are fully attributed to partial use of the combustion engine and that the charge-sustaining CO_2 emissions represent the case where all net propulsion energy stems from fuel, the distance share attributed to the combustion engine is estimated as the ratio of the average CD CO_2 emissions and the CS CO_2 emissions.

The AER can have any value between 0 km and the EAER. When the charge-depleting test is performed purely electric until the vehicle reaches charge-sustaining mode, AER, EAER and R_{CDA} are the same. More generally, the distances can always be sorted as follows: $R_{CDC} \geq R_{CDA} \geq$ EAER $\geq$ AER

Pollutant emissions. During type approval, manufacturers must demonstrate that the vehicle complies with the set pollutant emission limits. This requirement applies to each individual WLTC in charge-depleting and charge-sustaining mode. It would also apply to operation in charge-increasing mode, which is, however, not tested during type approval. Also, during real driving emission (RDE) testing, the measured emissions must not exceed the set pollutant limits in all possible operating modes.

2.3. ON-BOARD FUEL AND ENERGY CONSUMPTION MONITORING REQUIREMENTS

The monitoring and reporting of fuel and energy consumption data from passenger cars and light-commercial vehicles is a key element in the European CO_2 regulation (EU) 2019/631 to determine the gap between type-approval CO_2 emissions and the emissions encountered during real-world driving. The European Commission included in amendment (EU) 2018/1832 to the type-approval regulation (EU) 2017/1151 the requirement to apply on-board fuel and energy consumption monitoring devices in all new type-approved passenger cars and light-commercial vehicles of category N1 class I from January 1, 2020. One year later, the requirement is applicable to all first registered vehicles of the same categories.

For PHEVs, manufacturers are required to determine and store the OBFCM data listed below on board the vehicle:

» Total fuel consumed in liters

» Total distance traveled in kilometers

» Total fuel consumed in charge-depleting operation in liters

» Total fuel consumed in driver-selectable charge-increasing operation in liters

» Total distance traveled in charge-depleting operation with engine off in kilometers

» Total distance traveled in charge-depleting operation with engine running in kilometers

- Total distance traveled in driver-selectable charge-increasing operation in kilometers
- Total grid energy into the battery in kWh

In addition to these cumulative lifetime values, the instantaneous vehicle speed and engine fuel rate are accessible at the OBD interface.

Beginning in 2022, manufacturers will be required to report OBFCM data to the European Commission, collected during repair or maintenance or transmitted wirelessly by the vehicle. Similarly, member states will collect OBFCM data during periodical technical inspection, however, only starting on May 20, 2023. To fulfill the minimum transparency requirements set in the CO_2 standards, the European Commission will publish the PHEV OBFCM data annually, aggregated per manufacturer (Regulation (EU) 2021/392, 2021).

3. METHODOLOGY FOR TESTING A PLUG-IN HYBRID VEHICLE IN THE LABORATORY AND ON PUBLIC ROADS

For the study, we tested a 2020 model year BMW X1 xDrive25e, which is a state-of-the-art plug-in hybrid electric vehicle. The following section provides details on how the test vehicle was selected, how it was instrumented, and which tests were performed on chassis dyno and public roads.

3.1. SELECTION OF A PLUG-IN HYBRID TEST VEHICLE

For vehicle selection, we focused on two main criteria: First, the selected PHEV should be a compact to medium-size vehicle that is not considered a niche product. Second, the vehicle needed to be type-approved for the final Euro6d ISC-FCM emission standard to ensure the test vehicle contains the latest technology and OBFCM data is available. Euro6d ISC-FCM is applicable for vehicles type-approved after January 1, 2020. Due to the market stall caused by the Covid-19 pandemic, only a few PHEVs models fulfilling this requirement were available in the market at the start of the project in Q2 2020. The vehicle selected for testing is the BMW X1 xDrive25e SUV, which combines a 92-kW 1.5-liter gasoline engine with two electric motors. The test vehicle is shown in Figure 3, and Table 3 lists its main characteristics.

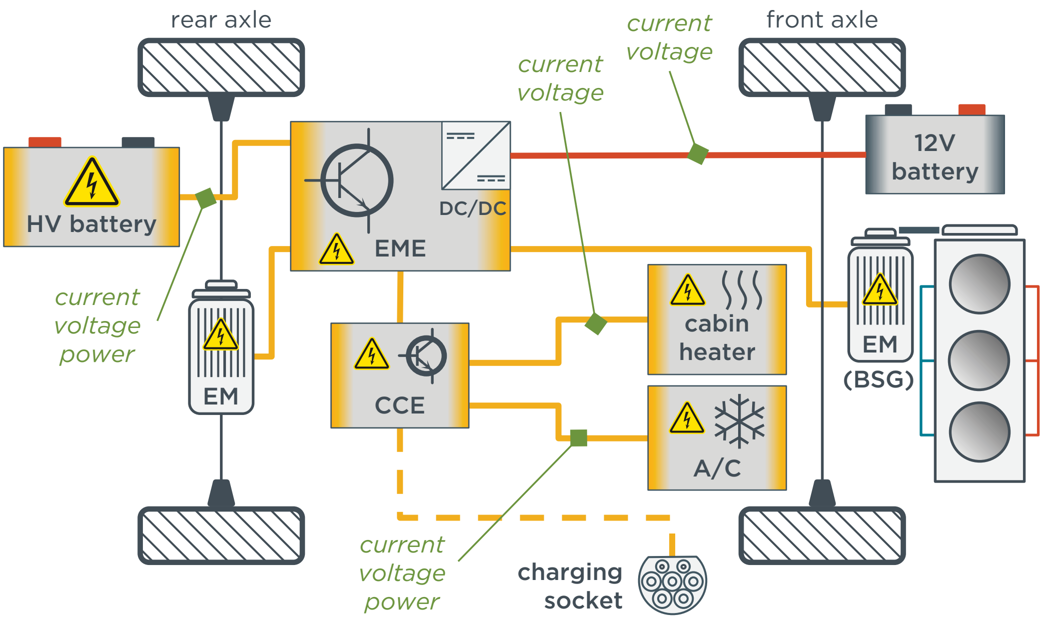
Figure 3. BMW X1 xDrive25e test vehicle on chassis dyno.

Table 3. Characteristics of the tested BMW X1 xDrive25e PHEV. All consumption and emission values stated in the table are WLTP type-approval values.

Parameter	Value
Model year and manufacturer type[a]	2020, F1X (F48 LCI)
Interpolation family ID[b]	IP-0000337-WBA-1
Power train architecture[c]	Plug-in hybrid
Hybrid topology	P0 (BSG) + P4 (on rear axle)
Transmission type[c]	Steptronic DCT 6 gears
Powered axle(s)[c]	AWD
Chassis type	SUV
Emission standard[a]	Euro 6d-ISC-FCM (Euro 6 AP)
OBD standard[a]	Euro 6–2
Date of first registration[a]	May 12, 2020
Mileage at test start	724 km
Frontal area[c]	2.47 m^2
Aerodynamic drag coefficient[c]	0.29
Combustion engine capacity[c]	1499 cm^3
Number of cylinders[c]	In-line 3
Combustion engine power[c]	92 kW at 5,000–5,500 rpm
Combustion engine torque[c]	165 Nm at 1,500–3,800 rpm
Nominal hybrid voltage[c]	295 V
Number of electric motors[c]	2
Rated power electric motors[c]	BSG: 15 kW Rear axle motor: 70 kW
Capacity of REESS at nominal voltage[c]	Gross: 10.0 kWh Net: 8.8 kWh
High-voltage auxiliaries	A/C compressor Electric cabin heater
On-board charger power[c)]	Max 3.7 kW
Fuel consumption—weighted, combined[b]	1.8 L per 100 km
Electric energy consumption ($EC_{AC, weighted}$) [b]	152 Wh/km
CO_2 emissions—weighted, combined[a, b]	41 g/km
Eco-Innovations[b]	None
Catalysts and position	Close-coupled three-way catalyst Underfloor gasoline particulate filter
Mass in running order[a]	1,820 kg
Actual mass of the vehicle[b]	1,871 kg
WLTP test mass[b]	1,953 kg

[a] Registration certificate.
[b] Certificate of Conformity.
[c] BMW AG (2020a).

As shown in Figure 4, a 70-kW electric motor (EM) powers the rear axle, called the P4 layout. For transmission a one-gear drive is used, and the motor can be decoupled from the axis through a clutch. The second electric motor is a 15-kW belt starter generator (BSG) integrated in the combustion engine belt drive, called P0 layout, and hence acting on the front axle through the clutch and transmission.



EME: electric machine electronics
CCE: convenience charging electronics
BSG: belt starter generator
HV: high voltage
EM: electric motor
A/C: air conditioning compressor
DC/DC: HV to 12 V converter

Figure 4. Electric system layout and sampling points for electric parameters of the tested BMW X1 plug-in hybrid vehicle.

Both motors are supplied with energy from one high-voltage (HV) battery installed behind the rear axle, operating at a nominal voltage of 295 V with a gross capacity stated as 10.0 kWh, whereof 8.8 kWh are usable (BMW Group, 2020b). All-electric energy transferred to and from the battery is routed through the electric machine electronics (EME). The EME serves three purposes. It integrates two bidirectional AC/DC converters to transform the direct current on the battery side to a three-phase alternating current connected to the electric motors, and vice versa. Furthermore, it contains a DC/DC converter to supply the 12 V DC circuit with energy from the HV battery. The EME also connects to the convenience charging electronics (CCE). Besides containing the on-board charger for the HV battery, the CCE controls the energy supplied to the air-conditioning (A/C) compressor and the cabin heater, both solely powered by HV electricity.

The on-board charger allows only one-phase AC charging with a power output of 3.7 kW when connected to a Type 2 charger, resulting in a charging time to full of at least 3.2 hours. Connecting to a Type 2 charger, which is typically used on public charging stations, requires an additional costly cable (BMW Group, 2021b) because the vehicle is only supplied with a 230 Vac Schuko Mode-2 charging cable. With the latter, the maximum power is further limited to 2.7 kW (BMW Group, 2021c), and hence, despite the relatively small battery capacity, the charging time to full increases to 5 hours (BMW Group, 2020a).

The driver can select from three different PHEV operating modes, which influences the share of electric driving and the HV battery SoC. In the standard mode referred to as *AUTO eDRIVE* in the test BMW, both combustion engine and electric motors are used to power the vehicle. At speeds above 135 km/h, the electric motor is decoupled from the rear axle to avoid damage.

For a second mode, to drive purely electric, the driver needs to select the *MAX eDrive* mode where the combustion engine is not used until the HV battery SoC cannot satisfy the propulsion power demand. The maximum speed in this mode is limited to 135 km/h. In the vehicle settings, the user can permanently activate this mode as the standard.

The third user-selectable mode, called *SAVE Battery,* is described by BMW as the mode where the current battery SoC is maintained or increased by recuperation only. From its description, we considered this mode a soft charge-increasing mode, as it does not use the combustion engine to charge the battery. However, our testing revealed that the *SAVE Battery* mode is a charge-increasing mode, where the combustion engine is used to recharge the battery, which entails very high CO_2 emissions.

In addition to these PHEV modes, the driver can select among three vehicle modes, called COMFORT, SPORT, and ECO PRO, which influence operation of the power train and auxiliaries (BMW Group, 2019). Furthermore, the driver can select between two modes of the automatic gearbox, D or S, with D being the standard when starting the vehicle.

3.2. MEASUREMENT EQUIPMENT INSTALLED IN THE TEST VEHICLE

Prior to the testing, we installed several measurement devices in the vehicle to allow for a detailed analysis of fuel and electric energy consumption, as well as operating strategies.

3.2.1 Electric power measurement

While measurement of voltage and current in a low-voltage system can be done with little effort, measuring the same signals in a high-voltage circuit is less straightforward for several reasons. Voltage measurement requires a direct connection to the positive terminal and the related ground cable. Therefore, special care must be taken to avoid accidental contact to live wires. Measurement of direct current can either be done using a shunt resistor, a Hall effect sensor, or a fluxgate sensor. Fluxgate sensors can be mounted around the isolated cable but require routing the cable through the sensor, which entails removing the connectors. A Hall sensor, on the other hand, often comes in form of a plier that can be clamped contactless around the cables. While this seems to be a simple solution, accurate measurement results require removing any kind of shielding at the sampling point. As shown in Figure 5, a shunt is directly integrated in the wire, measuring the current proportional voltage drop along it.

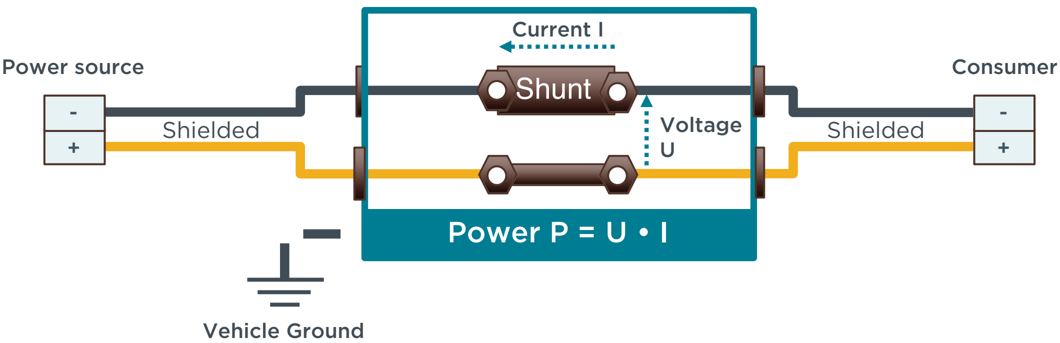


Figure 5. High-voltage breakout module for simultaneous voltage and current measurement.

Since the cable insulation and shielding had to be opened for all methods to measure both voltage and current, we used a high-voltage breakout module (HVBM) of type HV-BM 1.2 produced by the German company CSM. This module is integrated in the high-voltage loop and measures current and voltage simultaneously up to 1 MHz and calculates the instantaneous power. To accommodate for the high data transfer rates, the module sends the measured values using the EtherCAT protocol, which is converted to an XCP-on-ETH signal by an XCP gateway. For the HVBM integration, the power cables are cut and mounted to the shunt inside the water- and dust-proof housing of the module, which also becomes part of the cable shielding. Through a clean connection of the housing to the vehicle mass, the module becomes part of the HV system insulation monitoring conducted by the vehicle in regular intervals. The completed installation is, therefore, an intrinsically safe circuit.

For our investigation, we wanted to understand the energy consumption of the electrically powered auxiliaries, the energy consumption of the 12 V components, the power consumption of the electric motors and the charging efficiency of the HV battery. Three HVBMs were available for this project, which can measure voltage and current in one-phase AC and DC system but not in the three-phase AC supplied to the electric motors. The devices were, therefore, installed in a way that allowed the derivation of the values of interest either by direct measurement or by an energy balance calculation based on the measured values. As shown in Figure 4, we measured the energy flows between the HV battery and the EME, the energy supplied to the electric cabin heater and A/C compressor, and, using a current clamp around the unshielded 12 V cable, the energy supplied to the 12 V circuit.

Figure 6 shows the installation of the HVBM modules in the underfloor of the vehicle.

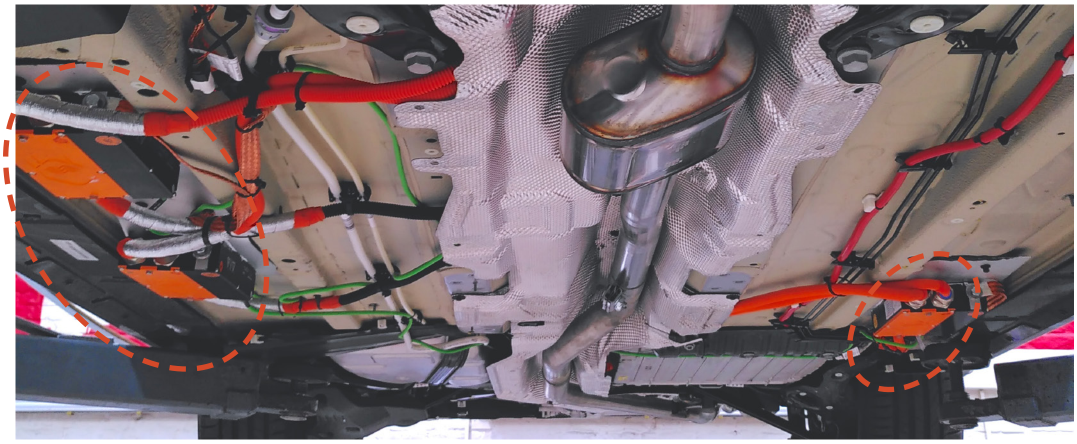


Figure 6. Installation of three high-voltage breakout modules in the test vehicle underfloor to measure energy flow at the high-voltage battery, air-conditioning compressor, and electric cabin heater.

Following the convention used in the type-approval regulation, we defined negative currents as battery depleting. This means conversely that the current to an electric motor consuming energy is positive while it is negative when energy is generated.

3.2.2 Fuel flow measurement

To evaluate the engines instantaneous fuel consumption, an ultrasonic fuel flow meter was installed in the pipes supplying fuel to the engine (Figure 7). The sensor applied is a Sentronics FlowSonic ULF, widely used in Formula 1 racing to ensure regulatory compliance, which was adapted to the flow range expected in light-duty road vehicles. Flow and sensor status signals are transferred to the data acquisition system through the controller area network (CAN) bus.

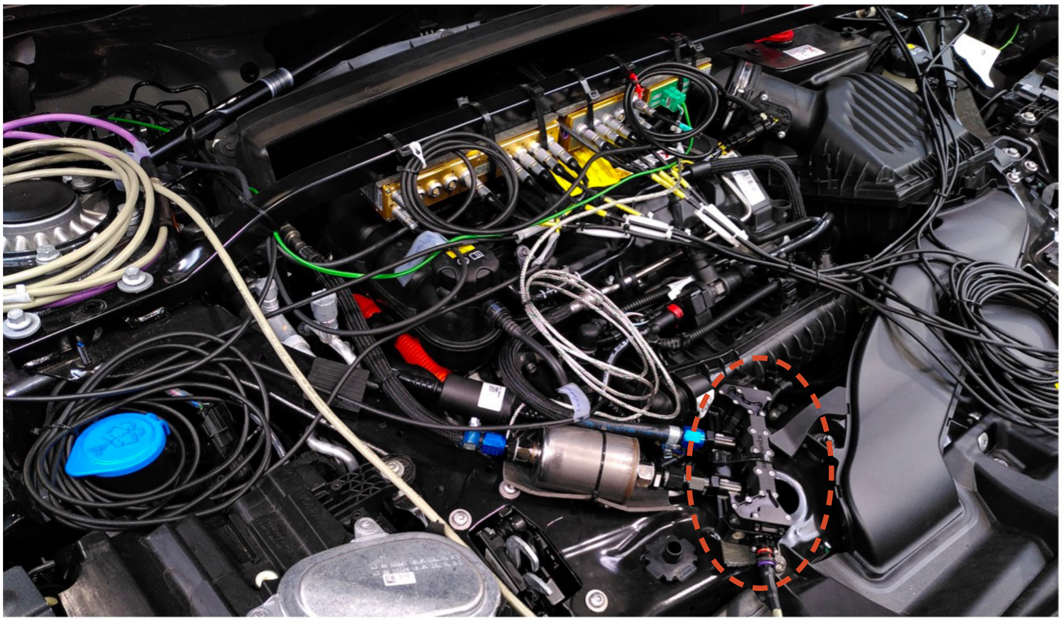


Figure 7. Installation of fuel flow sensor in the engine compartment of the BMW X1 test vehicle. The sensor was installed between the rigid chassis and engine fuel pipes, which were originally connected with a flexible hose.

