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Real-world driving, energy demand and emissions of electrified vehicles

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Abstract

Alternative vehicle drivetrain technologies as used in electric vehicles (EV) are expected to play a major role in future passenger car markets. Yet, there is a lack of knowledge on the benefits or drawbacks. The aim of this paper is to present energy consumption and emission data of a battery electric vehicle (BEV) and a plug-in hybrid electric vehicle (PHEV) taken from two measurement campaigns.
The BEV fleet is equipped with OBD data loggers, collecting information on the state of charge (SOC). Results for the chosen BEV show seasonal variations with an up to 60% higher energy demand in winter. Taking data on energy consumption at charging station, an average annual total energy demand of 19 kWh/100 km is computed. Well-to-tank NOx emissions per charging event are calculated based on hourly electricity mix data in Germany. Survey results of the BEV users show that there is a positive perception of EV, although only a minority is convinced that EV are suitable for daily use.
In the second measurement campaign, different EURO6 passenger cars are tested on a dynamometer at 23°C and 0°C. Results for a PHEV of the C segment show that exhaust emissions of air pollutants and greenhouse gases strongly depend on the vehicle`s operating strategy and ambient temperatures, influencing the electric range, the share of ICE use and the catalyst temperature notably. This in turn shows the importance of an appropriate design of PHEV.

Keywords: real world energy demand, electric vehicles, data loggers, well-to-tank emissions, exhaust emissions, dynamometer measurements

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1 Introduction

Electrified vehicles (EV) are seen as one instrument towards a mitigation of local air pollution and climate change (European Commission, 2011). However, it is yet not fully clear whether EV have these mitigation effects under real-world driving and charging conditions effectively (these being part of a number of studies, e.g. Fetene et al., 2015; Plötz et al., 2015; Ligterink et al., 2013). In Germany as of yet, user experiences with EV are still relatively rare and acceptance could pose a potential threshold towards an EV market uptake. Knowledge on driving and charging patterns, user acceptance, real-world energy consumption and well-to-tank/tank-to-wheel emissions of EV still has to be enhanced. For example, occurrences and amount of real-world exhaust emissions of PHEV in densely populated areas, which depend on driver behavior, driving patterns, operating strategies of the vehicle and ambient temperatures are still open questions.

The aim of this paper is to present real-world energy consumption and emission data of a BEV and a PHEV out of two measurement campaigns in Germany. In addition, user acceptance towards EV in Germany is analyzed.

The BEV measurement campaign is part of a project that aims for an electrification of commercial vehicle fleets in southern Germany. Over 40 BEV, mostly used for social services or as shared cars, have been equipped with OBD data loggers.

In order to assess the real-world emissions of a PHEV drivetrain, measurements of a C segment PHEV combining a gasoline internal combustion engine (ICE) with an E-motor in a parallel hybrid drivetrain have been undertaken, focusing on the analysis of exhaust emissions under different ambient conditions. Previous studies show that low ambient temperatures can lead to an increase of certain exhaust emissions of PHEV and hybrid electric vehicles (HEV) (Alvarez and Weilenmann 2012, Suarez-Bertoa and Astorga 2016). To analyze this effect for typical summer- and wintertime temperatures in Germany, the influence of different ambient temperatures at 0°C and 23°C are examined in terms of emissions of air pollutants and energy efficiency. Additionally, emissions during cold and hot start tests are compared.

Measurement devices and measured parameters differ, using on-road OBD data loggers and user questionnaires for the BEV campaign and chassis dynamometer OBD data and emission tests for the PHEV campaign. Therefore, methodology and results are presented separately for the two approaches.

2 BEV study: energy consumption and indirect emissions

2.1 Methodology

For the BEV campaign, over 40 vehicles have been equipped with OBD data loggers. Data includes hours of operation, state of charge as given to the driver ("user-SoC"), mileages driven, speed statistics and GPS information. Information on SoC changes and mileages driven was combined to derive the amount of energy used at traction battery and the amount of energy regenerated by decelerating or downhill driving. The logged user-SoC values (within the range of 0% to 100%) are, however, depending on the battery management system and operating strategies of the respective vehicle, and also on other external parameters such as ambient temperatures. In consequence, a logged user-SoC value of 100% can mean that the useable energy at traction battery is ranging from 22 kWh (maximum capacity) to e.g. 18 kWh. As an analysis of the range of usable capacity is not part of this campaign, the working hypothesis is that the maximum capacity is always available when the traction battery is fully charged. This in turn means that the derived energy consumption will represent a maximum.

For some vehicles, further data on the energy demand at charging station is available. On basis of that information, the total vehicle energy demand at the electricity grid is computable, as well as well-to-tank (WTT) emissions of nitrogen oxide (NOx). Several studies assessed air quality and climate effects of electric vehicles in combination with an electricity mix (JRC, 2014; Jungmeier et al, 2014). However, most of these studies are based on yearly average values. Now, in combination with hourly data of the German electricity mix, WTT NOx emissions due to charging can be computed much more accurately. Fossil sources, especially lignite and hard coal, were dominating the electricity production in Germany during winter 2014 with adverse effects on air quality and greenhouse gas emissions (Agora 2015).

