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# Analysis of tail-pipe emissions of a plug-in hybrid vehicle and its average emissions for different test cycles

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## Abstract

In order to assess the correlation of tail-pipe emissions with different impact factors, a PHEV is evaluated with real-driving emission RDE tests and on our chassis dynamometer. Apart from analysing the energy consumption of the vehicle and the resulting carbon dioxide (CO2) emissions, the main pollutants mainly analysed are, amongst others, carbon monoxide (CO), nitrogen oxides ($NO_x$) and particles. PHEV direct emissions strongly vary depending on the operating strategy. We compare the results of test with different modes in RDE tests and with the results from the dynamometer. Using this information, we evaluate the differences in emissions for the phases urban, rural and motorway driving of the test cycles.

Keywords: plug-in electric vehicle, dynamometer test, real-driving emissions

## Introduction

The electrification of passenger cars is seen as one instrument towards mitigation of local air pollution and climate change (European Commission, 2011). Nevertheless, up to now the market share of electric vehicles (EV) falls short of expectations in many European countries. Therefore, plug-in hybrid vehicles (PHEV) can be seen as a transition technology towards a fully electrified vehicle fleet, as they combine the advantage of locally emission free driving in certain areas without cutting the total vehicle range. However, knowledge on real-world driving, energy consumption and tail-pipe emissions of PHEV under different driving conditions still has to be improved.

PHEV direct emissions strongly vary depending on the operating strategy. We compared the emissions of various measurements with parameters like ambient temperature, catalyst temperature, air-fuel-ratio and others. First results have been presented in Kugler et al. (2016). In this paper, we present result of on-road emission measurements with a portable emission measurement (PEMS) device. We compare the results of these real-driving emission (RDE) tests with the results for the WLTC tested on the dynamometer. Main focus of this analysis is the range of overall emissions and energy consumption in different driving modes and battery states. Additionally, we consider the influence of the electric range on the absolute emissions for different driving situations which are “urban”, “rural” and “motorway”.

## Set-Up for PHEV Emission Tests

In order to assess the correlation of tail-pipe emissions with different impact factors, two different gasoline PHEVs are tested on our chassis dynamometer and on-road. Apart from analysing the energy consumption of the vehicle and the resulting carbon dioxide (CO2) emissions, the pollutants mainly analysed are, amongst others, carbon monoxide (CO), nitrogen oxides (NO, NO2) and particles as particle number (PN). The vehicle characteristics of the tested EURO6 compliant PHEV are listed in Table 1.

Table 1: Technical characteristics of the tested PHEV

| | |
|---|---|
| Internal combustion engine | **135 kW** |
| Electric motor | 65 kW |
| System power | 185 kW |
| Electric range | 40 km |
| Fuel consumption (NEDC) | 1,9 l/100km |
| CO2 emission (NEDC) | 44 g/km |
| Curb weight | 1735 kg |

Apart from exhaust emissions, data of the on-board-diagnostics (OBD) have been logged in order to evaluate the potential influence of parameters like catalyst temperature or air-fuel-ratio on the pollutant forming process.

Main goal of the tests is to evaluate the range of possible emissions from PHEV vehicles under different driving conditions. Therefore, RDE tests using one representative route which meets the requirement of the RDE directive (European Commission 2017) are performed. 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 turned on. Additionally, the worldwide harmonized light vehicles test procedure (WLTP) has been applied using the corresponding test cycle WLTC. The tests have been conducted in different modes according to the SAE standard on measure the electric range of hybrid electric vehicles (SAE 2010) and at different ambient temperatures. The tests at -7°C have the same vehicle conditions as at 23°C. Cold starts are performed after vehicle charging 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 analyzed. These tests are represents the situation where the electric range of the vehicle is exceeded and the driver uses the car as a common gasoline hybrid vehicle. Nevertheless, the vehicle recuperates the braking energy in this mode, and the electric driving share in this case is notable.

In case of PHEV, various factors determine the energy consumption and the formation of local emissions. Apart from the state of charge (SOC) of the battery which strongly influences the use of the internal combustion engine (ICE), other aspects like the selected driving mode, the ambient temperature, the used secondary consumers and the driving behavior

In order to assess the potential range of energy consumption and emissions, the RDE compliant route was operated in various driving modes. For the RDE tests the following modes have been chosen:

- Maximum electric drive in the eco mode with 100% SOC at the beginning of the test
- Hybrid driving in the comfort mode with 100% SOC at the beginning of the test
- Hybrid driving in the comfort mode with 0% SOC at the beginning of the test
- Most dynamic mode with 0% SOC at the beginning of the test

The first and the last modes span the potential range of energy consumption and emissions of the PHEV.