3.2.3 OBFCM data collection

As explained above, two types of OBFCM parameters are available on the on-board diagnostic (OBD) interface: instantaneous values, which are not stored in the vehicle, and lifetime values. The instantaneous values are part of the OBD Service 0x01, like other OBD parameters, such as engine speed, vehicle speed, and so on, for which continuous polling to retrieve time-series data is supported by most OBD scan tools. The OBFCM lifetime values, on the other hand, are located in OBD Service 0x09, together with other vehicle information like vehicle ID, calibration IDs, and so on, which are meant to be extracted only occasionally, such as when the vehicle is undergoing periodically technical inspection, in-service conformity testing, or repair and maintenance.

However, in this project we wanted to record the lifetime values at a high rate to ensure that for each drive cycle the initial and final OBFCM values are automatically recorded. The data are used to calculate the value change over the cycle. For this purpose, IPETRONIK, the supplier of our autonomous data acquisition system, developed in close collaboration an automation script to poll and store the OBFCM lifetime values every 20 seconds.

3.2.4 On-board test data acquisition

All parameters measured on-board were automatically and time synchronously recorded in an IPETRONIK IPElog2 v4 datalogger. During postprocessing, the logged data is first time aligned and merged with measurement data from the chassis dyno or portable emissions measurement system (PEMS) based on the vehicle speed signal. Subsequently, signals and statistics required for the analysis were calculated and aggregated.

3.3. OVERVIEW OF PERFORMED TESTS

After installing the measurement equipment, the vehicle was tested both on a chassis dynamometer in a laboratory as well as on public roads. All tests were conducted by the Institute for Powertrains and Automotive Technology IFA of the Technical University of Vienna, Austria.

3.3.1 Tests performed on chassis dynamometer

The chassis dynamometer tests were performed on an AVL ROADSIM dual-axle dynamometer supporting the four-wheel-drive power train of the test vehicle, using the road-load parameters and test mass from the certificate of conformity (CoC) accompanying the vehicle. To account for the higher friction and aerodynamic resistance encountered at low ambient temperatures, we increased the road-load parameters by 10% for the -5 °C test. Exhaust gas extracted from a full flow dilution tunnel was collected in bags and analyzed to determine emissions and fuel consumption. To evaluate the break-off criterion during the charge-depleting test, the test cell automation system required measuring the current from the HV battery with a Hioki current clamp in addition to the electric power measurement equipment we installed on board the vehicle. The clamp was mounted around a cable section where the shield was removed. As no safe access point to measure the HV battery voltage was available, the nominal voltage of 295 V was used for the break-off criteria determination. For the charge-depleting test at 35 °C, a solar radiation simulation set to 1,000 W/m^2 was used to impose a realistic stress on the air-conditioning system.

To analyze the vehicles' fuel and energy consumption and electric ranges at various ambient conditions, operating modes, and driving styles, a number of tests were performed, as shown in Table 4.

Table 4. Overview of chassis dynamometer tests.

Cycle type	Ambient temp. [°C]	A/C status/ setpoint [°C]	Coolant at start	Battery SoC at start	PHEV mode	Vehicle mode
WLTC	23	Off	Cold	Depleted	MAX eDrive	Comfort
WLTC	23	Off	Cold	Depleted	SAVE Battery	Comfort
WLTC	23	Off	Hot	Partially charged	SAVE Battery	Comfort
WLTC	23	Off	Cold	Full	MAX eDrive	Comfort
WLTC	-5	On / 22	Cold	Full	MAX eDrive	Comfort
WLTC	35	On / 22	Cold	Full	MAX eDrive	Comfort

In-line with BMW's settings during type approval derived from the transparency list, all charge-depleting tests were performed in the *MAX eDrive* PHEV mode. For the charge-sustaining test, the transparency list does not contain the name of the mode used during type approval but only states that it was performed in the predominant mode. The predominant mode is defined as "a single driver-selectable mode that is always selected when the vehicle is switched on, regardless of the driver-selectable mode in operation when the vehicle was previously shut down, and which cannot be redefined to another mode" (European Commission, 2019a). However, as explained in Section 3.1, the driver can set that either the *MAX eDrive* or the *AUTO eDrive* is the standard mode when starting the vehicle. To reduce the number of variables and because we expected a limited influence of the mode in charge-sustaining operation, we decided to use the *MAX eDrive* mode also for the charge-sustaining tests. On inquiry, BMW explained that the vehicle switches automatically to AUTO eDrive mode when the battery is depleted, which is therefore the predominant mode in charge-sustaining operation.

Two WLTCs were performed in charge-increasing mode (*SAVE Battery*); the first cold-started with a depleted battery and the second performed directly afterward.

All WLTC tests at 23 °C were performed with deactivated air-conditioning while automatic air temperature control with a setpoint of 22 °C was activated during all other tests.

3.3.2 Performed real-world driving tests

The vehicle was also tested under real-world conditions on roads in the vicinity of Vienna, Austria. Table 5 shows all on-road tests performed with the BMW X1. While not all tests are relevant for this analysis, they are shown for the sake of completeness. Tests were performed on two different routes applying a normal and a dynamic driving style. Normal driving is characterized by anticipatory driving and flowing with the traffic. For these tests, the total payload including the driver and PEMS was 190 kg. During the dynamic tests, the vehicle carried a payload of 455 kg and was driven more aggressively, including full-load accelerations. Vehicle and gearbox settings expected to result in higher dynamics were selected for these tests.

In addition to the on-board measurement equipment, emissions were measured using an AVL M.O.V.E PEMS consisting of an emission concentration analyzer (Gas PEMS iS) and a particle number counter (PN PEMS 496) combined with an exhaust flow meter (Exhaust Flow Meter 495).

Table 5. Overview of real-world driving tests performed with the BMW X1. All real-world tests were started with a depleted battery.

Route	Payload incl. driver and PEMS	Driving Style	Coolant at start/ PHEV mode/ Vehicle mode/ Gearbox mode
1	190 kg	Normal	Hot / MAX eDrive / Comfort / D Cold / MAX eDrive / Comfort / D Cold / SAVE Battery / Comfort / D
	455 kg	Dynamic	Hot / AUTO eDrive / Sport / S
2	190 kg	Normal	Cold / MAX eDrive / Comfort / S
	455 kg	Dynamic	Hot / AUTO eDrive / Sport / S

4. TESTING RESULTS

After completing the test campaign, the time series data collected from the various measurement devices were first checked for plausibility and time aligned before calculating additional values and extracting test summary data. Based on the results, we performed the following analyses:

» Determination of on-board charger efficiency

» Verification of type-approval values

» Determination of the effect of using air-conditioning at high and low ambient temperatures on energy consumption, electric ranges, and CO_2 emissions

» Analysis of the cold-start operating strategy applied at low ambient temperature

» Investigation of the effect of different vehicle and PHEV modes

» Assessment of how the OBFCM data can be used to determine the gap between real-world operation and type approval

4.1. ON-BOARD CHARGER EFFICIENCY WHEN CHARGING THE BATTERY FROM THE GRID

A PHEV consumes two types of energy: fuel and electric energy. While the fuel amount consumed by the vehicle is identical to the fuel filled in the tank, energy losses in the on-board charger and battery during recharging increases the vehicle electric energy consumption. Therefore, determining the vehicles' electric energy consumption requires applying a correction of the net energy flow from the battery to account for the charging losses.

The electric energy consumption values determined during type approval are corrected for efficiency, which is defined as the ratio of the total electric energy change of the battery divided by the total energy recharged from the mains at the end of the charge-depleting test until the battery has reached its full capacity (European Commission, 2019a).

During our test program, the recharged grid energy was not measured after the charge-depleting tests. However, five partial recharge events at public chargers were performed. From these events, the total recharged grid energy measured by the charging station and the energy supplied to the battery, measured by the HVBM, are available to calculate an average charging efficiency.

Figure 8 shows the total energy supplied from the grid, the energy supplied to the battery, and the resulting charging losses and charging efficiency for these recharge events. The efficiency for all events lies between 86.1% and 88.6%, with an average efficiency of 86.8%. This value used in our analysis is well in line with values reported in literature (Antonino Genovese et al., 2015). It should be noted that this approach disregards the losses inside the battery, and the value therefore reflects a best-case scenario.

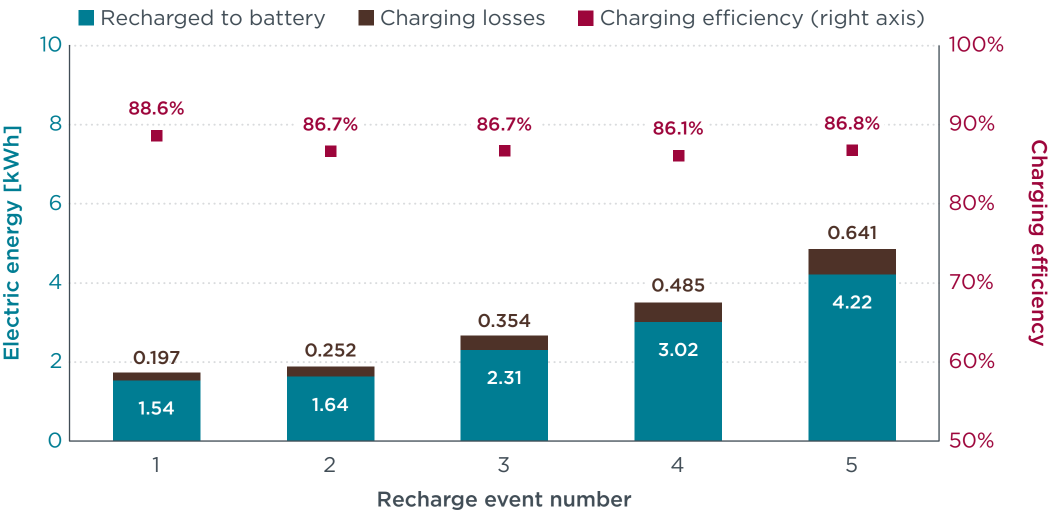


Figure 8. High-voltage battery charging efficiency for five partial recharge events on public chargers. Left axis: The bars show the recharged energy and charging losses. Right axis: The red dots reflect the resulting charging efficiency.

4.2. VERIFICATION OF WLTC TYPE-APPROVAL VALUES ON CHASSIS DYNAMOMETER

4.2.1 Obtaining and determining the test vehicle type-approval values

The registration certificate and the certificate of conformity accompanying the test vehicle contain only a limited number of values related to fuel and energy consumption of PHEVs:

- $FC_{weighted,combined}$ (weighted, combined fuel consumption) in L/100 km
- $CO_{2,weighted,combined}$ (weighted, combined CO_2 emissions) in g/km
- EAER (equivalent all-electric range) in km
- $EAER_{city}$ (equivalent all-electric city range) in km
- $EC_{AC,weighted}$ (weighted electric energy consumption) in Wh/km

While these parameters are mandatory for the registration and sale of vehicles, no separate data about CO_2 emissions in charge-sustaining and charge-depleting mode nor on the applied utility factor are provided.

Together with other data needed for independent vehicle testing, this information can be extracted from the transparency list, a document introduced in the type-approval regulation by the European Commission through amendment (EU) 2018/1832. The transparency list data are provided by the manufacturer to the type-approval authority and will eventually be incorporated in a European Commission database.

For this project, we obtained the transparency list directly from BMW. The transparency list contains data not for an individual vehicle but for the vehicles used for defining a CO_2 interpolation family.[3] In combination with parameters of the test vehicle listed in the CoC, the following values can be derived by linear interpolation:

- Charge-sustaining phase[4] and cycle CO_2 emissions in g/km
- Weighted charge-depleting CO_2 emissions in g/km

3 Vehicles can be grouped in a CO_2 interpolation family if their CO_2 emissions are linearly dependent on the cycle energy demand. In this case the CO_2 emissions of an individual vehicle can be determined by linear interpolation between two vehicles—vehicle High and vehicle Low.

4 The WLTC consists of four phases—low, medium, high, and extra-high—representing driving in different areas and road types. Emissions are determined individually for each phase and for the entire cycle.

For this purpose, first the cycle energy of vehicle High ($E_{cycle,High}$) and Low ($E_{cycle,Low}$), as well as for the individual test vehicle ($E_{cycle,ind}$) is calculated using the respective road-load parameters f_0, f_1, f_2 and vehicle test mass m_{TM}, taken from the transparency list and CoC. The cycle energy is the total energy at the wheel required to drive the vehicle along the speed profile. On this basis, an interpolation coefficient K_{ind} for the test vehicle is calculated:

$$K_{ind} = \frac{E_{cycle,ind} - E_{cycle,Low}}{E_{cycle,High} - E_{cycle,Low}} \quad \textbf{Equation 3}$$

To determine the values for the test vehicle, this coefficient is then used to linearly interpolate between vehicle High and Low, using the following exemplary equation, shown in this case for distance-specific CO_2 mass emissions:

$$CO_{2,ind} = CO_{2,Low} + (CO_{2,High} - CO_{2,Low}) \times K_{ind} \quad \textbf{Equation 4}$$

The list of relevant type-approval values stated in the CoC and derived from the transparency list is shown in Table 6. Except for energy consumption, the values derived from the transparency list closely match the CoC. We assume that BMW mistakenly entered the EAER specific energy consumption value in the transparency list, as discussed in Section 4.2.4.

Table 6. Certificate of conformity (CoC) and transparency list (TL) type-approval values.

Parameter	Unit	CoC	TL
$FC_{weighted, combined}$	L/100 km	1.8	NA
EAER	km	51	50.6
$EAER_{city}$	km	59	59
$EC_{AC, weighted}$	Wh/km	152	201.6
$CO_{2, weighted, combined}$	g/km	41	41.5
$CO_{2, CD, weighted}$	g/km	—	18.1
$CO_{2, CS, combined}$	g/km	—	168.7
$CO_{2, CS, phase Low}$	g/km	—	218.1
$CO_{2, CS, phase Medium}$	g/km	—	148.5
$CO_{2, CS, phase High}$	g/km	—	144.3
$CO_{2, CS, phase Extra-High}$	g/km	—	183.2

4.2.2 Utility factor: Test results versus type-approval values

Using Equation 2, the accumulated utility factor can be reverse calculated when the CD, CS, and weighted, combined CO_2 emission values are known, using Equation 5. It can be shown that the CO_2-based calculation equals the distance share in charge-depleting mode, that is, distance in CD mode divided by total distance.

$$UF = \sum_{j=1}^{n} UF_j = \frac{M_{CO_2,weighted,combined} - M_{CO_2,CS}}{M_{CO_2,CD,weighted} - M_{CO_2,CS}} \equiv \frac{distance_{CD}}{distance_{total}} \quad \textbf{Equation 5}$$

Based on the transparency list and CoC-based CO_2 values for the test vehicle, the accumulated UF used for type approval calculates to approximately 0.844. However, as described in Section 2.2, the accumulated utility factor calculation takes into account all phases of each WLTC up until the end of the transition cycle and can therefore take only certain values, as shown in Table 7. Since the calculated UF did not match any of the possible utility factors, we contacted BMW for clarification. BMW used a UF of 0.8376 for type approval, that is, the transition cycle number was 3, as we determined during the charge-depleting test at 23 °C.

Table 7. Possible values of utility factor and charge-depleting cycle range.

Transition cycle number	Accumulated utility factor	Charge-depleting cycle range R_{CDC}
1	0.5129	23.3 km
2	0.7343	46.5 km
3	0.8376	69.8 km
4	0.8912	93.1 km

One possible reason why the UF calculated from the type-approval CO_2 emissions does not yield the UF used during type approval can be found in the data requirements for the transparency list. It is not defined which weighted charge-depleting and weighted, combined CO_2 emission values need to be entered in the transparency list in case multiple charge-depleting tests were performed during type approval. Therefore, calculating the UF from the transparency list entries can only be an approximation.

4.2.3 CO_2 emissions: Test results versus type-approval values

As explained in Section 2.2, multiple CO_2 emissions values are determined during the type approval of PHEVs. The value used to evaluate a manufacturer's compliance with the CO_2 targets and to inform consumers is the weighted, combined CO_2 emissions, which is calculated by weighting the emissions in charge-depleting and charge-sustaining mode with the utility factor.

Figure 9 shows the charge-sustaining, weighted charge-depleting, and weighted, combined CO_2 type-approval values in comparison to the results from our laboratory measurements at 23 °C, which is equivalent to type-approval conditions. For cost and project schedule reasons, only one charge-depleting test sequence and one charge-sustaining test at 23 °C were performed.