In addition to the field data, users are asked via questionnaires for their attitudes towards BEV to gain insights on user acceptance and potential barriers for an EV market penetration.

2.2 Real-world energy demand

Results for one BEV of the B segment located in the southern black forest region show, as expected, that ambient temperatures have a significant influence on its energy consumption. In 2015, and under the above mentioned assumptions, the car had an annual average (maximum) energy demand of 17 kWh/100 km at traction battery, varying from 14 kWh/100 km in July to 23 kWh/100 km in January (Figure 1). The traction battery was fully charged in over 90% of the time with a SoC of $\geq$ 50% in 70% of the time, indicating that a) the electric range was sufficient in most cases and that b) the time needed for charging was no obstacle in the BEV's daily use. The car was used on a daily basis except on week-ends. 80% of the trips in 2015 had a length up to 80 km, 80 km being the range given at the beginning of a winter trip. Annual mileage in 2015 was about 13,000 km, which is comparable to the average annual mileage of that vehicle segment in Germany.

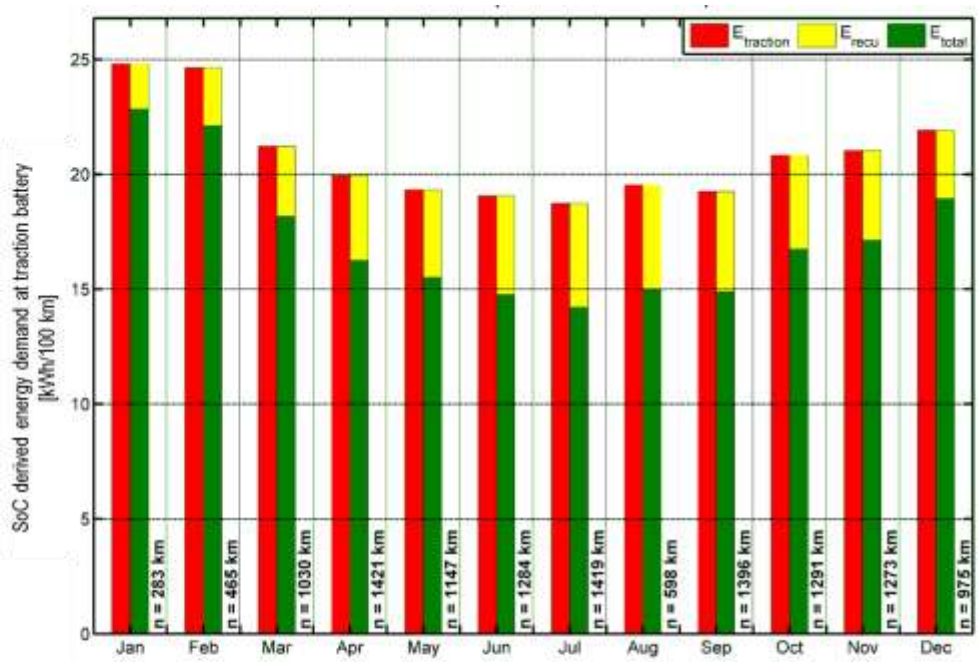

Figure 1: Maximum traction battery energy demand derived from user-SOC data (2015, B-Segment car, southern black forest region).

In addition, energy consumption data from the vehicle's charging station was available for the year 2015. The vehicle had been charged mostly at one work-based charging station and in some cases at home. In combination with its annual mileage, a total average energy demand of 19 kWh/100 km was computed. In comparison to the logged traction battery energy demand of 17 kWh/100 km, this represents an overall energy efficiency from charging station to traction battery of 90%.

The difference in energy demand at traction battery derived from user-SOC and in electricity charged was assessed for a number of other BEV of the same model by manually tracking electric meter readings of their charging stations over a 3 days period in September 2015 and January 2016 (Figure 2). All charging stations are provided by the same manufacturer with a type 2 connector and 22 kW charging power.

The analysis shows that there is a gap between energy demand read from the charging station meter on the one hand and energy loaded into the traction battery on the other hand varying from 72% to 96%. Reasons for this gap are energy demand during charging for auxiliaries such as heating or infotainment and power losses of the charging station.