## Energy Consumption of PHEV RDE Tests

The usage of the electric energy in hybrid vehicles depends strongly on the operating strategy of the car which results, for example, from the selected driving mode, the state of charge from the battery or the ambient temperature. The possibility to choose a driving mode leads to different electric driving ranges according to the chosen mode. For three of the analyzed RDE tests, the vehicle internal energy flows have been measured.

The ambient temperature varies between 24 - 28 ° C. This of course has an influence on the energy consumption for example on the AC. By using the measurement of the engine speed, the fuel flow and the current to the ignition coils it was possible to find the selections of the ride that where driven without the combustion engine. These parts are marked red in Figure 1. Blue is the fraction of the distance covered by the internal combustion engine.

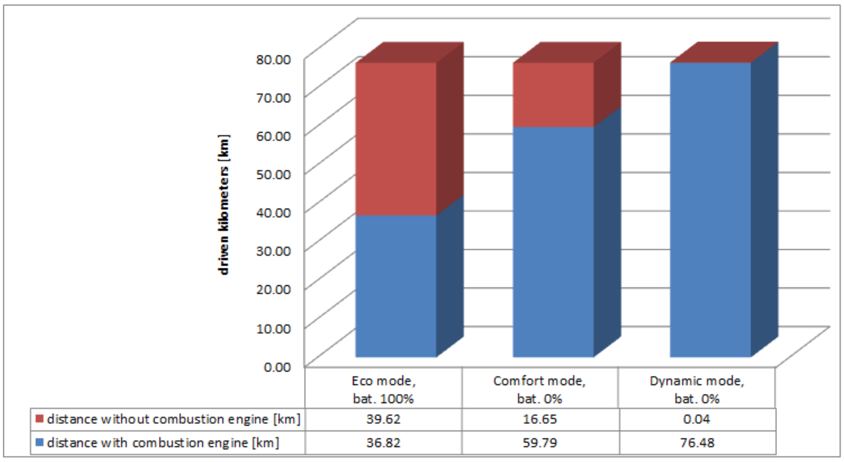


*Figure 1: Overview of the electric and combustional driven range depending on the driving mode*

Figure 2 intents to provide an overview of the energy content used for the route. Blue is the energy content from the used fuel. The energy balance from the high-voltage system is shown in red. The energy content from the used fuel (density corrected and a calorific value of 8760 kWh/m³) and the used energy from the high voltage battery are shown. It includes the propulsion power conversion losses, HV-AC, the 12V power transmission and the current into the drive converter.

In the case that during the ride the HV battery gets loaded by recuperation or from the combustion engine the energy that is in the end of the measurement in the battery will enter as negative energy value into to graphic. As a result the energy balance on the HV system has to consider the vehicle specific working strategy.

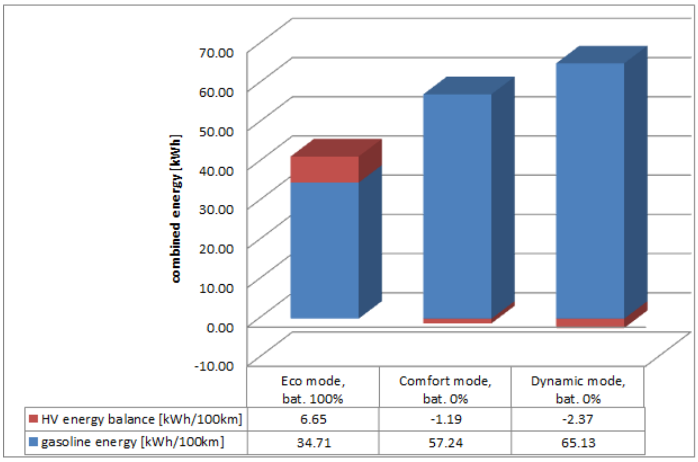


*Figure 2: combined energy used for the RDE drive dependent on the driving mode*

## Results of PHEV RDE Tests

The RDE tests have been performed under similar weather conditions and fulfil the requirements of the RDE directive. Figure 3 shows the cumulative emissions of four RDE measurements. The engine speed indicates the use of the ICE which is zero during phases of electric driving. The tests with a SOC of 100% at the beginning have a long period of electric driving. The ICE starts only in moments of certain acceleration and when the SOC reaches its lowest level. For both tests with full battery starts, this state is reached after more or less the same distance, although the eco mode test is slightly more energy efficient. The use of the ICE is directly linked to the $CO_2$ emissions which are in these two cases almost identical.