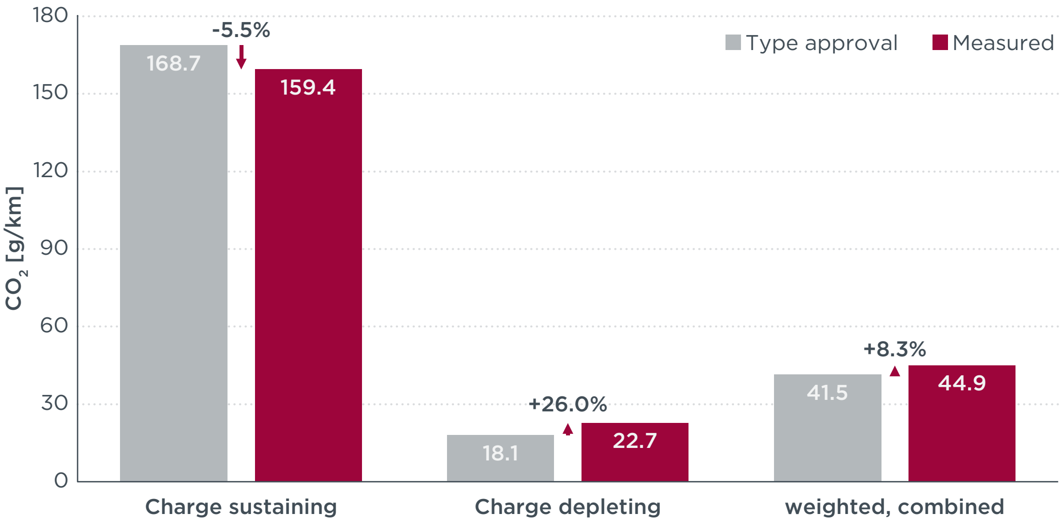


Figure 9. Comparison of type-approval CO_2 emission levels and the values measured when testing the vehicle at type-approval conditions. The figure shows from left to right the combined emissions in charge-sustaining mode, weighted charge-depleting emissions, and weighted, combined CO_2 emissions as the result of weighting the charge-sustaining and charge-depleting CO_2 emissions with the utility factor. The weighted, combined CO_2 emissions constitute the official type-approval value relevant to determine the manufacturer's compliance with its CO_2 targets.

The bars on the left represent emissions during the charge-sustaining test, performed with a fully drained battery. As explained in Section 2.2, measured CO_2 emissions in CS mode are corrected for changes in battery charge level and ambient temperature. At

159.4 g/km, the corrected value is approximately 5.5% lower than the type-approval value of 168.7 g/km.

In charge-depleting mode, the break-off criterion was first met at the end of the fourth WLTC. The third cycle is therefore the transition cycle, resulting in an accumulated utility factor of 0.838. The UF-weighted charge-depleting CO_2 emissions are 4.6 g/km higher (+26%) than the 18.1 g/km type-approval value derived from the transparency list.

Even though the CD CO_2 emissions are low compared to the CS emissions, the effect of the larger difference between type-approval CD CO_2 emissions and the test value is also visible in the weighted, combined CO_2 emissions, due to the high UF of 0.838 used for weighting CD and CS emissions (Figure 1). While the type-approval value is 41.5 g/km, the test vehicle's weighted, combined CO_2 emission value is 44.9 g/km, that is, 8.3% higher.

4.2.4 Electric energy consumption: Test results versus type-approval values

The weighted electric energy consumption ($EC_{AC,weighted}$) stated in the CoC is the utility-factor-weighted electric energy consumed over the charge-depleting test until the end of the transition cycle, corrected for the charging efficiency to a grid energy equivalent value. Figure 10 shows that the measured energy consumption of 146 Wh/km is 3.7% lower than the 152 Wh/km declared by the manufacturer. Part of this difference can stem from the charging efficiency of 86.8% we used in our calculation, which can be considered a best-case value, as explained in Section 4.1. Unexpectedly, the $EC_{AC,weighted}$ value derived from the transparency list is 202 Wh/km and thereby 33% higher than the CoC and 38% higher than the measured value. However, the transparency list value is only 3.1% less than the electric energy consumption (EC), determined on the test vehicle to be 208 Wh/km and shown on the right side of Figure 10. We therefore assume that the value entered is EC not $EC_{AC,weighted}$, that is, the energy consumption relative to the equivalent all-electric range was mistakenly entered in the transparency list.

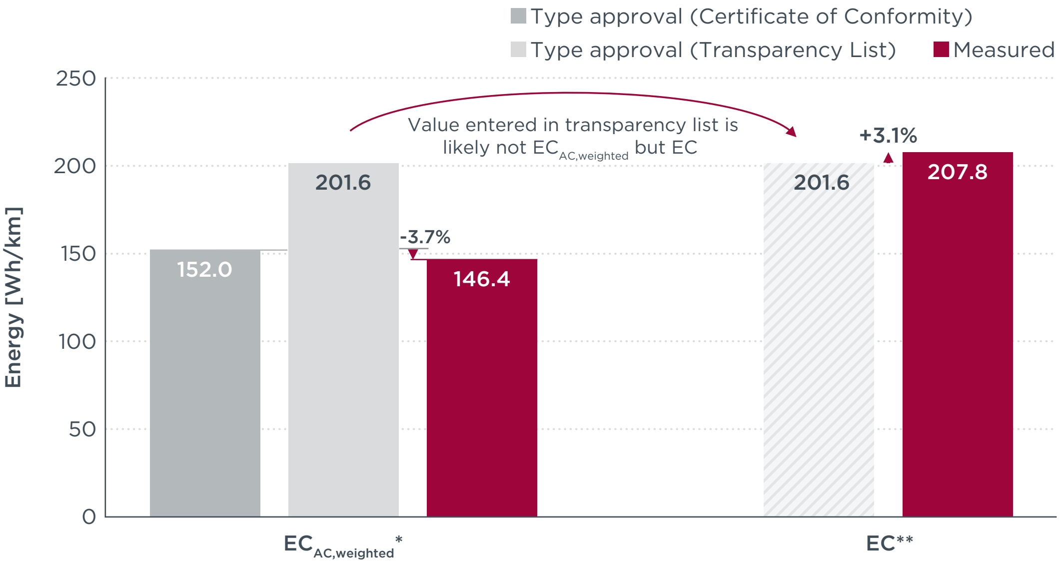


Figure 10. Comparison of type-approval electric energy consumption and the values measured when testing the vehicle at type-approval conditions. The left side shows the utility-factor-weighted electric energy consumption $EC_{AC,weighted}$ over the charge-depleting test until the end of the transition cycle. The right side shows the total electric energy consumption (EC) during the charge-depleting test relative to the equivalent all-electric range. Due to the large difference between the $EC_{AC,weighted}$ value from the transparency list and certificate of conformity, we assume that the EC was falsely entered in the transparency list instead of $EC_{AC,weighted}$.
*Utility-factor-weighted electric energy consumption
**Total electric energy consumption during the charge-depleting test relative to the equivalent all-electric range

4.2.5 Ranges: Test results versus type-approval values

The equivalent all-electric range is determined using the charge-depleting cycle range and the ratio of average charge-depleting and charge-sustaining CO_2 emissions as explained in Section 2.2. The comparison between measurement and type-approval values is presented in Figure 11. Shown on the left side is the EAER, where the measurement derived value of 44 km is about 14.1% shorter than the 51 km stated in the CoC. A similar discrepancy of 14.4% (type-approval 59 km, measured 51 km) is observed for the $EAER_{city}$, the equivalent all-electric range when city driving, depicted on the right side of Figure 11. The latter is calculated using solely the CO_2 emissions during the WLTC phases Low and Medium.

No explanation for this substantial discrepancy could be derived from the measurement data.

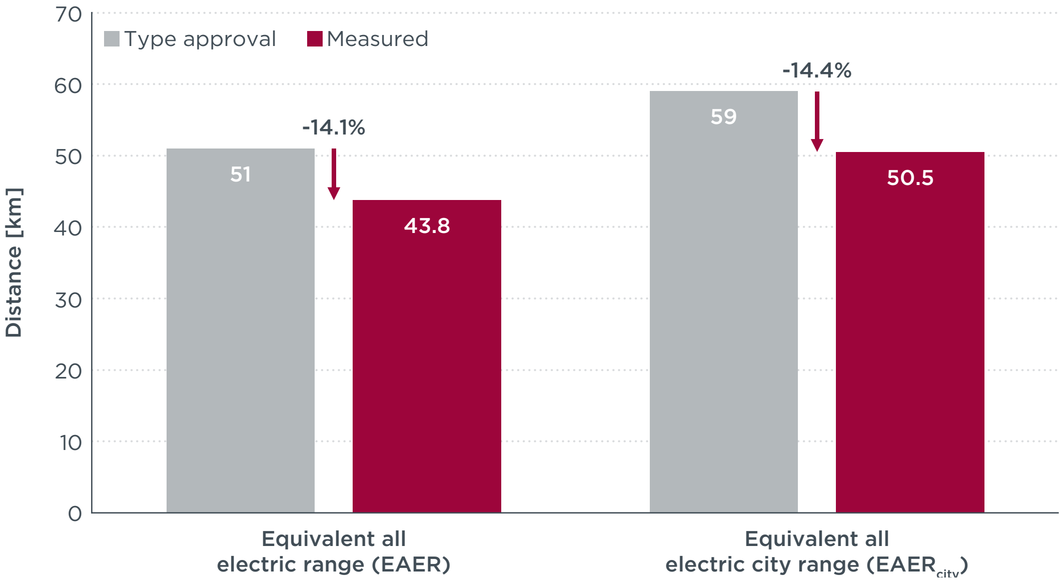


Figure 11. Comparison of type-approval and measured values of equivalent all-electric range or EAER (left) and equivalent all-electric city range or $EAER_{city}$ (right).

4.2.6 Effect of transition cycle number on CO_2 emissions and ranges

Figure 12 shows the measurement data of the charge-depleting test at 23 °C used to determine the break-off criterion. The upper graph presents the speed profile of four consecutive WLTCs with the accumulated driven distance shown on the left side of the center graph. The right side of the center graph shows the instantaneous fuel flow. The signal is clipped after about 7,500 seconds because the data acquisition for this signal was erroneous after this time. On the left side of the bottom graph, the continuous change in traction battery charge level is shown, while on the right side, the calculated REEC of the battery is depicted for each cycle.

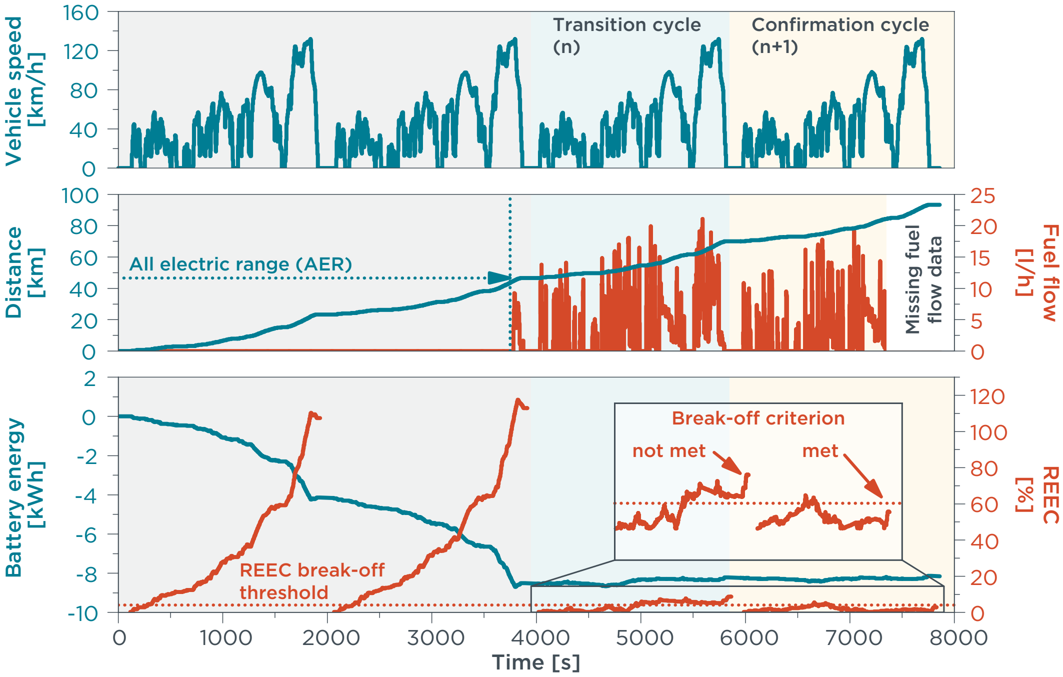


Figure 12. Determination of the charge-depleting sequence break-off criterion at 23 °C. The REEC (relative electric energy change) drops below the break-off threshold only during the fourth cycle, even though the battery is already fully drained at the end of the second cycle. The break-off criterion is not met in the third cycle because the battery charge is increased, as the battery energy curve (bottom left) shows.

The fuel flow recording reveals that the engine started consuming fuel for the first time at the end of the second WLTC, resulting in an all-electric range of 44 km. Even though the combustion engine was operated for most of the third cycle, the REEC exceeded the 4% break-off criterion threshold, however, not due to battery depletion but due to battery charging as the increase in battery charge level in the lower graph shows. The vehicle seems to follow an operating strategy where the battery is depleted to its maximum during charge-depleting operation but then requires some recharge of the battery once the vehicle switches to charge-sustaining mode. While this seems a reasonable approach for maximizing the all-electric range, it is unclear why the regulation considers a vehicle to be in charge-depleting mode when the battery shows a positive change in SoC of 4% or more. The break-off criterion is only met in the fourth cycle. Therefore, the third cycle is the transition cycle and consequently considered being part of the charge-depleting operation even though it is performed completely in charge-sustaining mode, as the constant battery SoC in the bottom graph of Figure 12 shows.

Since the calculation of many PHEV parameters is directly dependent on the transition cycle number, we analyzed the effect of considering the second instead of the third WLTC as transition cycle on CO_2 emissions, energy consumption, and ranges.

Performing the third cycle completely in charge-sustaining mode produces high CO_2 emissions. The effect of these CO_2 masses on the weighted charge-depleting CO_2 emissions is, however, reduced since the phase utility factors in the third cycle are low. Nevertheless, when considering the second WLTC as transition cycle, the weighted charge-depleting CO_2 level is reduced by almost 91% from 23 g/km to 2 g/km compared to the case where the third cycle is considered the transition cycle, as presented in Figure 13.

At the same time, the accumulated utility factor used to weight the CD and CS emissions drops from 0.838 to 0.734 when considering only the first two WLTCs as part of the charge-depleting sequence. Since the charge-sustaining emissions are not affected by the transition cycle number and therefore remain the same, the lower cycle utility factor almost completely counterbalances the lower weighted CD CO_2 emissions, resulting in nearly identical weighted, combined CO_2 emissions of 43.9 g/km when using the second cycle as the transition cycle compared to 44.9 g/km when the third cycle is used.

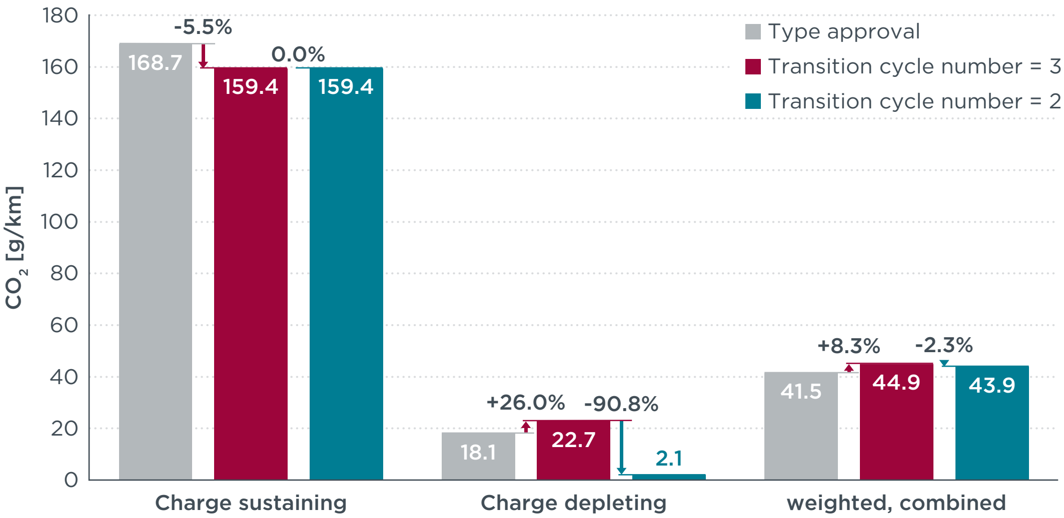


Figure 13. Effect of transition cycle number on CO_2 cycle emissions. The figure presents a comparison between the type-approval charge-sustaining value, weighted charge-depleting value, and weighted, combined CO_2 emission value and the values derived from the BMW X1 testing when considering the third or second WLTC of the charge-depleting sequence as transition cycle. The charge-sustaining CO_2 emissions are not affected by the transition cycle number.

For similar reasons, only a small effect of the transition cycle number is observed for the weighted energy consumption $EC_{AC,weighted}$, which is 145 Wh/km when using cycle number 3 and 147 Wh/km when using the second cycle as the transition cycle.

The charge-depleting cycle range R_{CDC} reflects the total distance driven until the end of the transition cycle and is thereby directly affected by the transition cycle number. As shown on the left side of Figure 14, considering the second instead of the third WLTC as the transition cycle reduces R_{CDC} by one-third. The actual charge-depleting range R_{CDA} reflects, however, only the distance where the vehicle is still operated in charge-depleting mode. As the battery was not further depleted in the third cycle, the almost identical results for using transition cycles 2 and 3, depicted in the middle of Figure 14, were expected. For the same reason, the similar results of the equivalent all-electric range when considering transition cycles 2 and 3 match the expectation, shown in Figure 14 on the right.

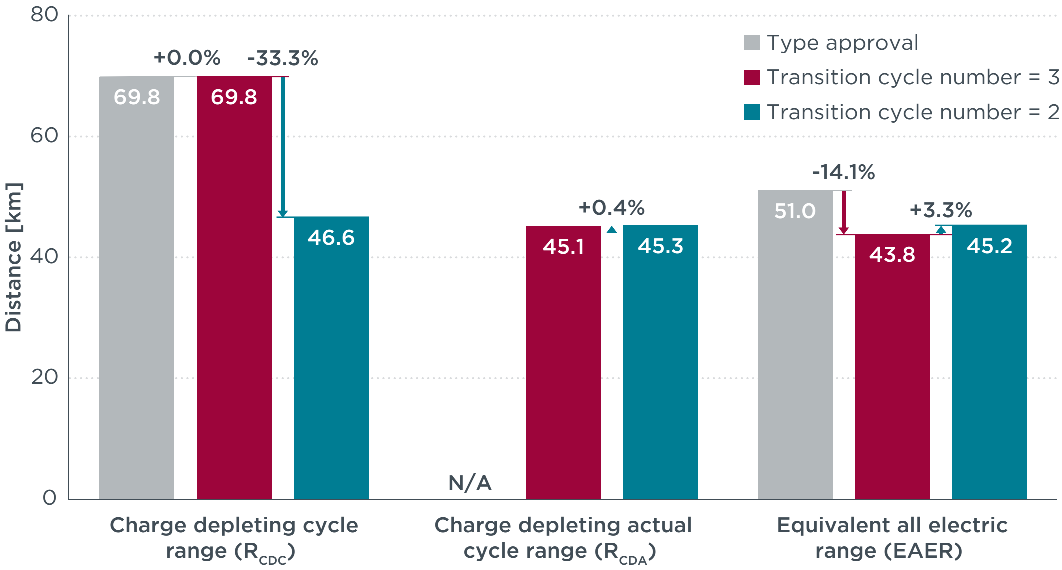


Figure 14. Effect of transition cycle number on charge-depleting cycle range (R_{CDC}), charge-depleting actual cycle range (R_{CDA}), and equivalent all-electric range (EAER).