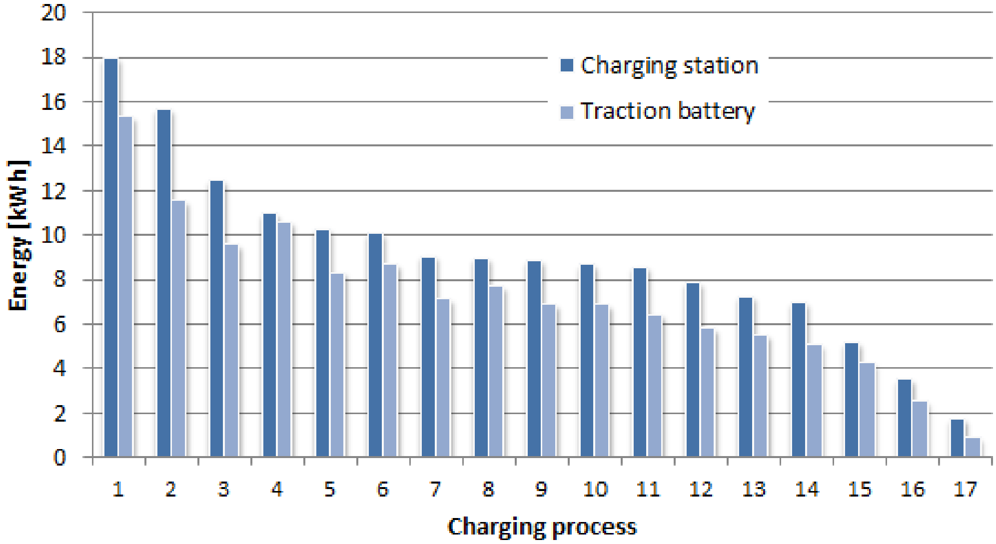

Figure 2: Energy demand: charging station vs. traction battery
(each pair of bars represents one charging process per individual vehicle)

2.3 Assessment of well-to-tank NOx emissions

In combination with the BEV`s charging processes and taking into account an overall energy efficiency of 90%, the respective NOx WTT emissions on basis of hourly data of the German electricity mix taken from (Agora 2015) are computed using emission factors (EF) from the database ecoinvent 3.2 (Ecoinvent 2016, Figure 3).

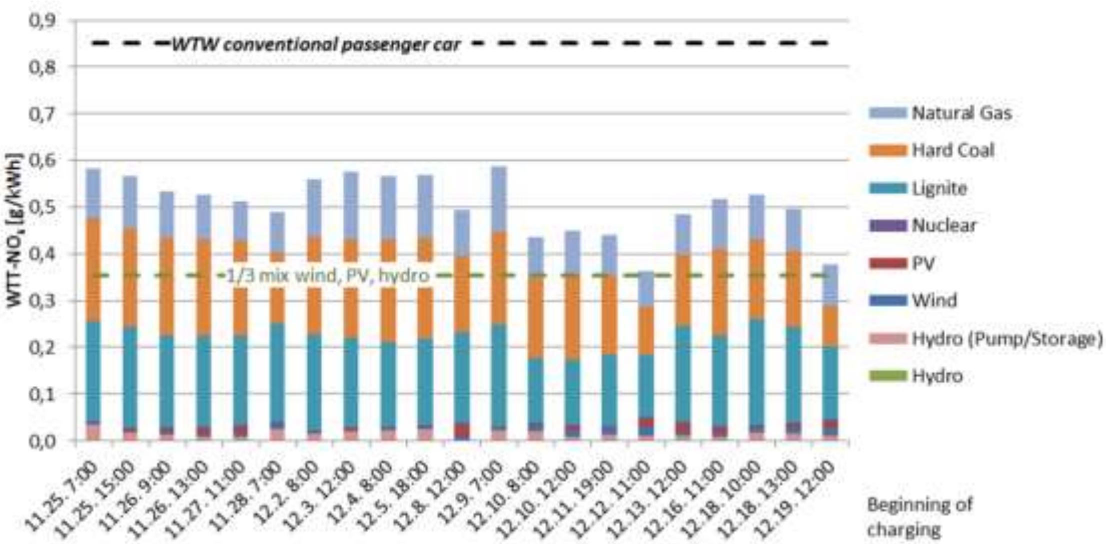

Figure 3: WTT NOx emissions due to charging events of one BEV (B segment) with the German electricity mix, November – December 2014.

Depending on the time of charging, 0.36 – 0.59 grams of NOx are emitted per kWh (0.07-0.13 g/km) when the average German electricity mix of that respective winter period is taken as a basis, due to the combustion of fossil energy sources, but also due to the production of renewable electricity installations. NOx well-to-wheel (WTW) emissions of conventional passenger cars of the German fleet were 0.85 g/kWh (0.36 g/km) on average in 2015 (tank-to-wheel - TTW – EF taken from HBEFA (2014), WTT EF taken from Ecoinvent (2016)). Compared to these figures, the WTT charging emissions are lower by up to 58%. Additionally, emissions from electricity production are emitted at higher heights and usually away from densely populated areas, such that health effects due to local direct emissions in urban areas as caused by conventional cars are supposed to be graver. Another important aspect is that EV users are more inclined to charge their vehicle with renewable electricity: 54% of the project's participants stated that they would use electricity from renewable sources, and 25% stated that they would use their own photovoltaics system to charge their BEV. When taking a 1/3 mix of renewable sources into account, WTT NOx emissions from electricity production can be constantly lowered to 0.35 g/kWh (0.07 g/km), 60% less than the WTW emissions of conventional cars.

