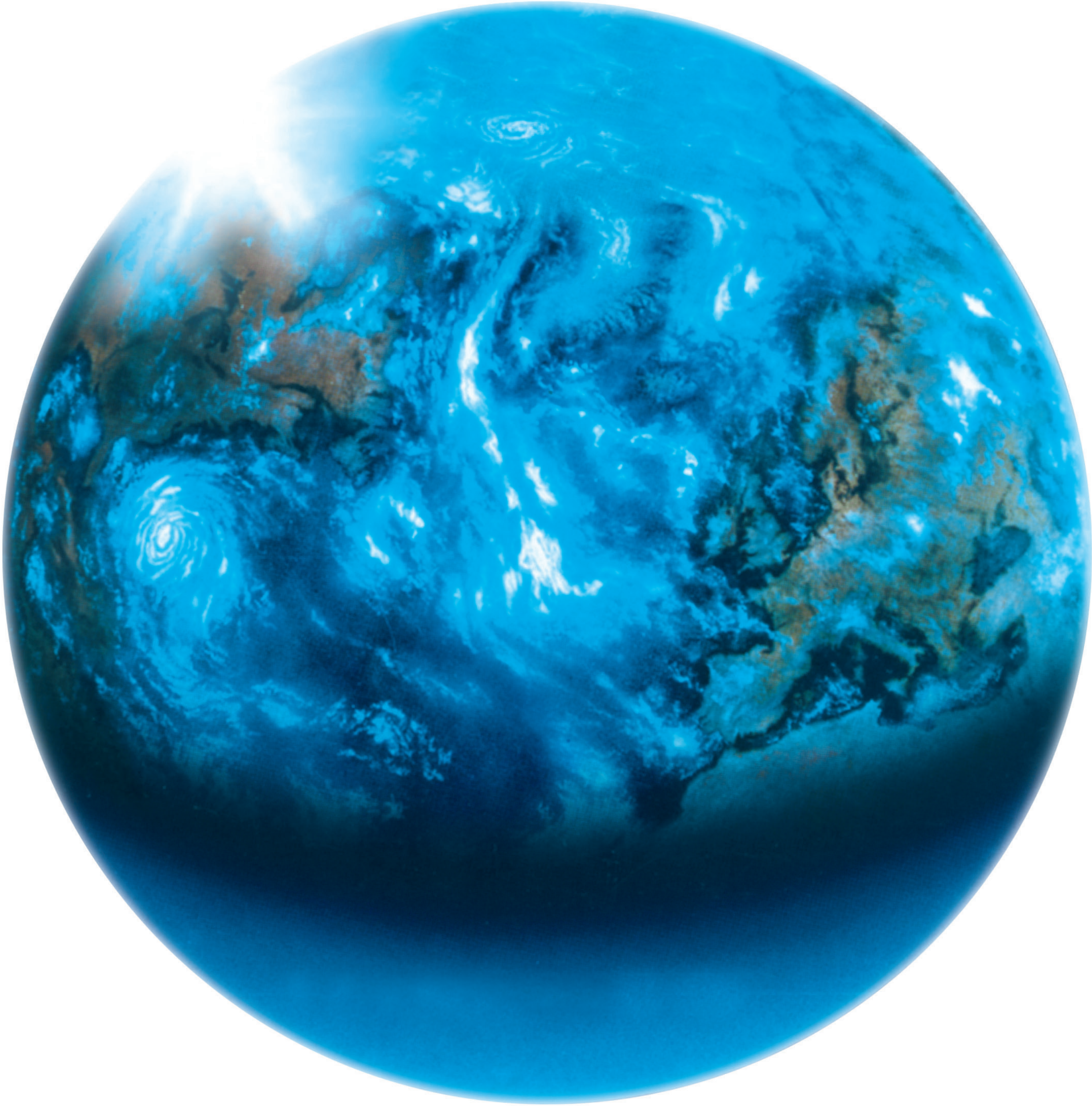

Real Driving Emissions from a Gasoline Plug-in Hybrid Vehicle with and without a Gasoline Particulate Filter

Joachim Demuynck, Cécile Favre, Dirk Bosteels – Association for Emissions Control by Catalyst (AECC); Jon Andersson, Carl Jemma, Simon de Vries – Ricardo UK Ltd.

1. Abstract

This paper investigates the Real Driving Emissions (RDE) performance of a Euro 6b C-segment PHEV, equipped with a direct injection gasoline (GDI) engine, and tested in different driving modes and with various initial battery states of charge (SOC). Selected tests were repeated with a Gasoline Particulate Filter (GPF) added in the exhaust line of the car.