In the eco-mode and comfort mode with full battery start, the operation strategy is quite similar. In contrast to that, the dynamic driving mode causes considerably higher $CO_2$ emissions. The larges fuel consumption does not imply higher pollutant emissions, as Figure 3 shows. The test in the eco mode with high shares of electric driving in the beginning has higher CO emissions than the other tests. Also the particle formation after the maximum electric range is reaches a high level.

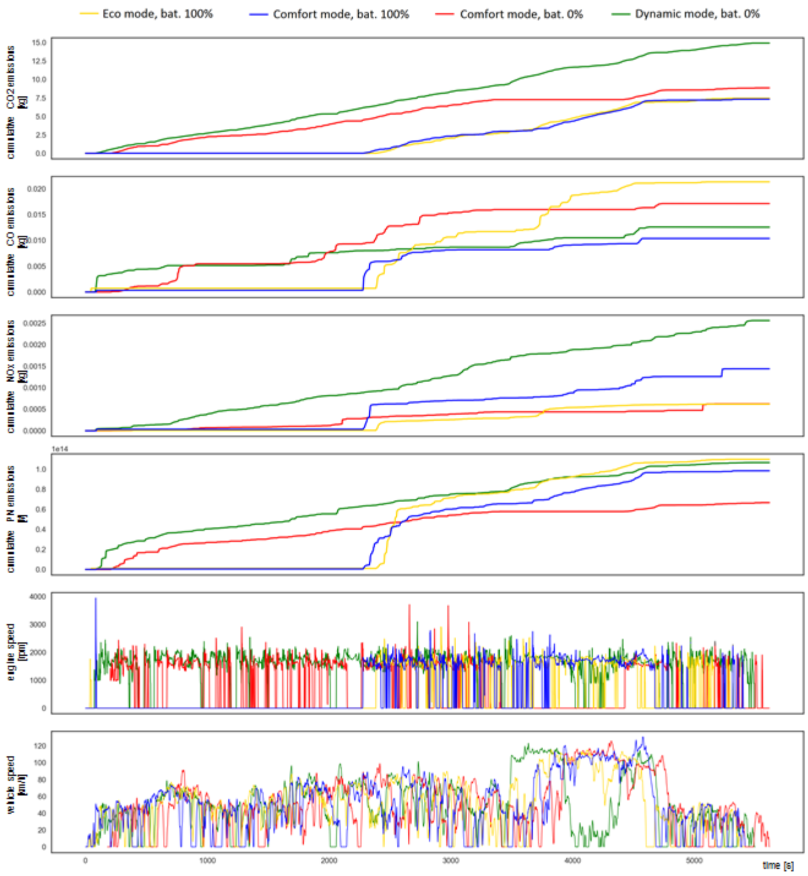


*Figure 3: Cumulative emissions, engine speed and vehicle speed of RDE tests*

The vehicle speed shows that the RDE test is not reproducible, although the route remains the same. Nevertheless, the three speed categories can be identified easily. In case of hybrid vehicles, the potential of recuperating and storing energy during driving adds variable vehicle behaviour to the test set-up. For example, during the test in the hybrid comfort mode which started with 0% SOC, the battery has been charged partially and the energy is used during the motorway phase of the test.

## Average Emissions of the PHEV

The results of the tests have been evaluated according to the average emissions for each speed category. These figures represent the average mass of emissions per kilometre for urban, rural and motorway driving.

Additionally to the RDE tests, standardized driving cycles have been measured. The WLTC has been tested on a dynamometer according to the requirements regarding the use of auxiliaries, temperature, conditioning etc. The standard temperature for these tests is 23°C. The cycle has been started as cold start with full battery and repeated until the battery has reached a constantly low SOC. For the tested PHEV, the third repetition represents a test in the charge sustaining mode as the test starts with 0% SOC.

Both the dynamometer and the RDE test have been evaluated according to the emission in different road categories. In case of the RDE test, the classification into “urban”, “rural” and “motorway” driving results from different speeds during the tests. For the WLTC, the four cycle phases have been separated and assigned to the road categories. Figure 4 and Figure 6 show the results for the three categories and the average total emission figures. The $CO_2$ emissions for the dynamic driving mode are higher than in other modes.