2.5 Results for user attitudes and acceptance

Among all participants of the project, attitudes and experiences towards EV (90% BEV, 10% plug-in hybrid electric vehicles (PHEV) and range-extended electric vehicles (REEV)) are reported via two-stage questionnaires (first one before EV lease and the second one after ca. 1 year). .

So far, survey results indicate that EV technical benefits such as their pronounced acceleration are not commonly known (asked before having used the vehicle for the first time, Figure 4). 49% stated that acceleration would be the same or inferior to conventional vehicles, and around 10% of the users did not have any knowledge on any of the asked EV features.

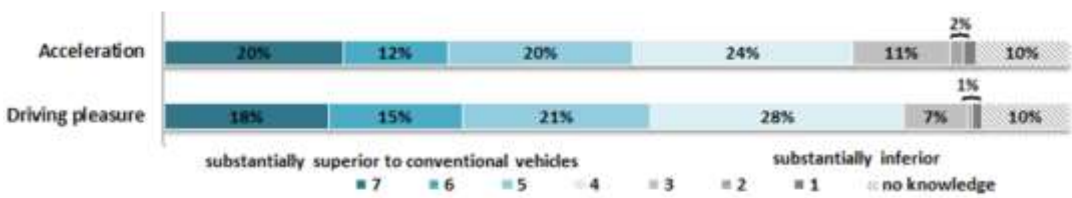

Figure 4: Survey results on technical aspects and handling:
Attitudes towards EV in comparison to conventional vehicles (198 users)

On the other hand, the image of EV concerning environmental benefits is positive (Figure 5). Around 70% of the users think that EV will be superior to conventional vehicles concerning the improvement of local air quality and the mitigation of noise as well as climate change. However, only 28% are convinced that an EV is suitable for their daily use.

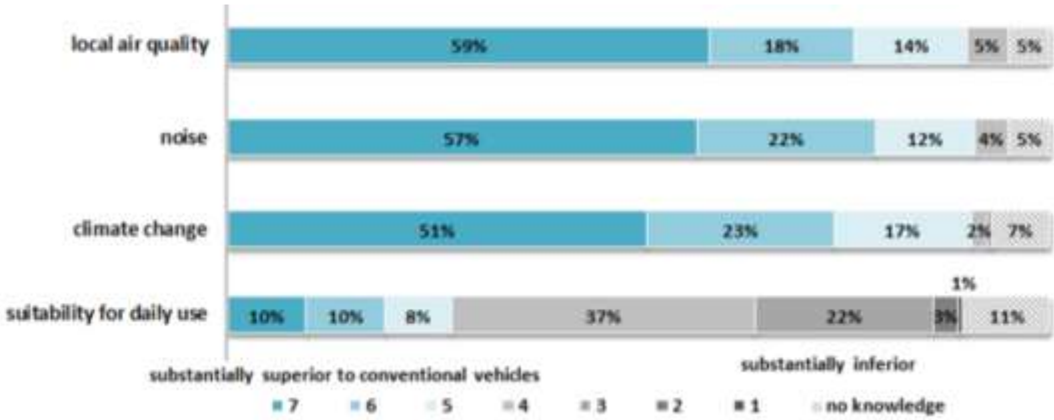

Figure 5: Survey results on perception and environmental effects:
attitudes towards EV in comparison to conventional vehicles (198 users)

3 PHEV study: energy consumption and direct emissions

3.1 Methodology and test set-up

A EURO6 compliant PHEV of the C segment has been tested at the four-engine all-wheel roller dynamometer in a climate chamber at the German Aerospace Center within the project. The vehicle combines a gasoline internal combustion engine (ICE) with an E-motor in a parallel hybrid drivetrain and has an engine power of 110 kW and an engine displacement of 1395 cm^3. Representing the fuel blend with the highest market share in Germany, a conventional gasoline fuel containing about 5 % ethanol (E5) is used for the tests. Several driving cycles have been analyzed to detect the influence of traffic situations (urban, suburban and motorway) on the vehicle emissions. The temperature influence on the exhaust emissions was studied running different tests including cold and hot starts both at 23 °C and 0 °C. 22 different exhaust gases were measured every second using a FTIR analyzer. To quantify the NOx emissions a separate CLD measuring instrument was also integrated in the exhaust measurement pipe. Absolute exhaust emissions were calculated using the volume flow data measured by a real-time ultrasonic exhaust gas flow meter at the end of the pipe. Apart from exhaust emissions, data of the On Board Diagnostics (OBD) has been logged in order to monitor various vehicle parameters like revolutions per minute of the combustion engine, catalyst temperature etc.

We present results of WLTC tests, as this cycle contains a representative share of urban, extra urban and highway driving situations and will be mandatory in the EU from 2017 on. The tests have been conducted in different modes and at different ambient temperatures (Table 1). The tests at 0°C have the same vehicle conditions as at 23°C. In order to evaluate the energy efficiency and the emissions as close to real life as possible, the tests have been performed with air condition running and without any other changes like in tire pressure etc. Cold starts are assumed to take place after vehicle charging in the morning and are driven with a charge depleting driving mode (CD mode). In addition to the CD mode tests, the results for the tests with charge sustaining (CS) mode are presented. These tests are supposed to represent the situation where the electric range of the vehicle is exceeded and the driver uses the car as a common gasoline hybrid vehicle. Although the vehicle recuperates the braking energy also in this mode, the electric driving share in this case is negligible.