Overall, the determination of weighted energy consumption and weighted, combined CO_2 emissions as well as R_{CDA} and EAER seems to be robust against variations in the transition cycle number and thereby in variations of the range considered to be operated in charge-depleting mode. This is helpful for future CO_2 in-service conformity testing and for evaluating the OBFCM data. However, the results also show that considering a cycle driven in charge-sustaining mode as being part of the charge-depleting operation results in substantially higher weighted charge-depleting CO_2 emissions.

4.2.7 Summary of type-approval value verification

The results presented in this section are summarized in Table 8. Considering the low absolute charge-depleting CO_2 emissions that lead to large relative deviations even for small absolute differences and taking into account that only one charge-depleting and one charge-sustaining test each was performed under type-approval conditions, the measured values meet the type-approval values stated in the CoC and transparency list reasonably well. Only the equivalent all-electric range values show an unexpectedly large discrepancy for which no explanation could be found.

Table 8. Comparison of WLTC test results at type-approval conditions (23 °C and deactivated air-conditioning system) with type-approval values retrieved from the Certificate of Conformity and transparency list.

	Type approval value	Test at 23 °C	
Charge sustaining CO_2 [g/km]	168.7	159.4	[-5.5%]
Charge depleting CO_2 [g/km]	18.1	22.7	[+26.0%]
Weighted, combined CO_2 [g/km]	41.5	44.9	[+8.3%]
EAER [km][a]	51	43.8	[-14.1%]
$EAER_{city}$ [km][b]	59	50.5	[-14.4%]
$EC_{AC,weighted}$ [Wh/km][c]	152	146.4	[-3.7%]
EC [Wh/km][d]	201.6	207.8	[+3.1%]
Utility factor	0.838	0.838	—
Transition cycle number	3	3	—

[a] Equivalent all-electric range.
[b] Equivalent all-electric range when city driving.
[c] Utility factor-weighted energy consumption.
[d] Energy consumption relative to EAER.

4.3. EFFECT OF AMBIENT TEMPERATURE AND THE USE OF AUXILIARIES ON WLTC LABORATORY TEST RESULTS

Type-approval testing is performed at an ambient temperature of 23 °C and, for better repeatability and comparability, with deactivated auxiliaries such as heating and air-conditioning, also referred to as HVAC. For vehicles that are not externally chargeable, this approach results in lower CO_2 emissions than under real-world conditions, but the HVAC effect can be estimated to some extent (Zacharof and Fontaras, 2016).

For PHEVs, HVAC devices are usually powered by high-voltage electricity to enable their operation when the combustion engine is not running. The electric energy consumed using the auxiliaries reduces the electric energy available for propulsion and therefore the electric ranges. To analyze the effect of auxiliaries on electric ranges and CO_2 emissions, charge-depleting tests at -5 °C and at 35 °C with activated automatic air-conditioning set to 22 °C were performed. For the 35 °C test, solar radiation simulation with a power of 1,000 W/m^2 was used.

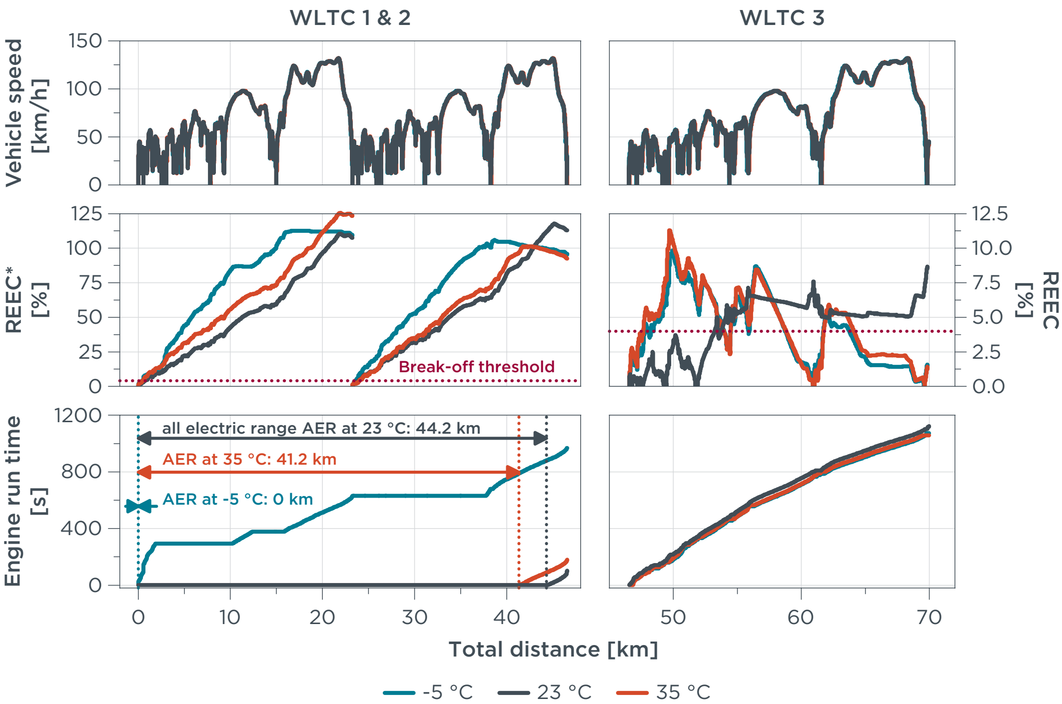


Figure 15. Effect of ambient temperature and use of auxiliaries on the transition cycle number and all-electric range. The figure shows on the left the first two WLTCs of the charge-depleting sequence at -5, 23, and 35 °C ambient temperatures. Automatic air-conditioning was active during the tests at -5 and 35 °C. The right side shows the same parameters for the third WLTC with a zoom of the REEC (relative electric energy change). At -5 and 35 °C, break-off criterion is reached in the third cycle and therefore the second WLTC is the transition cycle. At 23 °C, the third cycle is the transition cycle.
*Relative electric energy change of the battery.

Figure 15 shows the comparison of the first three WLTCs in charge-depleting mode at -5 °C, 23 °C, and 35 °C, respectively. The graphs on the left side show the results of WLTC 1 and 2, while the right side shows the REEC data recorded during the third cycle. The accumulated engine runtime is reset to zero at the beginning of the third cycle to allow for a direct comparison of the third WLTC at the three ambient temperatures.

4.3.1 Effect on transition cycle number

For WLTC tests 1 and 2 at all temperatures, the REEC of the propulsion battery, shown in the second graph of Figure 15, is at or above 100% and therefore well above the break-off threshold of 4%. As expected, the REEC curves show a faster draining of the battery at -5 °C and at +35 °C compared to 23 °C. When the engine is running, indicated by an increasing accumulated engine run time (bottom graph), the REEC stabilizes or even drops, meaning that no further energy is drawn from the battery. At -5 °C and 35 °C, the break-off criterion is met in the third cycle, therefore being the confirmation cycle, while it is met only in the fourth cycle at type-approval conditions. Consequently, the second WLTC is the transition cycle at -5 °C and 35 °C and thereby one cycle earlier compared to 23 °C, where the transition cycle number is 3 because the break-off criterion is only met in the fourth cycle.

However, since the battery state of charge data also shows that the vehicle reaches charge-sustaining mode at the end of the second cycle at 23 °C (Figure 12), we decided to consider the second instead of the third WLTC as the transition cycle at 23 °C. This way, only WLTCs are taken into account where the vehicle operates in charge-depleting mode and the CD CO_2 emissions at 23 °C are not skewed by including the de facto charge-sustaining emissions of the third cycle. However, as explained in Section 4.2.6., the charge-depleting values determined for the test at 23 °C are therefore not comparable to the type-approval values.

4.3.2 Effect on all-electric range

The bottom graph of Figure 15 shows the accumulated fueled engine running time as an indicator for when the engine consumes fuel. At 35 °C, the engine first consumes fuel toward the end of the second test after 41.2 km. This is about 7% shorter than the 44.2 km AER under type-approval conditions. At -5 °C, however, the combustion engine is used right from the start of the test for about 5 minutes, after which it is turned off again. The all-electric range, is therefore 0 km. The total combustion engine running time in the first WLTC at low ambient temperature is almost 60% of the time it is used during the third cycle, where the battery is in charge-sustaining mode. The cold-start strategy is investigated in more detail in Section 4.3.5.

4.3.3 Effect on equivalent all-electric range and electric energy consumption

A detailed comparison of electric energy consumption and production during the charge-depleting test for the three test conditions is shown in Figure 16.

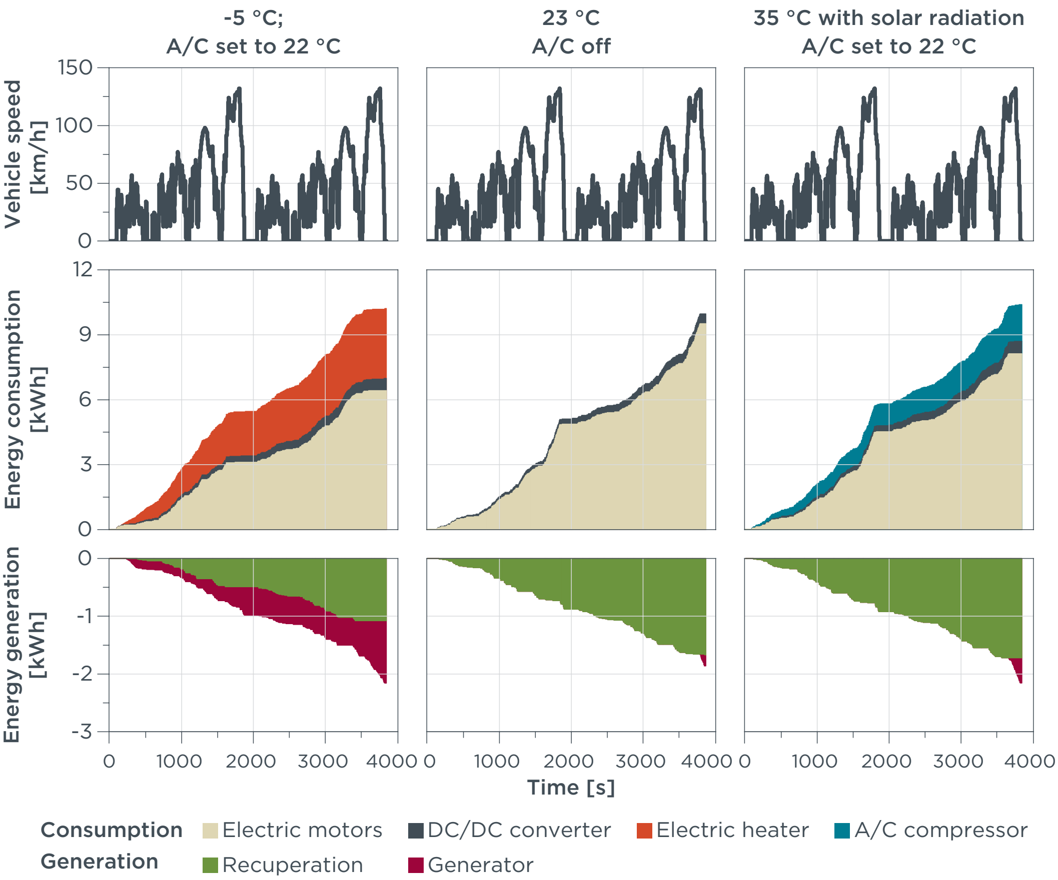


Figure 16. Electric energy flux during the first two WLTCs of the charge-depleting sequence at -5 °C, 23 °C, and 35 °C. While almost all-electric energy is available for propulsion at 23 °C with deactivated air-conditioning, the electric heater and air-conditioning compressor consume a substantial amount of the available electric energy at -5 °C and 35 °C respectively.

At type-approval conditions, that is, at 23 °C with deactivated HVAC, 10.0 kWh are consumed in total, with 9.5 kWh used by the electric motors and the remaining 0.5 kWh by the DC/DC converter supplying the 12 V circuit. Of this energy, 1.66 kWh are recuperated, and 0.15 kWh are generated by the combustion engine at the end of the second cycle. Thereby, the net change in battery SoC, that is, the difference between consumed and produced energy is 8.2 kWh.

At -5 °C, where the HVAC system is set to 22 °C, the total energy consumed is 10.2 kWh and thereby almost identical to the value at 23 °C. Also, the energy used by the DC/DC converter, accumulating to 0.6 kWh, is similar to that at type-approval conditions. However, it is apparent that almost one-third of the consumed energy (3.2 kWh) is used by the electric heater, whereof almost two-thirds of the heating energy (2.0 kWh) is consumed during the first cycle for the initial warm-up of the cabin, as the test sequence is cold-started after soaking. For propelling the vehicle, only 6.4 kWh are available. At the same time, about 34% less energy is recuperated (1.1 kWh) while a substantial amount of 1.1 kWh is generated when using the electric motor to increase the load on the combustion engine for a faster catalyst warm-up. (For a detailed discussion of the cold-start strategy refer to Section 4.3.5.) The net battery discharge is 8.0 kWh, about 2.4% less than at 23 °C.

At 35 °C, the portion of the total energy consumed (10.4 kWh) used by the electric motors (8.1 kWh) is also lower than the 9.5 kWh on the test at type-approval conditions, due to the energy consumption of the electric A/C compressor. This device consumes 1.7 kWh across the two tests. Like the test at cold ambient temperature, the larger portion of this energy (1 kWh) is spent during the first test. The consumption of the DC/DC converter is 0.6 kWh and thereby similar to the values observed at -5 °C and 23 °C. The amount of energy recuperated is 1.73 kWh, which is close to the test at type-approval conditions, whereas the energy created in generator mode (0.43 kWh) is almost three times as high. The net change in battery SoC amounts to 8.2 kWh, which is identical to the test at type-approval conditions.

The EAER is the distance in charge-depleting mode that can be attributed to the use of the electric motor. With no auxiliaries active, the difference in CO_2 emissions between a CD and CS test cycle is only related to the propulsion energy provided by the electric motor. The EAER can therefore be determined based on the ratio of CD and CS CO_2 emissions, as defined in the type-approval regulation and described in Section 2.2.

When using auxiliaries, however, part of the electric energy is used to climatize the passenger compartment, which reduces the energy available for propulsion and thereby the range that can be attributed to it. As shown in Figure 16, the initial energy consumed by the HVAC system during a WLTC after soaking at high and low ambient temperatures is very high but reduces in the subsequent cycles. Since the CD CO_2 emissions are determined in a number of consecutive WLTCs, whereof only the first one is started after soaking, the electric energy consumption of the HVAC system is lower than for repeated soaked tests, meaning more electric energy is available for propulsion. Comparing the CD CO_2 emissions with the CO_2 emissions of one cold-started CS cycle would therefore result in an overestimation of the EAER.

Therefore, we calculated the EAER based on the ratio of net energy provided by the electric motors at the wheels ($E_{EM,net,wheel}$) and the required cycle energy ($E_{cycle,wheel}$) according to Equation 6. In our case, R_{CDC} is the range of two complete WLTCs.

$$EAER = R_{CDC} \times \frac{E_{EM,net,wheel}}{E_{cycle,wheel}} = R_{CDC} \times \frac{\eta_{electric\ drivetrain} \times E_{EM,net}}{E_{cycle,wheel}} \qquad \textit{Equation 6}$$

The net energy provided by the electric motors at the wheels is the net electric energy consumed by the electric motors ($E_{EM,net}$), corrected for the efficiency of the electric drivetrain. This was derived separately for each ambient temperature by dividing the accumulated energy consumed by the electric motors by the cycle energy for the phases of pure electric driving, that is, when the combustion engine was shut off.

To estimate the energy consumed by the electric motors stemming from grid and recuperated energy only ($E_{EM,net}$), the total energy consumed by the electric motors ($E_{EM,gross}$) is multiplied with the grid energy share $r_{grid\ energy}$:

$$E_{EM,net} = E_{EM,gross} \times r_{grid\ energy} \qquad \textit{Equation 7}$$

The grid energy share is the share of consumed energy attributed to grid energy and recuperation. Since the total electric energy consumed by the electric motors and auxiliaries ($E_{total,consumed}$) is the sum of grid energy, recuperated energy, and energy produced by the electric motor in generator mode ($E_{EM,generated}$), that is, at fueled engine operation, the grid energy share can be calculated as follows:

$$r_{grid\ energy} = \frac{E_{total,consumed} - E_{EM,generated}}{E_{total,consumed}} \qquad \textit{Equation 8}$$

For the test at 23 °C, the EAER could be calculated according to the presented energy-based method or based on the CO_2 emissions following the procedure from the type-approval regulation. The values derived from both methods are in good agreement; when using the second WLTC as the transition cycle, as explained in Section 4.3.1., the energy-based EAER of 45.6 km is less than 1% higher than the CO_2-based value of 45.2 km. Using the energy energy-based method for deriving the electric energy consumption relative to the all-electric range (EC) results in 206.3 Wh/km, which deviates by about 1.6% from the CO_2-based EC value of 209.6 Wh/km. Due to this good match, we applied the energy-based approach to estimate the effect of using the auxiliaries at -5 and 35 °C on EAER and EC, shown in Figure 17.

On the left side of Figure 17, a comparison of the EAER at 23 °C with the values calculated for the tests at -5 °C and at 35 °C is shown. At 35 °C, the electric energy consumption of the A/C compressor reduces the EAER by 11% resulting in a range of about 41 km, which is identical to the AER. At -5 °C, the EAER is almost halved to 23.7 km. This has a direct effect on the EAER specific energy consumption EC, which is almost twice as high at -5 °C (390 Wh/km) than under type-approval conditions (206.3 Wh/km). The increase at 35 °C to 234 Wh/km is less pronounced (+14%).