Clearly, the battery SOC determines the absolute $CO_2$ emissions (Figure 5). Generally, the higher the electric share, the lower the gasoline consumption and the $CO_2$ emissions. In motorway conditions, the ICE is turned on at a certain speed, independently from the SOC. In addition to the test at 20 to 30°C, the WLTC has been measured at -7°C. The conditioning has been equal to the 23°C test, but the PHEV is driven mostly with the ICE in the first cycle, although the SOC is 100% and heating is turned off. This affects the average emissions in the urban and rural part of the cold start test which are much higher compared to the mainly electric driven cold start test at 23°C. In most cases, the gasoline consumption and the $CO_2$ emissions of the motorway driving are higher than in the urban and rural phases, but higher shares of electric driving, e.g. due to the recuperated energy in the RDE test with comfort mode, can turn around this finding. The NEDC emissions are slightly higher than the official standard value. As these figures are calculated with the artificial formula for hybrid vehicles, they are not comparable to the other tests.

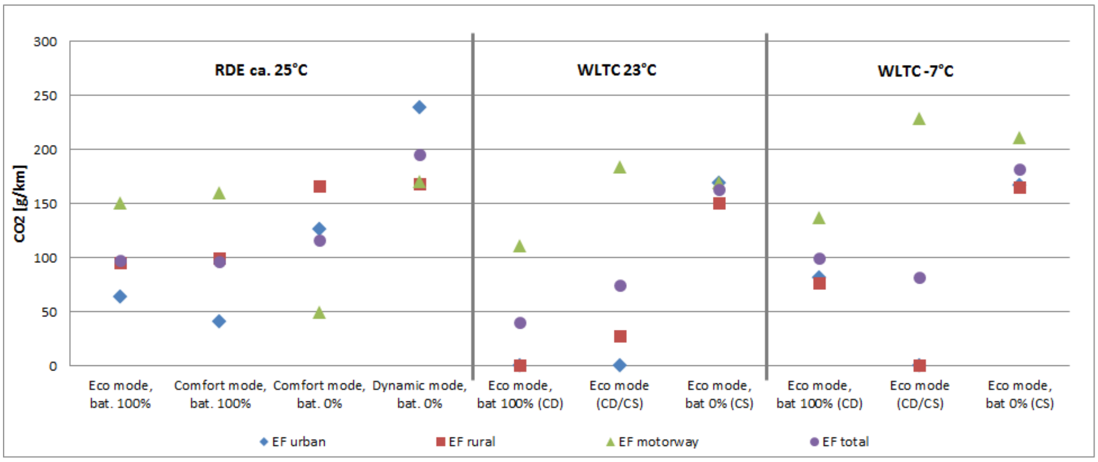


*Figure 4: Comparison of $CO_2$ emissions of RDE and WLTC tests*

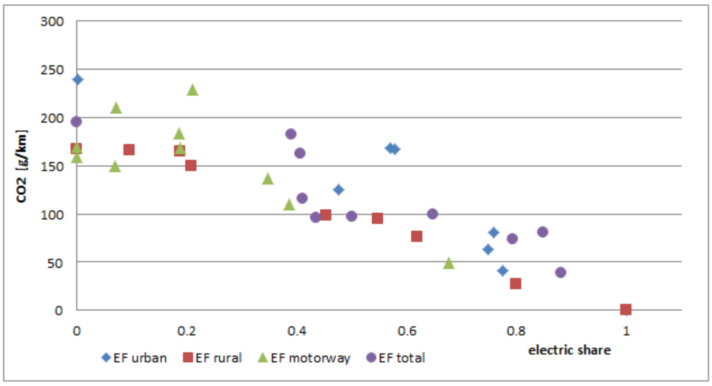


*Figure 5: Relation between $CO_2$ emissions and share of electric driving*

The emission figures for CO and $NO_x$ show that the PHEV emissions are lower than the legal limits (Figure 6). The only exception are the tests at -7°C which indicate different emission characteristics of the ICE or the exhaust gas treatment at lower temperatures. But the particle number exceeds the legal limits in many cases. In general, the average emissions of the RDE test are similar to the WLTC tests. The average pollutant emissions are less related to the speed or road category. In general, CO and PN emissions show fewer differences between the three categories "urban", "rural" and "motorway" than the $CO_2$ or $NO_x$ emissions. The test in the dynamic mode shows high $NO_x$ emissions in the urban part of the RED test which is mainly driven in the first third of the test and influenced by cold start motor behaviour. At -7°C, cold start emission have a high influence on the average emissions of driving cycle, especially in the urban phase. At this temperature, the variance of average emissions in the three categories is generally higher.