Table 1: Overview of test conditions of the presented WLTC tests

Test	Temperature	Driving Mode	Starting condition
WLTC-1-0°	0 °C	CD	cold
WLTC-2-0°	0 °C	CS	hot
WLTC-1a-23°	23 °C	CD	cold
WLTC-1b-23	23 °C	hybrid[1]	cold
WLTC-2-23°	23 °C	CD / CS	hot
WLTC-3-23°	23 °C	CS	hot

[1] In the hybrid mode, the vehicle operates both in the electric and ICE mode according to an internal operation strategy.

3.2 Results for driving range

The WLTC driving cycle has different dynamic speed intervals which represent the driving situation in urban and non-urban environments and on highways. The measured speed and acceleration curves for this driving cycle are equal within a defined tolerance range (Figure 6). The urban part of the cycle is characterized by low speeds and idle periods. The highway section with speeds higher than 100 km/h is less dynamic, but due to the high speed the ICE motor is used also in the all-electric driving modes (Figure 8).

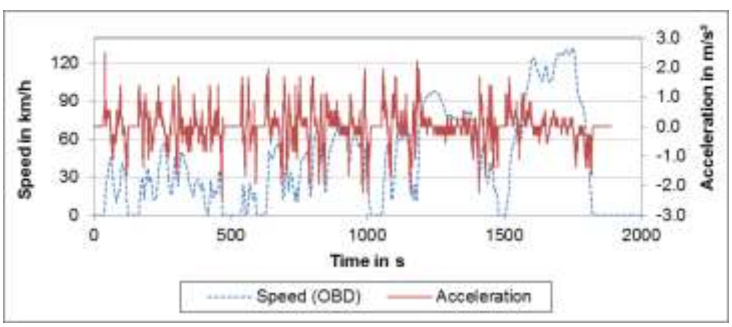

Figure 6: Measured acceleration and speed for the WLTC test

The energy consumption of the tested PHEV in the CD mode changes notable with lower temperatures (Figure 7, upper part). The settings of the air condition are identical for both ambient temperatures with a passenger compartment temperature of 23°C and the blower controls set on automatic mode. In the 23°C test, WLTC test in the CD mode has to be performed twice as the battery has not been discharged after the first WLTC test.

In contrast to this, the 0°C test revealed that the battery is discharged faster and reaches the status of constantly low SOC at the end of the first WLTC. Furthermore, the battery lost about 2.4 percentage points SOC during a standstill time of 220 s before the cold start WLTC and 4 percentage points SOC during the 20 minutes break between the two WLTC test drives at 0°C (see Figure 7). A similar, but much lower discharging is observed between the tests at 23°C ambient temperature. Assuming a linear decrease of SOC in this range, the energy loss per second during the break time between the tests at 0°C was lower than the loss before the test at the same ambient temperature. This relatively lower loss between the tests can be explained by the fact that after the first cycle, the vehicle interior was already warmed by the air conditioning for 30 minutes. We assume that the energy lost before the test and during the break was mainly used for air conditioning (heating). If the same amount of power would be used for heating during the driving as in stand still, the loss for one WLTC cycle would be between 8 to 19 percentage points. If about 19 percentage points SOC are subtracted for heating, this would still leave a difference of 17 to 7 percentage points to the SOC delta of the cold start WLTC at 23°C. This indicates an increased power loss of the battery at lower temperatures.
The recuperation of braking energy is visible in an increase of SOC and is particularly high when decelerating at the end of the highway part at the end of each WLTC.