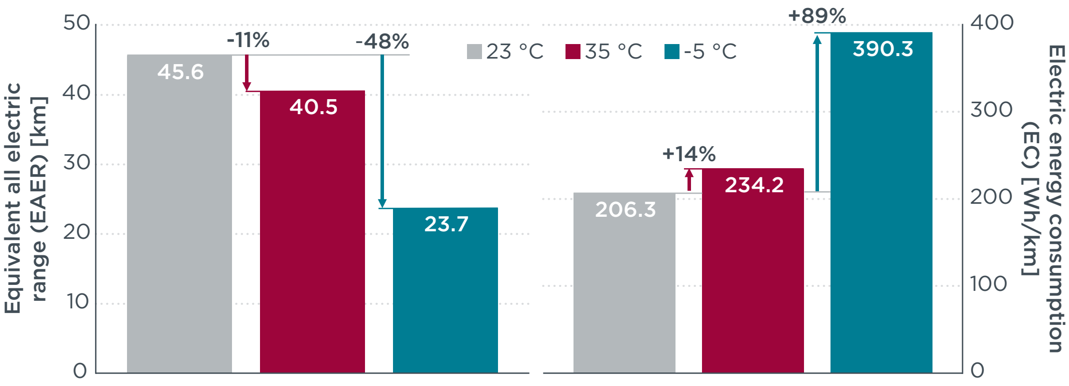


Figure 17. Effect of using auxiliaries at -5 °C and 35 °C ambient temperature on equivalent all-electric range (left) and electric energy consumption relative to the equivalent all-electric range (right) at -5 °C and 35 °C ambient temperature compared to type-approval conditions (23 °C). The data shown uses the second WLTC of the charge-depleting sequence as the transition cycle for all temperatures.

4.3.4 Effect on WLTC CO_2 emissions

For the analysis of the effect on CO_2 emissions, it is important to mention that a dedicated cold-start charge-sustaining test was only performed at 23 °C but not at -5 °C and 35 °C. To calculate not only the weighted charge-depleting but also the weighted, combined emissions, we took the following approach: As explained previously, the charge-depleting sequence consists of consecutive WLTCs until the break-off criterion is reached. Subsequently, we performed one additional WLTC. In this cycle, the vehicle operates in charge-sustaining mode. For the test at type-approval conditions, that is at 23 °C and with deactivated auxiliaries, this test resembles, therefore, a warm-started WLTC in CS mode. At -5 °C and 35 °C, however, it needs to be considered that, at the beginning of this cycle, the vehicle cabin temperature has already been climatized closer to the setpoint of 22 °C and hence substantially lower CO_2 emissions compared to a cold-start test with active HVAC are expected. For comparability of the CS equivalent test cycles, and subsequently the weighted, combined CO_2 emissions, we use for all three temperatures a warm-start CS test but corrected the CO_2 emissions at 35 °C and -5 °C for the electric energy consumed by the HVAC system during a cold-start test. The correction is done by calculating the electric energy consumption equivalent CO_2 emissions using the correction factor of 0.789 g CO_2 per Wh supplied in the transparency list.

As shown in Figure 18, at -5 °C the electric cabin heater is only active until the engine has reached a coolant temperature of approximately 85 °C. Thereafter, the cabin is heated using combustion engine waste heat. To take this into account, we extrapolated the coolant warm-up curve measured in the first test, assuming continuous engine operation as would be encountered in a CS test, and thereby derived that 85 °C coolant temperature would approximately be reached by the end of the first WLTC phase (phase Low). The electric energy consumed by the heater during that time is about 600 Wh, equivalent to 474 g CO_2. It was not possible to estimate the additional fuel required to warm up the engine and the catalyst at -5 °C. Therefore, the calculated CS and weighted, combined CO_2 emissions at this temperature represent a best case and are expected to be higher when measured in a cold-start WLTC.

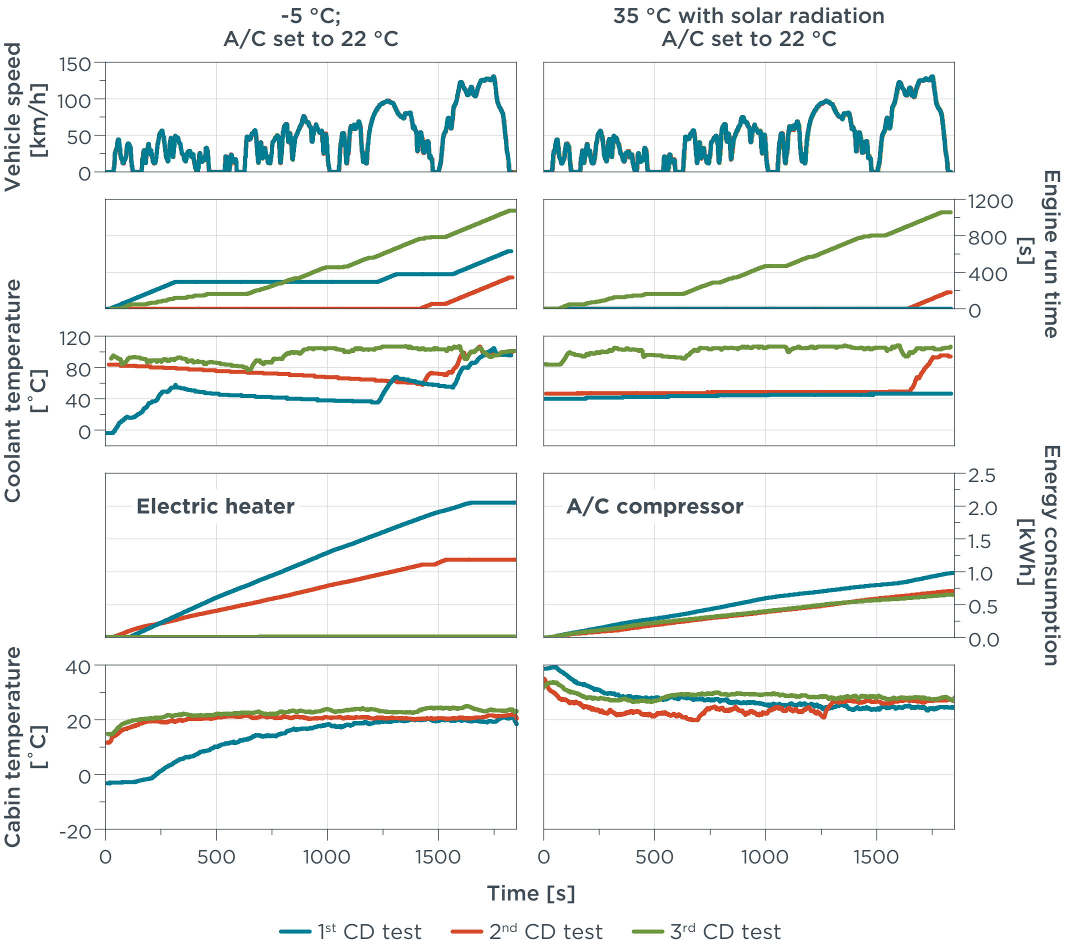


Figure 18. Comparison of the first three WLTCs of the charge-depleting test sequence at -5 °C (left) and 35 °C (right). At -5 °C, the cabin is heated using the electric heater for most of the first and second WLTC (third and bottom graph). Only when the coolant has warmed up to about 85 °C is the electric heater deactivated (third and fourth graph from top). At 35 °C, the air-conditioning compressor needs to operate continuously and constantly consumes electric energy independent of the vehicle being in charge-depleting or charge-sustaining mode, even though at a lower power than for the initial cabin cooldown after soaking.

Similarly, we corrected for the A/C compressor related energy consumption at +35°C. Since the A/C compressor is solely powered by electricity, it continuously consumes electric energy, which remains fairly constant from the second cycle onward, that is, after the initial cabin cool down has been performed, as can be seen on the right side of Figure 18. As the air-conditioning was active during the WLTC used as the charge-sustaining cycle for our calculations, only the difference in energy consumption between the first cycle and the one used in the calculations needs to be accounted for, as opposed to the total energy consumed during the first cycle. The A/C-compressor-related energy consumption sums up to a total of 275 Wh or an equivalent of 217 g CO_2.

It should be noted that the charge-sustaining and weighted, combined CO_2 emissions determined by this approach are comparable to each other but not fully comparable to the type-approval values. However, due to the high utility factor, the weighted, combined CO_2 emissions at 23 °C using the warm-started confirmation cycle are only about 2.7% lower than the weighted, combined CO_2 emissions calculated using the cold-start CS test results.

Figure 19 shows the effect of the ambient temperature and HVAC electric energy consumption on the WLTC CO_2 emissions. Since the charge-depleting range at 23 °C is driven almost purely electric, very low average (4.5 g CO_2/km) and weighted CD CO_2 emissions (2.1 g CO_2/km) are the result. Compared to these low values, the increase in CO_2 emissions at -5 °C is very high. The weighted CD CO_2 emissions are more than 40 times higher than for the test at 23 °C. This increase is the result of over 20 times higher average CO_2 emissions throughout the CD test sequence in combination with the early use of the combustion engine, resulting in high CO_2 emissions in the early phase of the CD test sequence where high utility factors apply. Together with an increase by 30% of the charge-sustaining CO_2 emissions, the weighted, combined CO_2 emissions at -5 °C are approximately 2.9 times higher than for the test under type-approval conditions.

At 35 °C, the extra energy consumption of the A/C compressor increases the weighted CD CO_2 emissions more than 4.5 times and the charge-sustaining emissions by 22%. As result, the weighted, combined CO_2 emissions at 35 °C exceed the value at 23 °C by 34%.

It should be noted that all results are determined in the laboratory performing WLTC tests. Real-world CO_2 emissions can be much higher if the vehicle is not charged frequently.

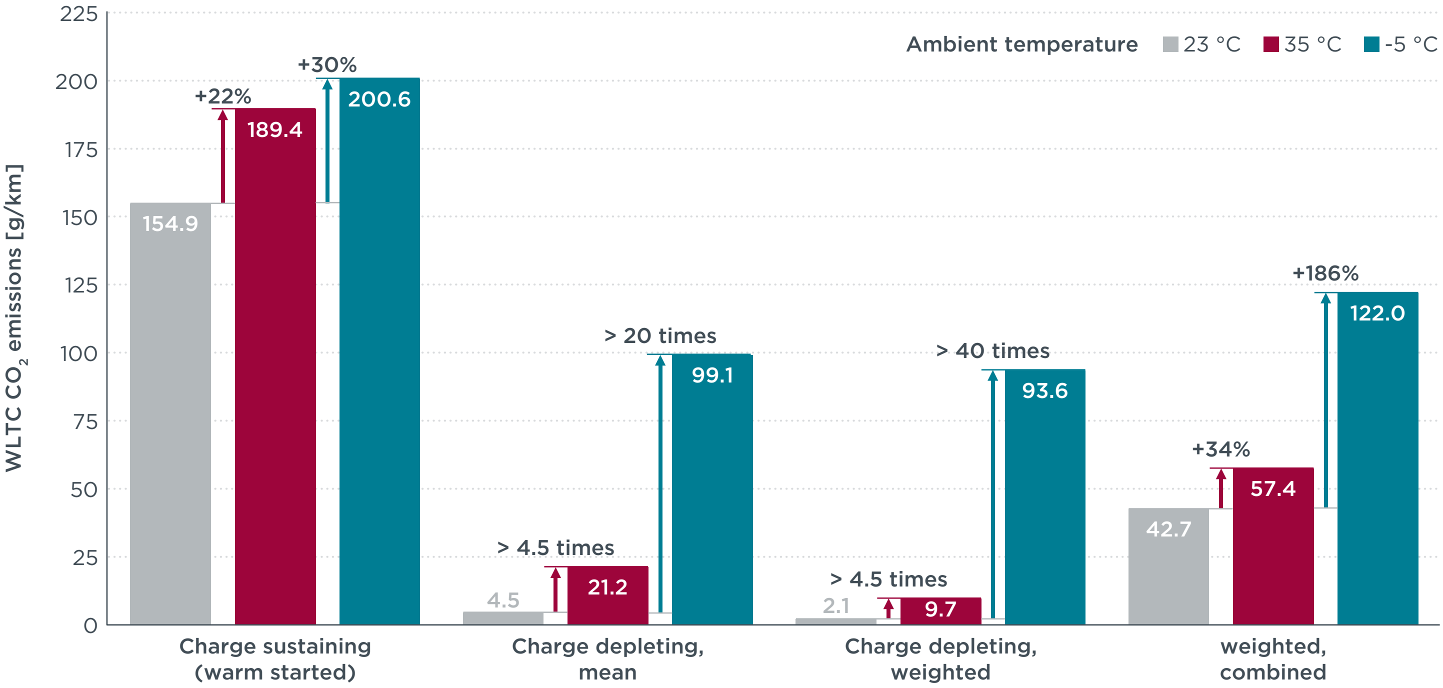


Figure 19. Comparison of CO_2 emissions at -5 °C, 23 °C, and 35 °C. The figure shows the weighted emissions measured in charge-sustaining mode, the average emissions over the charge-depleting sequence, the utility-factor-weighted charge-depleting emissions, and the weighted, combined CO_2 emissions. The data shown uses the second WLTC of the charge-depleting sequence as transition cycle for all temperatures, and the utility factor is therefore 0.73.

4.3.5 Cold-start strategy applied at low ambient temperature

Even when started with a fully charged battery and in the *MAX eDrive* mode, where, according to BMW, the vehicle is operated in pure electric operation as long as possible, the combustion engine was in operation right from the beginning for a cold-start test at -5 °C. When tested at 23 °C and 35 °C, this behavior was not observed. We therefore analyzed the cold-start strategy at low ambient temperature in more detail and arrived at the following results.

Figure 20 shows on the left side a zoom of the first 450 seconds and on the right side of the last 800 seconds of the cold-start charge-depleting WLTC at -5 °C. On the top, engine and vehicle speed signal are shown. The second graph from the top shows the tailpipe emissions concentrations and the exhaust temperature upstream from the three-way catalyst (TWC). The cream-colored curve of the bottom graph reflects the current engine brake power, that is, the power of the combustion engine at the clutch, a signal that was available on the OBD interface. Using the measured electric motor power, we calculated the engine brake power that would be required if the electric motor would not be used for boosting (green) or for creating electricity in generator mode (red). In other words, when the green curve exceeds the cream curve, the electric motor assists the ICE, which therefore needs to produce less power. When the red curve tips below the cream curve, the electric motor is used to charge the battery, and therefore the combustion engine produces more energy than needed for propelling the vehicle.

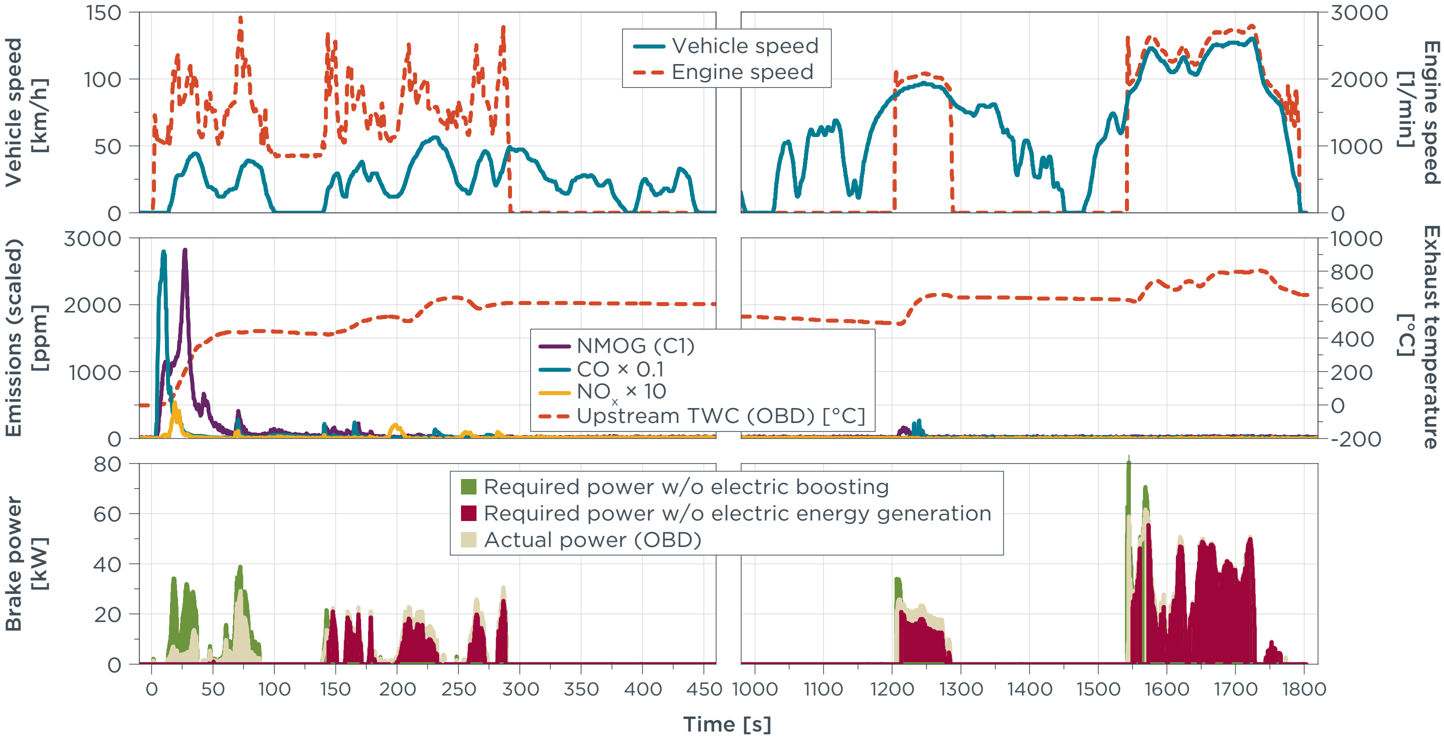


Figure 20. Combustion engine and electric motor operating strategy for the cold-start WLTC in charge-depleting mode at -5 °C. The combustion engine is activated at the beginning of the drive cycle to warm up the catalyst. The electric motor first assists the engine to reduce engine load and thereby raw emissions. Once the catalyst has warmed up, the electric motor is used to put additional load on the combustion engine to further increase the exhaust temperature and thereby catalyst temperature.