Unlike for $CO_2$ emissions, the correlation between pollutant emissions and share of electric driving is not visible (Figure 7). Apart from the ambient temperature, the driving conditions in the moment of ICE starts strongly influence the absolute emissions. Figure 7 also depicts the higher average electric driving share in the urban road category, while the motorway in average goes along with lower electric shares. This is due the forced ICE use at higher speeds and the recuperated energy in driving situation with phases of breaking and slowing down. This recuperated energy is used for electric driving until the SOC reaches is lowest level again.

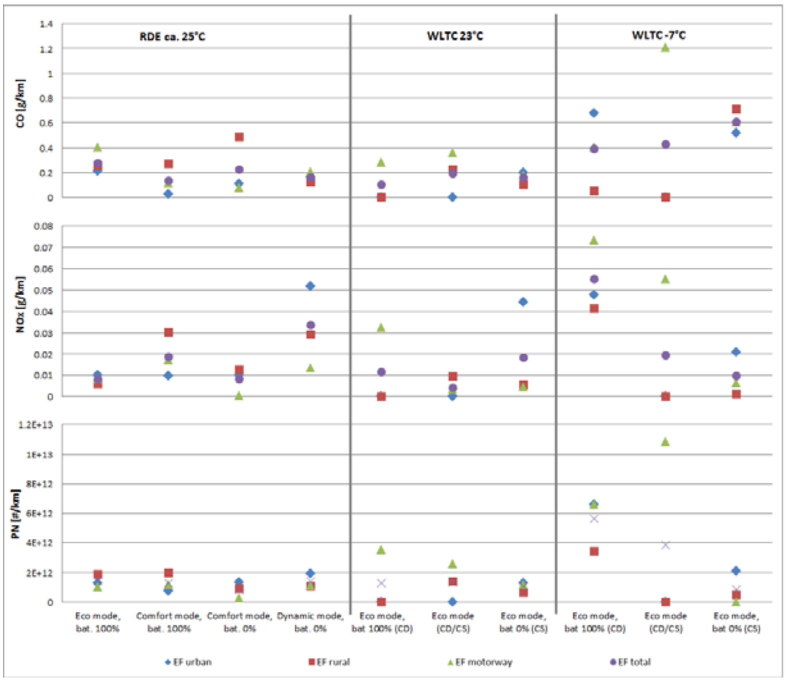


*Figure 6: Comparison of pollutant emissions of RDE and WLTC tests*

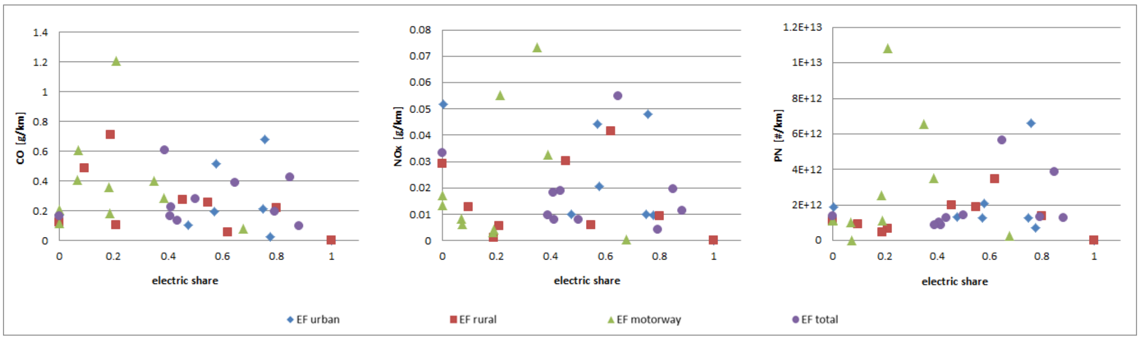


*Figure 7: Relation between pollutant emissions and share of electric driving*

## Conclusions

The test presented in this paper have shown that the $CO_2$ emission strongly correlate with driving mode and battery SOC of the PHEV. Compared to the results of the WLTC and RDE teste, the calculated NEDC results are much lower. In case of pollutants, the CO and $NO_x$ emissions are generally below the legal limits. Particle number, however, is above the allowed limit. The test at an ambient temperature of -7°C show a notably different operation strategy and emission formation that the measurements at moderate temperatures. Future works will apply the same test set-up with other PHEVs in order to validate these findings and in order to narrow down the potential range of PHEV emissions to a more realistic level. So far the test have clearly shown that the standard $CO_2$ emissions for a PHEV as well as approaches for calculating the pollutant emissions as a function of electric driving share do not reflect the real life emissions of such vehicles.

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