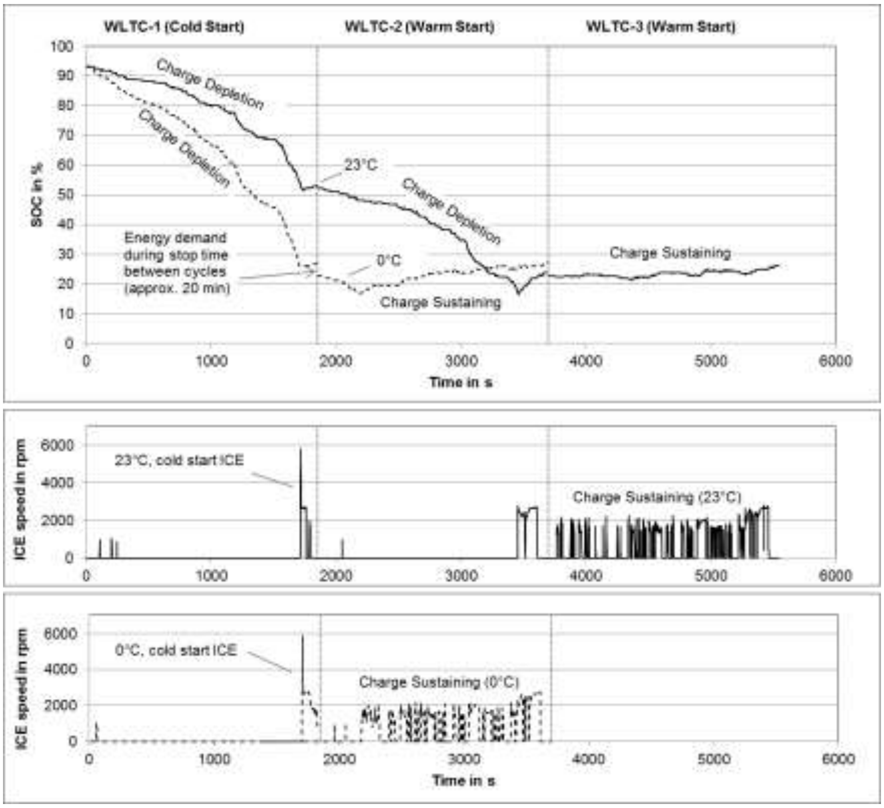

Figure 7: Development of the SOC during the WLTC at different temperatures (top), ICE speed vs. time (bottom)

3.3 Results for exhaust emissions

Although the cold start tests have been driven in the CD mode, none of the WLTC could be driven purely electric, as the ICE started automatically during the highway section at a speed higher than 125 km/h due to the implemented operation strategy of the tested PHEV. This behavior could be observed for an ambient temperature of 23°C as well as for 0°C and is shown by the curve of the ICE speed vs. time in Figure 7 (bottom). The start of the ICE leads to direct emissions from the fuel combustion and shows peaks for CO and NO_x emissions, as the catalyst has not reached its optimal operating temperature yet (Figure 8). For both tests, higher emissions could be observed at 0°C.

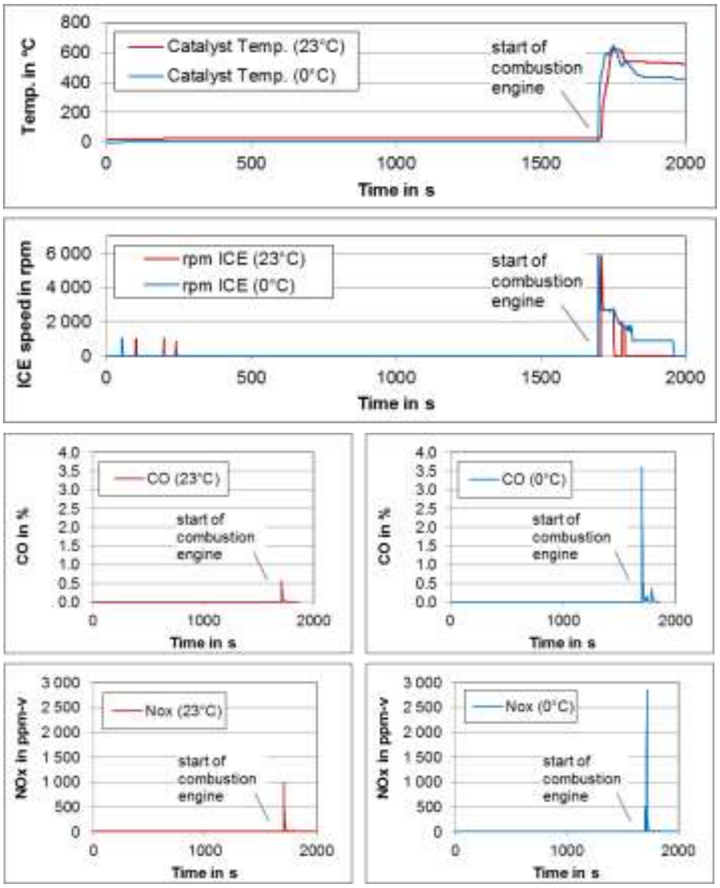

Figure 8: Cold start WLTC test at 0°C and 23°C in charge depletion mode (WLTC-1-0° and WLTC-1a-23°)

In order to compare the cold start in different modes, an additional cold start test at 23°C has been carried out in the hybrid mode. In this driving mode, the vehicle software alternates between the electric and ICE drive or combines both of them following an internal operation strategy. As the ICE is only used in specific situations during the test, the catalyst temperature reaches its optimum only in late stage of the cycle (Figure 9). This leads to several CO emission peaks during the test every time the ICE is started. These peaks completely disappear when the catalyst runs in optimal conditions. As the catalyst is not preheated during electric drive time (see Figure 8, top) the disadvantageous effect of an insufficient catalyst temperature can be assumed to be more important for the hybrid mode in lower ambient temperatures.