The engine speed signal reveals an ICE start as soon as the propulsion system is activated by the driver. The brake power data shows that in the first 40 seconds after engine start the electric motor is the main source of propulsion power. In the subsequent acceleration, the electric motor further assists the engine to reduce the required brake power. As the catalyst is below the light-off temperature at test start, tailpipe concentrations of carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane organic gases (NMOG) peak in this phase. Reducing the engine load in this phase therefore reduces exhaust and pollutant mass flow. The graph in the middle of Figure 20 shows that for CO and NO_x, light-off at the low mass flows begins at about 350 °C, whereas the larger NMOG molecules seem to require a temperature of at least 440 °C. Once a catalyst temperature of 450 °C is reached, the electric motor is no longer used to boost the engine but instead to increase the combustion engine load by generating electricity, visible by the cream-colored curve exceeding the red curve. The higher engine load causes a further increase of the exhaust temperature above 600 °C. At this temperature, the low tailpipe emission concentrations despite the higher engine load indicate full catalyst light-off. Once the exhaust temperature has stabilized above 600 °C after 290 seconds, the combustion engine is switched off and the vehicle is propelled purely electric. At 1,200 seconds after test start, when the exhaust temperature has dropped to approximately 485 °C, the combustion engine is started again for about 85 seconds. By increasing engine load with the electric motor, the exhaust temperature is raised above 630 °C. The temperature is maintained well above 600 °C during a subsequent engine-off phase of about 250 seconds, allowing the extra-high phase of the WLTC to be driven mostly by using the combustion engine while maintaining full emission conversion in the catalyst.

While the results do not provide a clear explanation for this strategy, a reason could be to compensate for a reduced battery power due to the low ambient temperature and the energy consumption of the electric heater, which might not be able to support the electric motor power demand during the high and extra-high WLTC phase. To avoid high tailpipe pollutant emissions related to a cold catalyst in combination with high exhaust mass flows when the combustion engine is used for the first time in these phases, the applied strategy ensures a catalyst at or close to light-off temperature.

The strategy therefore seems to target low pollutant emissions in a low temperature WLTC or RDE test, as the catalyst warm-up is only sensible if a high-load operation exceeding the available battery power is to be expected. While a pure electric operation would be possible for an average German inner-city trip of 5.5 km and an average 10.3-km trip that starts and ends in a city (Gerike et al., 2020), the applied strategy results in CO_2 emissions of 116 g/km and 62 g/km over the first 5.5 km and 10.3 km of the WLTC, respectively. Even though the pollutant emissions of the tested almost new vehicle over the same periods are well below the Euro 6 limits, the vehicle, instead of operating in zero-emission mode, emits harmful substances during city driving where the effects of pollutants are especially severe.

Since no tests were performed at temperatures between 23 °C and -5 °C, it cannot be determined below which temperature this strongly CO_2 increasing change in operating strategy occurs.

4.3.6 Summary of ambient temperature effect on vehicle laboratory test results

Using air-conditioning and heating at high and low ambient temperatures has detrimental effects on the CO_2 emissions, energy consumption, and electric ranges of a plug-in hybrid vehicle due to the electric energy consumption of the HVAC system and the subsequent reduced energy available for propulsion. Table 9 summarizes the results presented in the previous sections.

It should be noted that the results presented here are not directly comparable to the results presented in Section 4.2 for the following reasons. First, for the temperature comparison the second instead of the third charge-depleting WLTC at 23 °C was used as the transition cycle, as explained in Section 4.3.1. Furthermore, only warm-start charge-sustaining test results were available for all three temperatures and therefore used instead of values from cold-start tests.

Table 9. Summary of ambient temperature and air-conditioning/heating use on CO_2 emissions, energy consumption and ranges.

Parameter	23 °C – A/C off	35 °C – A/C on		-5 °C – A/C on	
Charge sustaining CO_2 [g/km][a]	154.9	189.4	[+22%]	200.6	[+30%]
Charge depleting CO_2 [g/km]	2.1	9.7	[> 4.5 times]	93.6	[> 40 times]
Weighted, combined CO_2 [g/km]	42.7	57.4	[+34%]	122	[+186%]
EC[b]	206.3	234.2	[+14%]	390.3	[+89%]
EAER[c]	45.6	40.5	[-11%]	23.7	[-48%]
AER[d]	44.2	41.2	[-6.8%]	0	[-100%]
Utility factor	0.734	0.734	—	0.734	—
Transition cycle number	2[e)]	2	—	2	—

[a] For this comparison, the results of warm-start charge-sustaining WLTC tests were used instead of cold-start tests.
[b] Utility factor weighted energy consumption.
[c] Equivalent all-electric range.
[d] All-electric range
[e] The test vehicle reached charge-sustaining mode at the end of the second WLTC at 23 °C. Therefore, 2 was used as the transition cycle number at all three temperatures.

4.4. EFFECT OF USER-SELECTABLE MODES ON VEHICLE OPERATION AND CO_2 EMISSIONS

4.4.1 Plug-in hybrid specific modes: SAVE Battery versus charge-sustaining mode

As described in more detail in Section 3.1, three user-selectable operating modes are implemented on the BMW X1. To assess the effect of the modes on CO_2 emissions, we tested the vehicle in the so-called *SAVE Battery* mode, a mode that according to BMW should maintain the battery level at its current SoC except for charge increase through energy recuperation (BMW Group, 2020a). We therefore expected only modestly increased CO_2 emissions in the *SAVE Battery* mode compared to operation in charge-sustaining mode, where recuperated energy is consumed during subsequent operation.

After activating the *SAVE Battery* mode, a cold-start WLTC at type-approval conditions was performed with a depleted battery at test start. Directly afterward, a second test in the same mode was performed, with the engine coolant being hot at test start. The battery was not drained nor recharged between the two tests. Figure 21 shows the phase and cycle CO_2 emissions of these two tests in comparison to the cold-start WLTC in charge-sustaining mode, the latter corrected for a change in battery charge level, as described in Section 2.2.

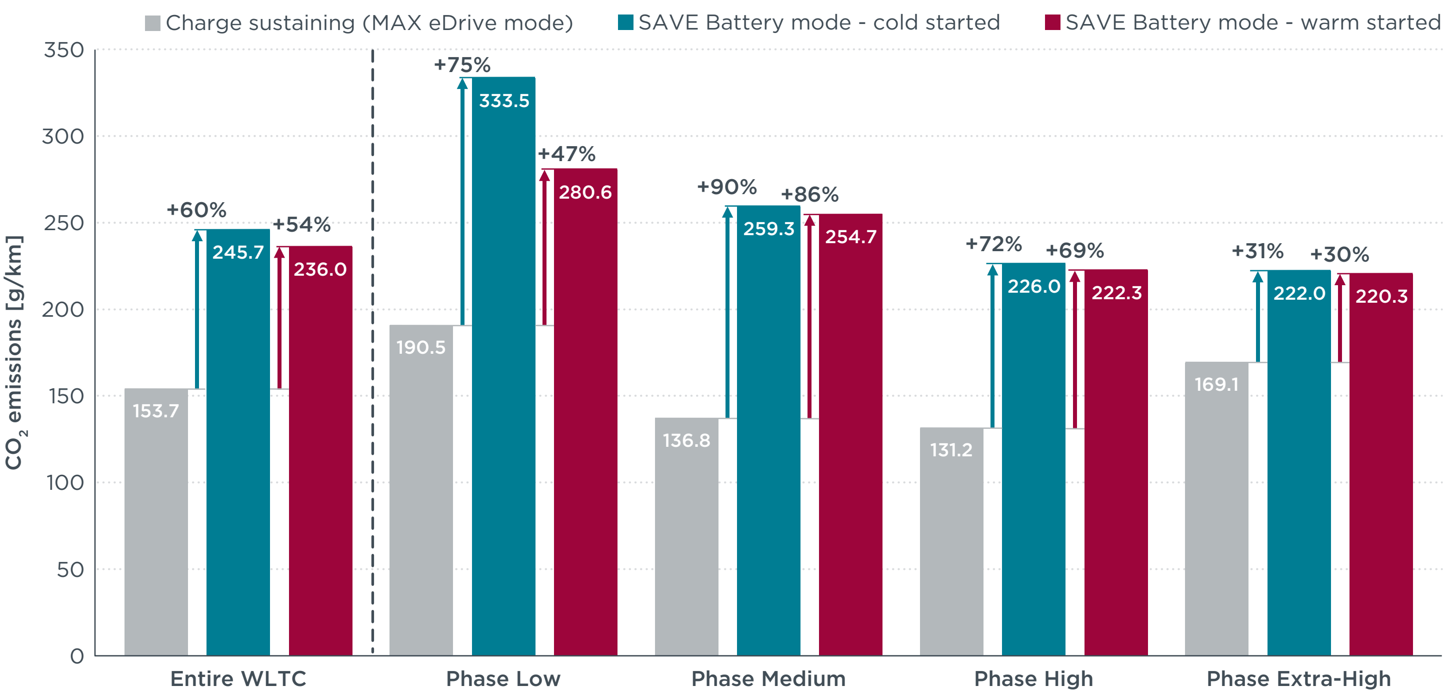


Figure 21. Effect of plug-in hybrid mode on WLTC CO_2 emissions. The emissions recorded for a cold-start test in charge-sustaining mode (MAX eDrive) are compared to the CO_2 levels in the SAVE Battery mode for both a cold- and subsequent warm-start WLTC. The SAVE Battery mode emerged as a charge-increasing mode. The tests were performed at 23 °C with deactivated air-conditioning. Before the cold-start tests the traction battery was depleted. The warm-start test was performed directly after the cold-start test.

Unexpectedly, the CO_2 emissions for the cold-start WLTC in the *SAVE Battery* mode are substantially higher than in CS mode, ranging from about 31% increase in the extra-high cycle phase to almost twice as high in the medium WLTC phase (90%). Over the entire cycle, the CS CO_2 emissions are elevated by 60% for the cold-start test. This suggests that the electric motors are used as fuel-powered generators to increase the battery SoC in all cycle phases when using the *SAVE Battery* mode.

Since the cold-started *SAVE Battery* test was commenced with a drained battery, we then assumed that the battery is charged to a certain minimum level. However, a comparison between the cold- and the following warm-start tests reveals that the phase CO_2 emissions are almost identical, except for the first cycle phase (phase low), where the higher CO_2 emissions for the cold-start test are attributed to the lower fuel efficiency of a cold engine and vehicle. We therefore conclude that even though the battery was partially charged in the cold-started WLTC, charging continues at the same rate throughout the warm-started WLTC, resulting in a CO_2 emission increase of 54% for the whole cycle.

To further investigate engine operation in the *SAVE Battery* mode, we performed a real-world driving test in *SAVE Battery* mode. Figure 22 shows a comparison of electric and fuel energy flow recorded during tests in charge-sustaining and charge-increasing (*SAVE Battery)* modes.

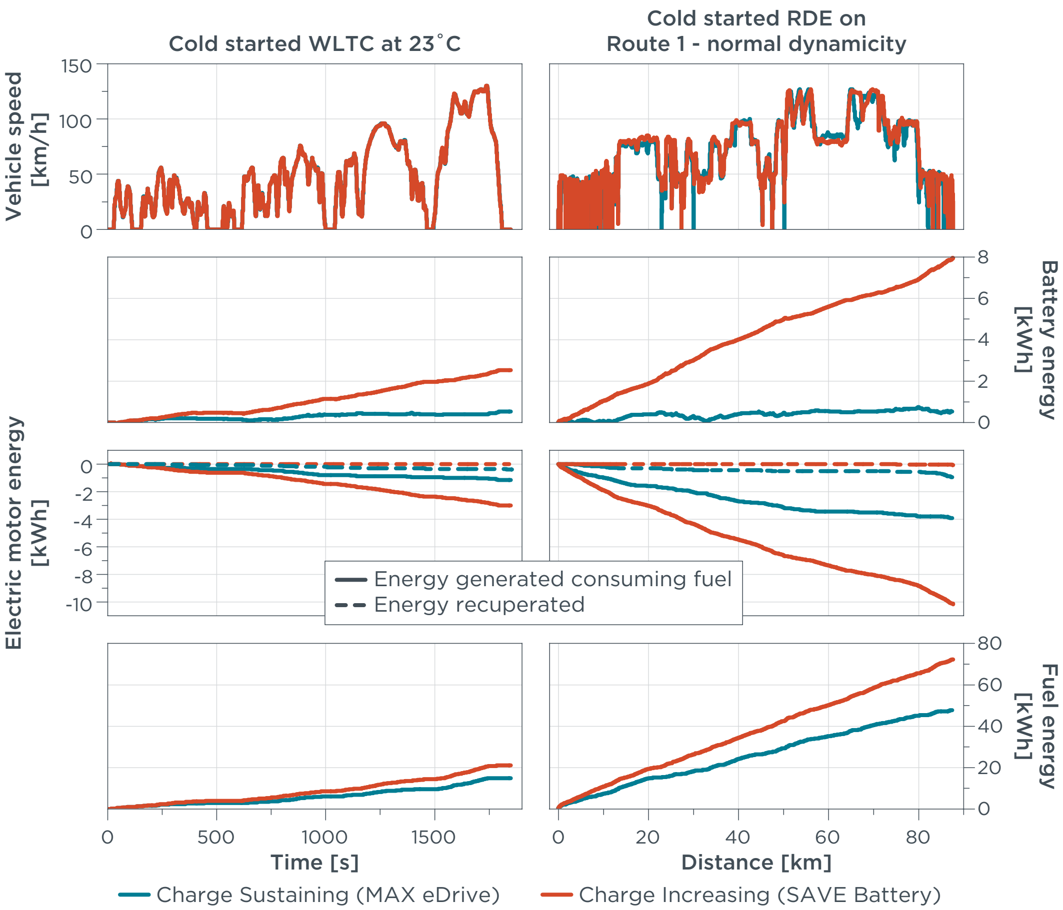


Figure 22. Comparison of electric energy and fuel consumption tests in charge-sustaining (MAX eDrive) and charge-increasing (SAVE Battery) mode. The left side shows the results for WLTC and the right side for real-world driving tests. Even though BMW describes the SAVE Battery mode as a battery charge hold mode, it is evident that the combustion engine is used to fully charge the battery in this mode.

The left side presents the results of the WLTCs while the right side depicts the results of on-road driving tests on Route 1. All tests were started with a cold engine and a depleted battery. The top graph shows the speed profile of the performed tests and the graph below the accumulated net battery energy change. To assess how the electric energy was generated, the third graph from the top depicts separately the energy produced by recuperation and by using the electric motor as a combustion engine powered generator. The energy of the fuel consumed is shown in the bottom graph.

While the net battery charge level remains close to the initial SoC for both the WLTC and real-world test in charge-sustaining mode, the charge level substantially increases in the *SAVE Battery* mode. The analysis of the electric motor energy components in the third graph from the top shows that charging in CI mode is almost exclusively done using the electric motor in generator mode, that is, powered by the combustion engine, while in CS mode part of the battery energy stems from recuperation. At the end of the *SAVE Battery* real-world test, 7.9 kWh were recharged to the battery compared to a maximum battery discharge during the charge-depleting tests of 8.2 kWh, indicating that engine charging continues until the battery is fully recharged.

This shows that the *SAVE Battery* mode is a charge-increasing mode, using the combustion engine to charge the battery. The observed mode of operation does not match BMW's description of only increasing charge through energy recuperation, and its usage entails substantial excess CO_2 emissions.

To assess the charging efficiency and CO_2 intensity when charging the battery in charge-increasing mode, we calculated the difference in fuel energy and recharged electric energy between the tests in charge-sustaining and charge-increasing mode. Compared to the real-world test in charge-sustaining mode, 7.2 kWh more were charged to the battery in charge-increasing mode, which required burning an additional fuel volume of 2.9 liters of gasoline E10, equivalent to an energy of 24.7 kWh and resulting in extra CO_2 emissions of approximately 6,500 g. The charging efficiency, that is, recharged electric energy per additional fuel energy consumed, calculates to about 29%. A similar efficiency is determined for the WLTC test, where the net energy charged to the battery compared to the test in CS mode is 2.01 kWh and the additional fuel energy adds to 6.00 kWh, equivalent to 1,584 g CO_2, corresponding to an efficiency of 33%.

The resulting CO_2 mass per charged kWh is about 790 grams per kWh for the WLTC, which is identical to the CO_2 correction factor contained in the transparency list and used during type approval to correct the charge-sustaining CO_2 emissions for changes in battery charge level as described in Section 2.2. For the RDE test, 874 g CO_2 are emitted per kWh produced. Compared to the 2019 EU-average electricity greenhouse gas intensity of 275 g CO_2/kWh and taking into account the on-board charger efficiency of about 87%, using electric energy generated from fuel in charge-increasing mode results in 2.5 to 2.8 times higher CO_2 emissions per kWh (EEA, 2020).

4.4.2 Vehicle modes: Sports mode versus normal mode

In addition to the test in charge-increasing mode, one real-world test on each route was performed with a more dynamic driving style and using dynamics focused vehicle settings to mimic less fuel-efficiency-oriented drivers. In particular, the vehicle mode was changed from COMFORT to SPORT and gearbox mode S instead of D was used. While gearbox mode D is the standard when starting the vehicle, mode S targets more dynamic driving by operating at higher engine speeds through later gear shift thresholds, presumably resulting in lower fuel efficiency. In addition, the payload was increased by 265 kg for these tests. For simplification, these settings are from hereon referred to as "sports mode," whereas the settings for normal driving (gearbox in D, driving mode set to COMFORT) are referred to as "normal mode." The battery at test start was depleted, and by choosing the *AUTO eDrive* hybrid mode, the vehicle was expected to operate in charge-sustaining mode.

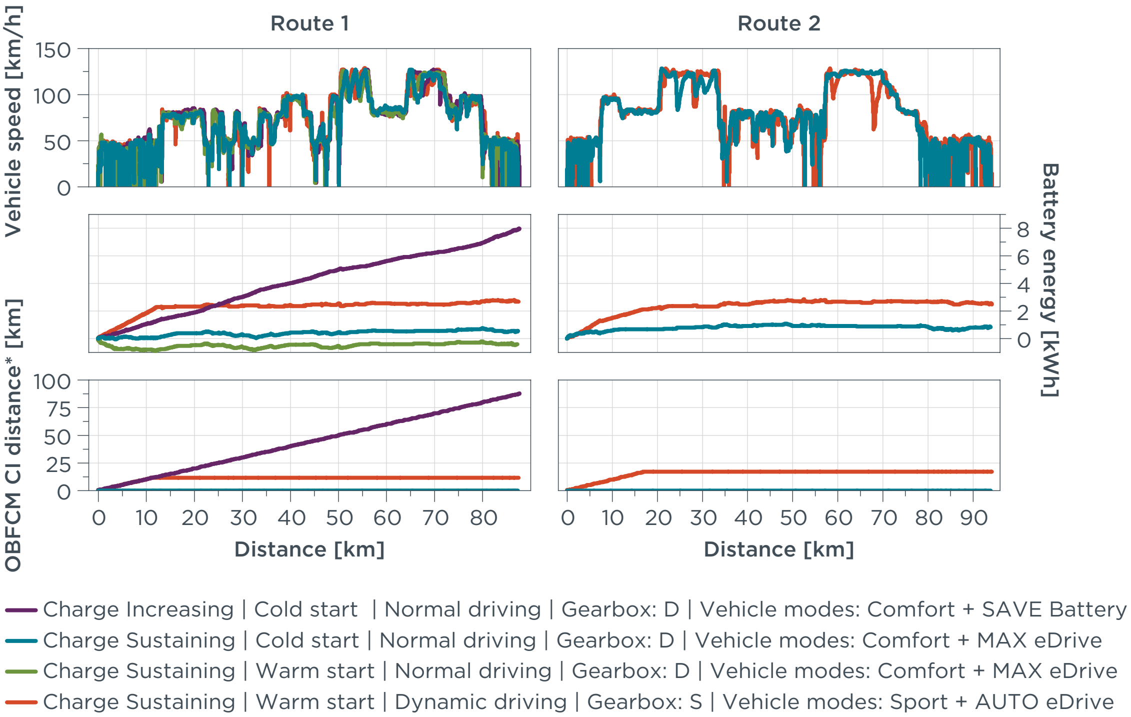


Figure 23. Effect of plug-in hybrid modes and vehicle settings on battery energy charge level during real-world driving tests. When the vehicle is operated in sports mode, it activates CO_2 intensive charge-increasing operation even though the user did not select actively the charge-increasing plug-in hybrid mode.
*On-board fuel and eneryg consumption monitoring signal of distance in charge-increasing mode.

It was therefore unexpected that the vehicle initially switched to charge-increasing mode when operated in sports mode, as Figure 23 shows. While the battery energy level shown in the center graph increases only slightly during the charge-sustaining tests in normal mode (blue and green line), the tests in sports mode (red line) show a fast battery charge during approximately the first 12 km on Route 1 and first 17 km on Route 2. This switch in operating mode is also reflected in the OBFCM signal representing the distance driven in charge-increasing mode, depicted in the bottom graph. Similar behavior is observed on both Routes 1 and 2 and is therefore considered repeatable.

An example of a more detailed analysis of this behavior is shown in Figure 24 for the warm-start tests on real-world Route 2.

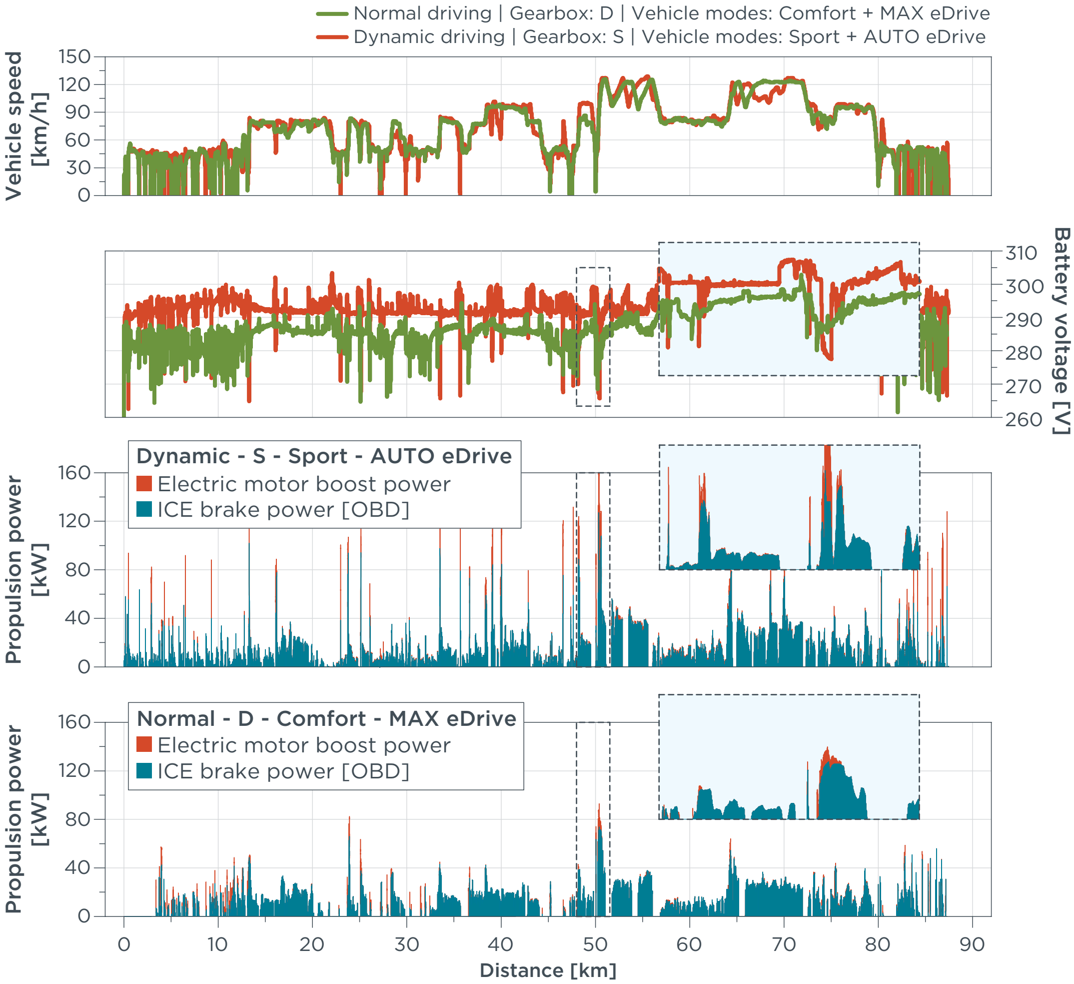


Figure 24. Effect of vehicle settings on the nonload voltage level setpoint of the high-voltage battery during real-world driving, starting with a depleted battery. For sports settings (gearbox in mode S and vehicle in sports mode), the battery voltage is increased to a nonload voltage of 295 V to support high propulsion power demands, while no charging is performed in normal mode (gearbox in mode D, vehicle in normal mode).

The first two graphs present the vehicle speed profile and the recorded battery voltage. The two lower graphs show the internal combustion engine power (blue) and the additional boost power from the electric motors (orange) separately for the test in sports mode and in normal mode.

The analysis reveals that the reason for this operating strategy is likely to be found in a battery power allowance for impetuous accelerations. When using sports mode, the vehicle charges the HV battery at test start using the electric motor as generator until the nonload voltage has reached approximately 295 V (orange line), while it remains at a 5 V–15 V lower level in normal mode (green line). Shown in the magnified details, the HV battery can, as a result, deliver higher peak power for extended periods, allowing 80 kW of electrical boost while staying within the allowed battery voltage range.

The energy charged to the battery during the charge-increasing operation is about 2.1 kWh, which requires burning about 0.8 liters gasoline E10, resulting in 1.83 kg CO_2, taking into account the combustion engine charging efficiency of 30% determined in Section 4.4.1. However, similar to the driver-selectable charge-increasing mode, the observed vehicle and gearbox mode related charge-increasing operation is not assessed during type approval when determining CO_2 emissions.

4.5. HOW OBFCM DATA CAN BE USED TO ASSESS PLUG-IN HYBRID REAL WORLD USAGE

On the test vehicle, all retrievable instantaneous and lifetime OBD signals related to on-board fuel and energy consumption monitoring were recorded and analyzed. For the subset of chassis dyno test data, we compared the values measured by the OBFCM with our independently measured on-board data. While recording distance and fuel consumption data for the different PHEV modes by the OBFCM device is required by the type-approval regulation, recording charge-depleting mode specific energy consumption is not. Nevertheless, those parameters were retrievable on the tested vehicle as well. The results of this comparison are shown in Table 10.

Table 10. Comparison of OBFCM and independently measured parameters. The OBFCM values show the difference in lifetime values between end and start of the chassis dyno test campaign.

Parameter	Symbol	Unit	Mandatory?	Measured	OBFCM
Total distance	d_{tot}	km	Yes	477.0	480.1
Distance in CD mode—engine on	$d_{CD,Eng\ on}$	km	Yes	11.4	11.3
Distance in CD mode—engine off	$d_{CD,Eng\ off}$	km	Yes	111.4	115.6
Distance in CI mode	d_{CI}	km	Yes	46.2	70.9
Distance in CS mode (calculated)	—	km	—	308.1	282.3
Distance in CI + CS mode (calculated)	—	km	—	354.2	353.2
Fuel consumed—total	$fuel_{tot}$	liter	Yes	30.6	32.7
Fuel consumed—CD mode	$fuel_{CD}$	liter	Yes	1.2	1.2
Fuel consumed—CI mode	$fuel_{CI}$	liter	Yes	4.9	7.9
Fuel consumed—CS mode (calculated)	—	liter	—	24.6	23.5
Fuel consumed—CS + CI mode (calculated)	—	liter	—	29.4	31.4
Grid energy—total	—	kWh	Yes	24.5	0
Grid energy—CD engine off	$egy_{CD,Eng\ off}$	kWh	No	—	28.5
Grid energy—CD engine on	$egy_{CD,Eng\ on}$	kWh	No	—	0.5
Total energy consumed—CD (calculated)	egy_{tot}	kWh	No	29.2	29.0

The OBFCM distance values match well our measurement results, except for the distance in charge-increasing mode. This is because we only considered distances that were driven in user-selectable charge-increasing mode, as defined in the OBD standard (SAE International, 2019), while the BMW also activates partial charge-increasing operation when sports mode is selected, as described in Section 4.4.2. For the same reason, the OBFCM fuel volume consumed in CI mode differs notably from the measured value, but when added to the CS fuel consumption, the OBFCM and measured value are in better agreement. A detailed analysis of the OBFCM data accuracy and the unexpectedly high deviation in total fuel-consumption is not part of this report but will be presented in a future study.

There is an abnormality in the grid energy value. Even though three charge-depleting test sequences were performed with interjacent recharging from the grid, the total lifetime grid energy recorded by the OBFCM on chassis dyno is 0 kWh. The recording worked properly during normal use of the vehicle on public type-2 chargers performed before and after the chassis dyno test program. Therefore, the reason for this erroneous behavior must either be the activated chassis dyno mode during laboratory testing or the use of the original 230 V charging cable supplied with the vehicle, which are the only differences between the public and test center charging. Fortunately, the recording of the not-mandatory grid energy values in CD mode worked as intended and could be used for the analysis.

The OBFCM grid energy is defined as the net energy charged to the battery when connected to the mains, excluding any charging losses. Furthermore, the grid energy consumed during charge-depleting operation is the net energy consumed and excludes any nongrid energy, that is, energy generated by recuperation or by using the electric motor in generator mode (SAE International, 2019). A comparison of the net battery energy change measured with the HVBM at 24.5 kWh and the energy recorded by the OBFCM in CD mode of 29.0 kWh reveals a large difference of 4.5 kWh or 18%. We first assumed that the OBFCM grid energy falsely included the charging losses, but an analysis of each charge-depleting test separately showed that the OBFCM value of the test vehicle represents well the total electric energy consumed from the battery during charge-depleting mode, that is, including the nongrid energy, which is 29.2 kWh, according to our measurement, and thereby almost identical to the 29.0 kWh indicated by the OBFCM.

We then used the OBFCM data to calculate parameters that characterize the real-world usage of a PHEV and that can be compared to type-approval values to determine the real-world gap; the equations and results are shown in Table 11. It should be noted that the goal of the analysis presented here is to demonstrate the methodology but not to determine representative values for the usage of PHEVs in general.

During the analysis, we made the following observations:

- Calculating the utility factor based on the charge depleting and total distance yield the same result as calculating it based on the fuel consumption according to Equation 5. It can be shown that both equations are the same.
- The distance share in CD mode and thereby the UF can in principle be increased when using the electric motor more for boosting rather than for pure electric driving.
- Furthermore, according to the OBD requirements, the vehicle is considered being in charge-depleting mode as long as electric energy is consumed with the intent to deplete the battery. It is irrelevant if this energy stems from charging by the engine in charge-increasing mode or when connected to the mains (SAE International, 2019). Therefore, using the high CO_2 emitting CI mode increases the range in charge-depleting mode.
- A UF based on distance alone is therefore not a sufficient metric to assess how PHEVs are used. It should always be evaluated together with the total fuel consumption, the fuel consumption in the different modes, and the distance share in the different modes.

Table 11. Calculation of parameters characterizing the PHEV real-world usage based on OBFCM data.

Equivalent type-approval parameter	Calculation based on OBFCM parameters	Unit	Measured	OBFCM
Weighted, combined fuel consumption	$\frac{fuel_{tot}}{d_{tot}}$	L/100 km	6.42	6.80
Weighted, CD fuel consumption	$\frac{fuel_{CD}}{d_{CD,Eng\ on} + d_{CD,Eng\ off}}$	L/100 km	0.97	0.95
Charge-sustaining fuel consumption	$\frac{fuel_{tot} - fuel_{CD}}{d_{tot} - d_{CD,Eng\ on} - d_{CD,Eng\ off}}$	L/100 km	8.31	8.91
Charge-increasing fuel consumption	$\frac{fuel_{CI}}{d_{CI}}$	L/100 km	10.5	11.2
UF-weighted energy consumption[b]	$\frac{egy_{tot}}{d_{tot}}$	Wh/km	61.1[a]	60.4
Weighted energy consumption in CD mode, engine off (≈ electric energy consumption[b,c]**)**	$\frac{egy_{tot}}{d_{CD,Eng\ off}}$	Wh/km	261.6	250.9
Distance share in CD mode (= UF)	$\frac{d_{CD,Eng\ on} + d_{CD,Eng\ off}}{d_{tot}}$	%	25.7	26.4
Distance share in CD mode, engine off	$\frac{d_{CD,Eng\ off}}{d_{tot}}$	%	23.4	24.1
Distance share in CI mode	$\frac{d_{CI}}{d_{tot}}$	%	9.7	14.8

Notes: In the calculations, fuel = fuel volume, d = distance, egy = energy, Eng = engine, CI = charge increasing, CD = charge depleting, and tot = total.
[a] *Using the total battery energy consumed for comparability, as explained above.*
[b] *Not comparable to type-approval value; see explanation below.*
[c] *Only valid if* $d_{CD,Eng\ on} << d_{CD,Eng\ off}$*; see explanation below.*

As explained before, the OBFCM grid energy does not, by definition, include the charging losses. The type-approval weighted energy consumption ($EC_{AC,weighted}$) does, however, include these losses. Therefore, without knowledge about the charging efficiency, the gap between type-approval and real-world electric energy consumption cannot be determined from this parameter.

Another interesting parameter for assessing the real-world operation of PHEVs would be the electric energy consumption (EC), that is, the electric energy consumption relative to the equivalent all-electric range (EAER). During type approval, the EAER can be determined from the ratio of CD and CS CO_2 emissions because both relate to the same drive cycle and test conditions. An approach to determine real-world EAER ($EAER_{real\text{-}world}$) over a vehicles' lifetime from the OBFCM values is suggested as follows, with FC_{CS} as the average fuel consumption in CS and CI mode per km; $FC_{CD,Engine\ on}$ as the fuel consumption in g/km while the vehicle is in charge-depleting mode with the engine running; $d_{CD,Engine\ off}$ as the distance in CD mode with the engine off; and $d_{CD,Engine\ on}$ as the distance in CD mode with the engine running:

$$EAER_{real\text{-}world} = d_{CD,Engine\ off} + \frac{FC_{CS} - FC_{CD,Engine\ on}}{FC_{CS}} \times d_{CD,Engine\ on} \qquad \textbf{\textit{Equation 9}}$$

This approach is only valid if engine operation during charge-depleting mode occurs also under average conditions. For the tests we performed on chassis dyno, this mode was only observed at -5 °C, resulting in higher fuel consumption than the average value in charge-sustaining mode. This would lead to an underestimation of the EAER. To understand if this approach could be used to determine the equivalent all-electric driven distance during real-world operation, more test data where the engine is active in charge-depleting mode would be needed. Alternatively, if the distance in CD mode with the engine off is substantially higher than the distance in the same mode with the engine running, EC could be estimated by dividing the consumed grid energy by the distance in CD mode with the engine off.

5. CONCLUSIONS AND RECOMMENDATIONS

Recent studies demonstrate that plug-in hybrid electric vehicles show a large gap between real-world and type-approval CO_2 emissions (Plötz et al., 2020). The gap is to a great extent attributed to a lower charging frequency by vehicle owners than anticipated in the type-approval regulation. However, the use of heating and air-conditioning in combination with high and low ambient temperatures also contributes to a lower share of distance driven using electricity.

To assess these effects in detail, we tested a model year 2020 BMW X1 xDrive25e PHEV both at 23 °C with deactivated air-conditioning and at -5 °C and 35 °C while climatizing the cabin to 22 °C. Furthermore, the vehicle was tested in different plug-in hybrid operating modes to evaluate their effect on CO_2 emissions.

This section provides a summary of our findings and related recommendations to ensure that type-approval CO_2 emissions of PHEVs better reflect the emissions during real-world operation.

Consider the effect of ambient temperature and air-conditioning on CO_2 emissions, electric ranges, and energy consumption during type approval and, as short-term solution, revise the utility factor.

When cooling or heating the passenger compartment, less electric energy is available for propulsion. In combination with a higher driving resistance at -5 °C, the distance driven attributed to the use of grid energy is almost halved compared to the test under type-approval conditions. At 35 °C, the effect is less pronounced with a range reduction of 11%. Even more severe is the effect on the all-electric range or the range driven until the engine consumes fuel for the first time. At 23 °C and 35 °C, the vehicle operates free of CO_2 and pollutant emissions for the first 44 km and 41 km, respectively, until the battery is depleted, whereas at -5 °C, the vehicle applies a different operating strategy and uses the combustion engine right from test start. The all-electric range at -5 °C is therefore 0 km.

While the charge-depleting CO_2 emissions at 23 °C are very low at 2 g/km, the operating strategy at -5°C causes additional CO_2 emissions of 92 g/km, as shown in Figure 25. Together with a 30% increase in charge-sustaining emissions, the final CO_2 value increases by 186% at -5 °C compared to 23 °C. At 35 °C, the weighted, combined CO_2 emissions increase by 34%. The substantially higher increase at -5 °C is attributed to the higher energy consumption of the heating system at this temperature and to a larger extent to the early usage of the combustion engine instead of pure electric driving.

The increase in CO_2 emissions at 35 °C could in principle be compensated for by charging more frequently. If the vehicle is driven about 82% of its distance in charge-depleting mode, the resulting weighted, combined CO_2 emissions would be the same as those during operation at 23 °C, where 73% of the distance is considered to be driven in charge-depleting mode. At -5 °C, the weighted, combined CO_2 emissions would still be 2.2 times higher than the type-approval value even if operated entirely in charge-depleting mode.