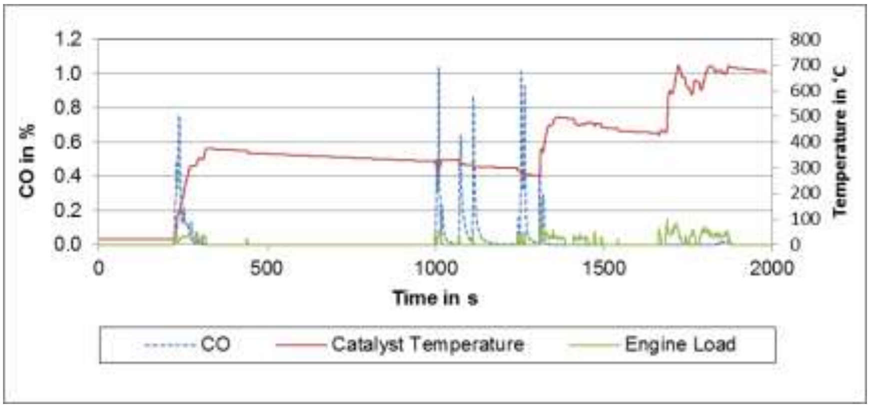

Figure 9: Cold start WLTC test at 23°C in hybrid mode

For the evaluation of absolute exhaust emissions, the volume flow rate is correlated to the relative concentration of exhaust gases. In order to assess the potential emissions of the PHEV in cases where the battery is discharged and the vehicle operates as gasoline vehicle, hot start WLTC tests have been performed as both 0°C and 23°C after the PHEV reached the maximum electric mileage and the battery showed a constant low SOC. In this case, the vehicle operation strategy switches to the CS mode, but the remaining and recuperated battery energy is still used at low speeds in the urban part of the WLTC. The hydrocarbon HC and CO emissions show higher concentrations in the comparatively dynamic urban part of the WLTC (Figure 10). The CO_2 emissions are higher at high motor loads during the highway part as expected. The NO_2 and especially the NO emissions are highest when the acceleration of the driving cycle is most intensive. What is most notable is that the emissions of all exhaust gas emissions are significantly higher at 0°C than at 23°C. Two main possible reasons can be identified: the higher energy consumption for heating and the less effective exhaust gas treatment. In both cases, the catalyst has reached its optimal temperature in the prior tests. In the 0°C test, the catalyst cools down significantly during the 20 minutes break between the two WLTC tests (WLTC-1-0° and WLTC-2-0°).

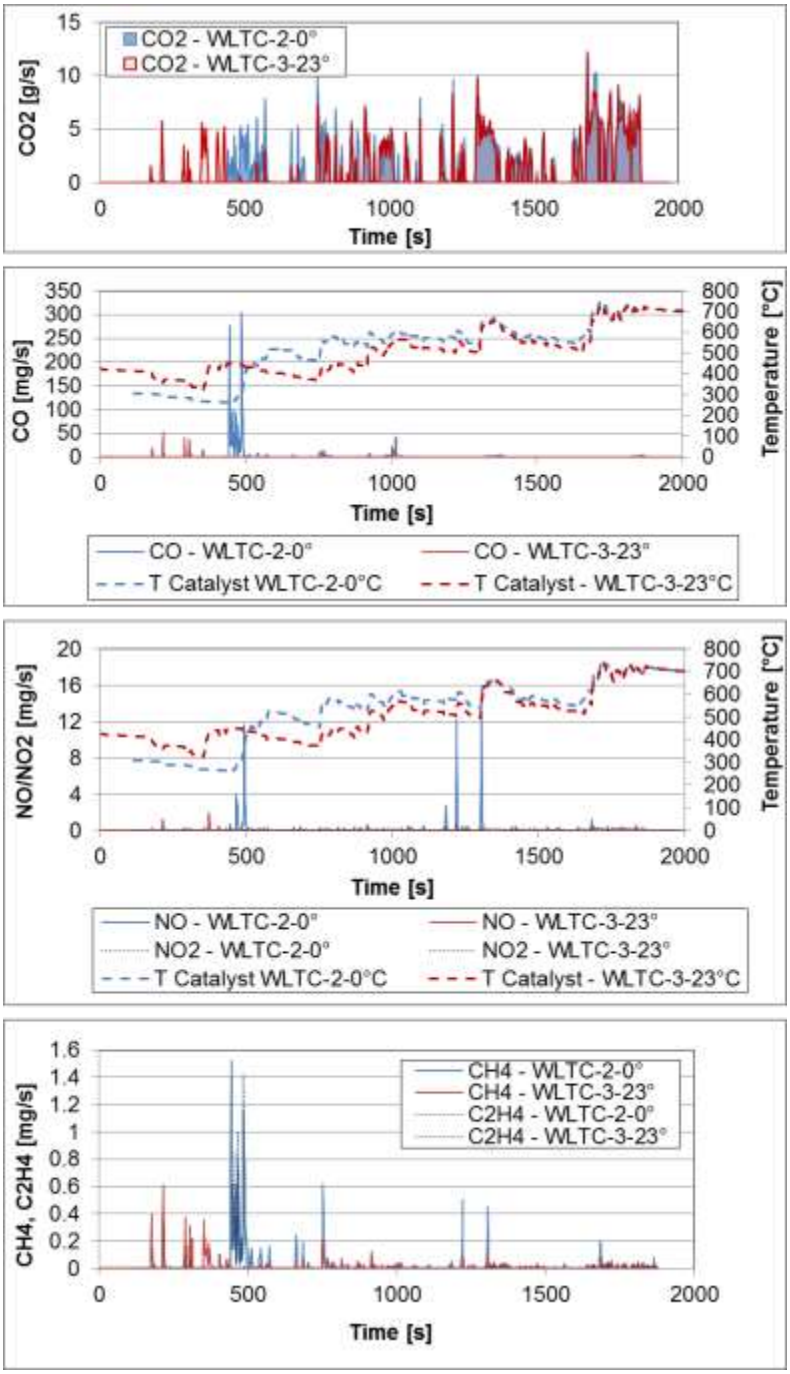

Figure 10: Absolute emissions of the WLTC-2-0° and the WLTC-3-23° tests in g/s and mg/s for different exhaust gases

The evaluation of the average emissions shows that for most pollutants and for CO_2 a temperature dependency is observed (Table 2). This is a direct result of higher emissions per time as shown in Figure 10. Additionally, the ICE-in-use share is higher when the temperature is low which again increases the absolute emissions during the WLTC. The emissions refer to the length of the entire WLTC test and, therefore, include phases without local emissions. This results from the recuperation of the battery and to the use of this energy for certain driving situations. The CO_2 emissions of the test in the CS mode at 23°C are below the limit of 130 g/km which is currently the target for the average passenger car vehicle in the EU, while the emissions at 0°C are above this limit. Although 130 g CO_2/km is the target for the fleet average, the emissions of medium sized vehicles are a good indicator for the potentials of reaching this goal with certain technologies. In contrast to the CO_2 limits, the emission standards for other pollutants are valid for every single vehicle of this test series. In our WLTC tests, the gasoline PHEV meets the EU standards with the analyzed exhaust gases, but the benefits from the PHEV technology are significantly lower in periods with low ambient temperatures.

Table 2: Average emissions of the presented WLTC tests in g/km for different emitted gases (background concentration of ambient air is included)

Test	CO_2 [g/km]	CO [mg/km]	NO [mg/km]	NO_2 [mg/km]	SO_2 [mg/km]
WLTC-1-0°	23	333	27	1	0.4
WLTC-2-0°	133	186	10	3	5
WLTC-1a-23°	14	25	6	1	0.4
WLTC-1b-23	74	209	9	0.4	3
WLTC-3-23°	115	40	4	3	5

The strong influence of a low ambient temperature has been observed in other tests of this measurement project as well. Especially in the case of a tested diesel PHEV, the temperature influenced the share of ICE driving considerably. Furthermore, the temperature and cold start effects are visible not only for NO_x and CO, but also for HC and volatile organic compound VOC emissions. Such effects need to be considered when the emissions from passenger cars are quantified and the effects of such emissions on air pollution and climate changed are modelled.

4 Conclusions

The measurement results of a BEV and a PHEV showed that both vehicles have the potential to reduce air pollution and greenhouse gas emissions compared to their conventional counterparts. The survey among users of the BEV fleet

indicated that user perception of EV is positive concerning environmental benefits, although technical benefits such as higher acceleration are not commonly known. Monitoring a BEV on-road during 2015, it could be shown that its user-SoC derived traction battery energy demand is 17 kWh/100 km, while the total energy demand at charging station is 19 kWh/100 km (both figures include auxiliaries). The electricity mix as of today in Germany with a 50% share of hard coal and lignite in winter is resulting in well-to-tank NOx emissions that are not negligible, although this improves during summer months with a higher share of photovoltaic sources. Even so, these NOx emissions are 30 to 58% lower when compared to well-to-wheel emissions of conventional cars. In addition, 54% of the BEV users stated that they would use electricity from renewable sources to charge their vehicle, and 25% stated that they would use their own photovoltaics system. Based on these findings, WTT NOx emissions could be constantly lowered by 60% lower compared to WTW emissions of conventional cars if taking a renewable electricity mix into account.
The shift of emissions from tailpipe to power plant locations also takes place in the case of electric driven PHEV. Basically, these vehicles have the potential to reduce local emissions, but our dynamometer measurements indicate that the actual saving potential strongly depends on ambient conditions. The tests show that ambient temperatures influence the range, the share of ICE use and the catalyst temperature notably, which is directly reflected by the exhaust emissions. Though cold start effects are avoided by electric driving in the beginning, such effects are shifted to later stages when either a higher speed or acceleration or a low SOC is reached. Additionally, PHEV emissions strongly depend on the user behavior, but due to the low number of registered vehicles in Germany, little is known about a representative or typical PHEV driver. Data from a Dutch study indicate that the real electric driving share is lower than expected due to individual charging habits (Ligterink, Smokers, and Bolech, M. 2013). Other studies present a wide variety of values for PHEV utility factors depending on parameters like annual mileage, regularity of daily driving, likelihood of long-distance trips and charging behavior (Plötz et al., 2015; Davies, 2014).

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