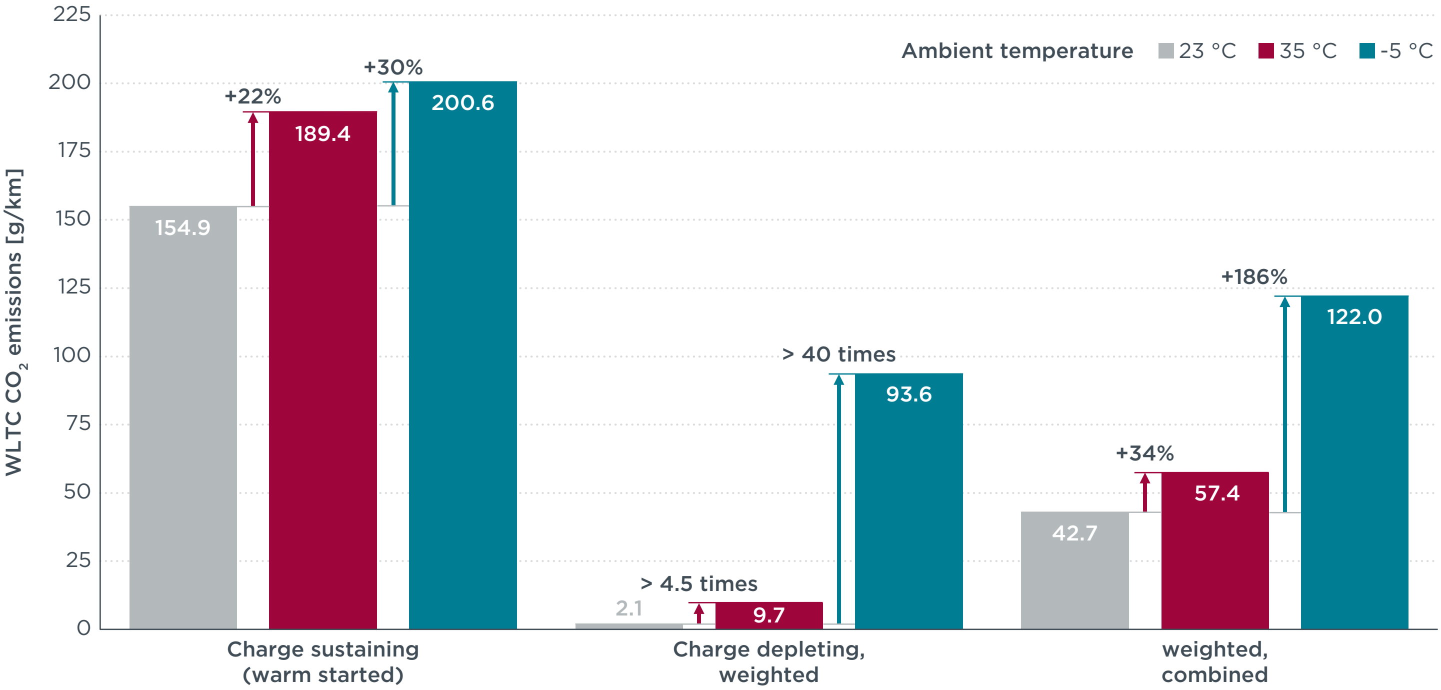


Figure 25. Effect of ambient temperature and use of air-conditioning on WLTC CO_2 emissions. The data shown uses the second WLTC of the charge-depleting sequence as transition cycle for all temperatures, and the utility factor is therefore 0.73.

A change in ambient temperature does not only increase the CO_2 emissions due to higher energy demand but also due to changes in the hybrid system operating strategy. Therefore, to correctly take PHEVs CO_2 emissions into account in emission inventories for taxation and incentive schemes as well as for consumer information, we recommend that type approval includes testing at low and high ambient temperatures with active heating and air-conditioning. Furthermore, we recommend that temperature-dependent changes in operating strategy affecting the electric range, energy consumption, or CO_2 emissions shall be reported to and assessed by the granting authority during emission type approval.

As a short-term solution, we recommend adapting the utility factor to better reflect real-world usage. In a first step, we suggest using an estimated utility factor derived from empirical studies, as presented by Plötz (2021). Based on OBFCM real-world data collected by the European Commission, starting in April 2022, the utility factor can then be continuously updated.

Prohibit engine charge-increasing, plug-in hybrid operating modes and determine type-approval CO_2 emissions in vehicle settings producing the highest emissions.

The vehicle was further tested in a user-selectable hybrid mode described by BMW to maintain the battery charge at its current level and to recharge it through recuperation only. However, in this mode the vehicle also charges the battery until full using the engine to power the electric motor as a generator. Due to the low efficiency of generating electric energy from fuel, which we calculated to be about 30%, the WLTC CO_2 emissions in this mode are 60% higher than in charge-sustaining mode, as shown on the left side of Figure 26. Compared to using EU grid energy, 2.5 to 2.8 times more CO_2 is emitted when using the charge-increasing mode to charge the battery (right side of Figure 26).

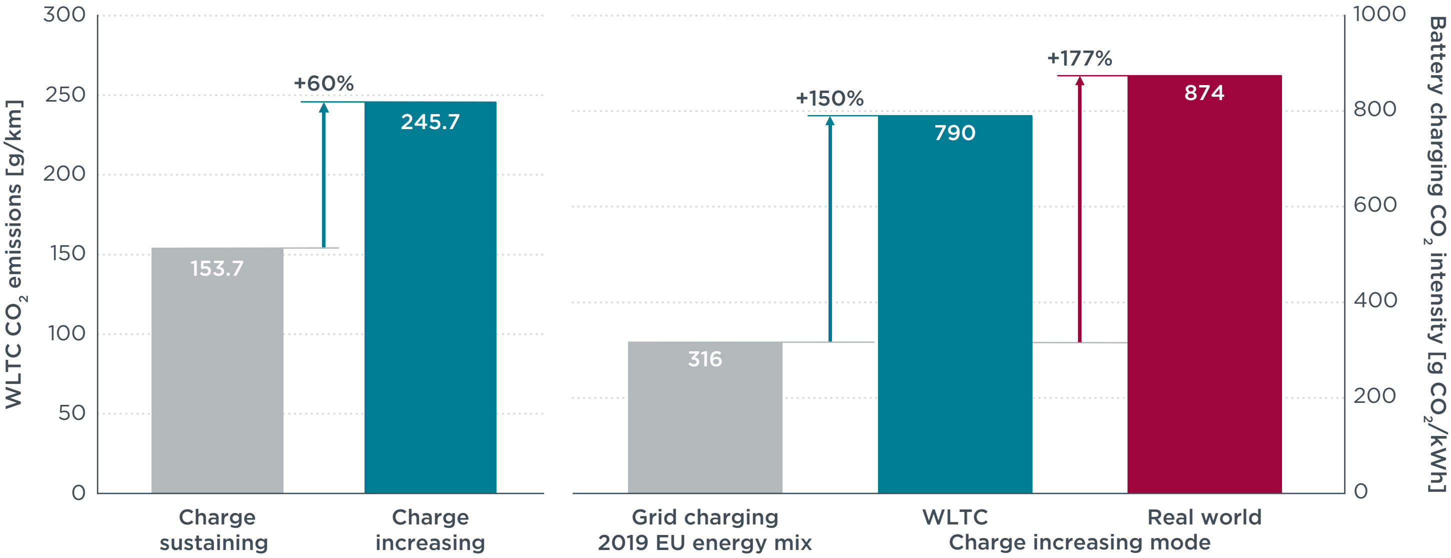


Figure 26. Left: WLTC CO_2 emissions increase by 60% when using the user-selectable charge-increasing mode. Right: The CO_2 intensity of charging the battery using the charge-increasing mode increases by about 150%–180% compared to using energy from the grid (EU mix 2019). The grid energy is corrected for the charging losses of the on-board charger.

Engine charge-increasing operation was also activated in charge-sustaining mode for 12 to 17 km after test start when sports mode settings for gearbox and vehicle were selected. This also resulted in extra CO_2 emissions, likely with the goal to allow for higher vehicle dynamics.

Recharging using the vehicle's engine may frequently occur for company cars. These vehicles often come with a with fuel card that allows the user to refuel free of charge while recharging typically happens at home at the user's expense or requires complex reimbursement by the employer. It is therefore reasonable to assume that company car PHEVs are regularly charged through the charge-increasing mode, especially in areas where zero-emission zones require pure electric driving, instead of recharging them by plugging into the electricity grid. As a result, instead of reducing CO_2 emission levels, the vehicles would likely have higher real-world CO_2 emissions than a comparable ICE-only vehicle.

While it seems reasonable to implement a mode to maintain the current battery charge level with the intent to save energy for entering zero-emissions zones, we recommend prohibiting modes that increase the battery charge level by using the combustion engine.

Furthermore, to yield more real-world representative plug-in hybrid CO_2 type emission values, we suggest that the charge-sustaining type-approval test should be performed with user-selectable vehicle and gearbox settings producing the highest CO_2 emissions.

Plug-in hybrid vehicles should have powerful on-board chargers and should be delivered with a charging cable for public chargers.

To prevent consumers from using a charge-increasing mode and encourage them to drive as often as possible in charge-depleting mode, long real-world electric range and short recharge duration are key. However, when recharging with the supplied 230 V Schuko plug cable, recharging of the battery takes at least 5 hours. In the best-case scenario, that is, plugging into a public charger or a wall box, recharging still takes about 3 hours due to a maximum on-board charger power of only 3.7 kW. And the latter is only possible if a type-2 charging cable is purchased by the owner—currently priced at about 290 euros.

We recommend that new plug-in hybrid vehicles have more powerful on-board chargers allowing a full recharge in less than 1 hour and are delivered with a charging cable for public charging stations.

Define limits for electric energy consumption.
A comparison of the consumer information for the tested plug-in hybrid vehicle with the same vehicle model powered by a gasoline engine revealed a 160 kg or 10% increase in mass attributed to the additional electric power train components. The high mass not only adversely affects the fuel consumption in charge-sustaining operation, it also reduces the electric range and increases electric energy consumption. As shown by Henning et al. (2019), weight reduction has a considerable potential to reduce electric energy consumption. For the same target electric range, a smaller battery would be required in turn, reducing the resource intensity and the mass even further.

To limit the resource and energy intensity of electrified vehicles and to encourage manufacturers to focus on lightweight design, we recommend introducing mass-independent electric energy consumption limits. Similar to the CO_2 targets, this would likely also have a positive effect on the overall efficiency of electric power trains, including the on-board charger and battery.

Align definitions of OBFCM and type-approval parameters and analyze OBFCM data regarding cause of the PHEV real-world CO_2 gap.
Our analysis showed that data from the on-board fuel and energy consumption monitoring device can, in principle, be used to assess key characteristics of PHEV usage. However, it seemed that not all parameters were correctly implemented on the test vehicle, and a closer analysis of the OBFCM parameter definitions revealed that the grid energy, determined by the OBFCM, is not directly comparable to the type-approval value as it excludes the charging losses. We therefore recommend requiring that the recharged grid energy excluding charging losses during type approval be recorded, using the measurement equipment already installed on the vehicle for the charge-depleting test. This will also allow type-approval authorities to calculate the efficiency of the on-board charger, which we recommend reporting in the certificate of conformity or transparency list as well, a request also made by the German automobile association ADAC (2020).

Furthermore, we recommend OBFCM data for PHEVs to not only be analyzed per manufacturer but also per model or interpolation family to gain further knowledge regarding what parameters affect the gap between real-world and type-approval emissions.

REFERENCES

ADAC (Allgemeiner Deutscher Automobil-Club). (2020, July 22). *Kosten für E-Autos: Ladeverluste nicht vergessen; ADAC ermittelt bis zu 25 Prozent mehr an realen Stromkosten* [Cost for e-cars: Don't forget the charging losses; ADAC determines up to 25 precent more in real electricity costs] [Press release]. Retrieved from https://presse.adac.de/meldungen/adac-ev/technik/ladeverlust.html

BMW Group. (2019). *Nachhaltige Fahrfreude mit zwei Motoren und intelligentem Allradantrieb: Der neue BMW X1 xDrive25e* [Sustainable driving pleasure with two engines and intelligent all-wheel drive: The new BMW X1 xDrive 25e]. Retrieved from https://www.press.bmwgroup.com/deutschland/article/attachment/T0300928DE/438895

BMW Group. (2020a). *Kompakte BMW X Modelle mit Plug-in-Hybrid-Antrieb: Der neue BMW X1 xDrive25e kommt, der neue BMW X2 xDrive25e folgt* [Compact BMW X models with plug-in hybrid drive: The new BMW X1 xDrive 25e is coming, followed by the new BMW X2 xDrive25e]. Retrieved from https://www.press.bmwgroup.com/deutschland/article/attachment/T0303969DE/445475

BMW Group. (2020b). *Technische Daten—BMW X1—X1 xDrive25e, gültig ab 01/2020* [Technical data BMW X1 xDrive25e, valid from 01/2020]. Retrieved from https://www.press.bmwgroup.com/deutschland/article/attachment/T0314292DE/457887

BMW Group. (2020c). *Transparency list for interpolation family IP_EU_F48_F39_XB2131M0_AA_1* [Database].

BMW Group. (2021a). Der BMW X1—Preisliste für Deutschland—Juli 2020 [The BMW X1—price list for Germany—July 2020]. Retrieved from https://www.bmw.de/content/dam/bmw/marketDE/bmw_de/new-vehicles/pdf/Preisliste_F48_II_28_05.pdf.asset.1590685388188.pdf

BMW Group (2021b, March 10). *BMW Ladekabel (Mode 3, 1-phasig)* [BMW charging cable (mode 3, phase-1)]. Retrieved from https://shop.bmw.de/bmw-de/de_DE/p/original-bmw-zubehoer/bmw-i/ladekabel/ladekabel-mode3/PID_733662/

BMW Group. (2021c, March 12). *Standardladekabel/Mode 2 Ladekabel* [Standard charging cable/Mode 2 charging cable]. Retrieved from https://shop.bmw.de/bmw-de/de_DE/p/original-bmw-zubehoer/bmw-i/ladekabel/standardladekabel-mode-2-ladekabel/PID_668838/

EEA (European Environment Agency). (2020, December 8). *Greenhouse gas emission intensity of electricity generation* [Data visualization]. Retrieved from https://www.eea.europa.eu/ds_resolveuid/7e1d0edbc6b4488a89fb1686d8239858

European Commission. (2019a). *Commission Regulation (EU) 2017/1151 of 1 June 2017 supplementing Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Commission Regulation (EC) No 692/2008 (Consolidated version)*. Retrieved from EUR-Lex https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1553789751781&uri=CELEX:02017R1151-20190101

European Commission. (2019b). *Communication from the Commision to the European Parlament, the European Council, the Council, the European Economic and Social Committee and the Committee of the regions. The European Green Deal* (COM(2019)). Retrieved from EUR-Lex https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1596443911913&uri=CELEX:52019DC0640#document2

European Commission. (2019c). *Sustainable mobility—The European Green Deal*. https://doi.org/10.2775/0460

European Commission. (2021a). *Commission implementing regulation (EU) 2021/392 of 4 March 2021 on the monitoring and reporting of data relating to CO_2 emissions from passenger cars and light commercial vehicles pursuant to Regulation (EU) 2019/631 of the European Parliament and of the Council and repealing Commission Implementing Regulations (EU) No 1014/2010, (EU) No 293/2012, (EU) 2017/1152 and (EU) 2017/1153 (Text with EEA relevance).* Retrieved from EUR-Lex http://data.europa.eu/eli/reg_impl/2021/392/oj

European Commission. (2021b). *Transparency list*. Draft. Retrieved from https://circabc.europa.eu/ui/group/f4243c55-615c-4b70-a4c8-1254b5eebf61/library/0932f8c1-0fd2-435e-9732-83ed3f7038c3/details

Gerike, R., Hubrich, S., Ließke, F., Wittig, S., & Wittwer, R. (2020). *Sonderauswertung zum Forschungsprojekt „Mobilität in Städten – SrV 2018" Stadtgruppe: SrV-Städtepegel*. Technische Universität Dresden. Retrieved from https://tu-dresden.de/srv

Genovese, A., Ortenzi, F., & Villante, C. (2015). On the energy efficiency of quick DC vehicle battery charging. *World Electric Vehicle Journal*, *7*(4), 570–576. https://doi.org/10.3390/wevj7040570

GRPE (Working Party on Pollution and Energy). (2017, June). *Technical report on the development of Amendment 2 to global technical regulation No. 15 (Worldwide harmonized Light vehicles Test Procedures (WLTP)).* Economic Commission for Europe, Inland Transport Committee, World Forum for Harmonization of Vehicle Regulations, 172nd session. Retrieved from UN Economic Commission for Europe https://wiki.unece.org/download/attachments/54427738/GTR%2315_ECE-TRANS-WP29-2017-099e_Amd4.pdf?api=v2

Henning, F., Gauterin, F., Dollinger, A., & Burgert, T. (2019, April). *Leichtbau für die Elektromobilität—eine gewichtige Strategie? Auswirkung von Leichtbau auf den Energiebedarf eines Elektrofahrzeugs.* Presented at Forum Leichtbau (Lightweight Construction Forum), Hannover Messe 2019, Hannover, Germany. Retrieved from https://lightweight.vdma.org/documents/266675/33646023/ICT_Prof.%20F.%20Henning_1557835775879.pdf/7316ebb8-bf24-535c-af8b-3a937186d762

Mock, P., Tietge, U., Wappelhorst, S., Bieker, G., & Dornoff, J. (2021). *Market monitor: European passenger car registrations, January 2021*. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/market-monitor-eu-feb2021

Plötz, P. (2021). *Realistic test cycle utility factors for plug-in hybrid electric vehicles in Europe* (p. 16). Fraunhofer ISI. Retrieved from https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2021/BMU_Kurzpapier_UF_final.pdf

Plötz, P., Moll, C., Li, Y., Bieker, G., & Mock, P. (2020). *Real-world usage of plug-in hybrid electric vehicles: Fuel consumption, electric driving, and CO_2 emissions*. Retrieved from the International Council on Clean Transportation https://theicct.org/publications/phev-real-world-usage-sept2020

SAE International. (2019). J1979-DA, Digital Annex of E/E Diagnostic Test Modes (J1979DA_201905 J1979DA). Retrieved from https://www.sae.org/standards/content/j1979da_201905/

Zacharof, N., & Fontaras, G. (2016). *Review of in use factors affecting the fuel consumption and CO_2 emissions of passenger cars*. JRC Science for Policy Report, European Commission. https://doi.org/10.2790/140640