The on-road test route and PEMS equipment (for gaseous and PN emissions) fulfilled the requirements of the European RDE procedure that entered into force as of 1 September 2017. All data measured lay within the RDE boundary conditions defined for ambient temperature, altitude and driving dynamics. In addition to tests on the road, RDE tests were also conducted on a chassis dyno to explore the impact of going towards these RDE boundary conditions. The so-called 'severitized' RDE trip was derived from the reference RDE trip on the road by increasing simultaneously the vehicle accelerations and dyno load, and by running the test at 0°C ambient temperature.

All on-road NOx and PN emissions of the vehicle were below the Euro 6d Not-to-Exceed (NTE) limit that enters into force as of 1 January 2020, except for the PN emissions in the rarely-used "Charge" mode. Even when close to the RDE boundary, NOx emissions remained below the RDE limit of 90 mg/km. PN emissions approached $3x10^{12}$ #/km during testing in the OEM exhaust configuration, but were reduced below the Euro 6d NTE limit of $9 \cdot 10^{11}$ #/km with the GPF installed. Different combinations of driving mode and initial battery SOC did not show a straightforward impact on pollutant emissions. The data shows that the urban RDE NOx emissions of this vehicle can be the highest in "Electric" mode when the battery has not been fully charged (i.e. initial SOC below 100%). The paper reports that this is linked to a cold start of the Internal Combustion Engine (ICE) in the middle of the RDE trip. Overall, the paper demonstrates the challenges faced with pollutant emissions control and that the need for well-integrated exhaust aftertreatment systems, including thermal management, also exists for PHEVs.

2. Introduction

Electrification of the vehicle fleet is put forward as a solution to decarbonise mobility and improve air quality at the same time. As a result, a number of public incentives target these technologies. Amongst them, Plug-in Hybrid Electric Vehicles (PHEVs) are expected to play an important role because they offer a zero tailpipe emission capability (with range of ~50 km currently) combined with the driving range of a conventional vehicle. PHEVs are offered by the OEM with various driving modes, from Electric to Sport.

The aim of this paper is to investigate the pollutant emissions of a gasoline PHEV with a direct injection engine under chassis dyno and real driving conditions. The paper discusses and presents emissions performance for all possible operation modes available on the vehicle, in combination with various levels of the battery State of Charge (SOC) at the start of the test.

3. Experimental Set-up

3.1 Vehicle

The test vehicle was a C-segment gasoline PHEV with a direct injection engine certified to the Euro 6b standard. Maximum power for the vehicle was 110 kW @ 5000 rpm.

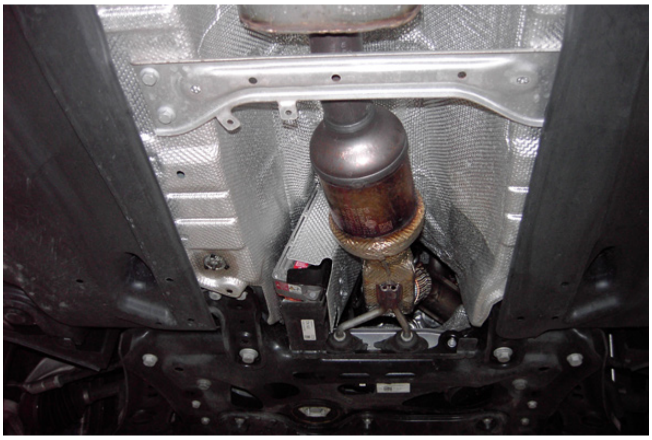

Figure 1: GPF mounted underfloor to replace original downstream three-way catalyst

The vehicle was equipped with two three-way catalysts to control tailpipe emissions. Most tests were performed in the original OEM configuration. Some additional tests were conducted with a three-way catalytically-coated Gasoline Particulate Filter (GPF) mounted in underfloor position and to directly substitute the original downstream 3-way catalyst, see Figure 1. The GPF was degreened on an engine bench to match the vehicle mileage of around 10,000 km.

The test vehicle had 4 different user-selectable modes of operation: Electric, Hybrid, Sport and Charge. Testing was performed in all these modes.

3.2 Measurement systems

Chassis dynamometer tests were performed in the Vehicle Emissions Research Centre (VERC) of Ricardo UK, using road load terms generated from values published by the US EPA for a similar vehicle. During in-lab measurements, MEXA ONE analysers from Horiba were used to measure the continuous raw and bag tailpipe emissions. A MEXA 2000 SPCS was used to measure dilute PN tailpipe emissions.

A Horiba OBS-ONE-GS PEMS and OBS-ONE-PN unit was used to measure CO2, CO, NOx and PN emissions during RDE trips, both on-road and on-dyno. All PEMS data shown in this paper derives from compliant PEMS measurements. The PEMS was validated against lab-based analysers during both WLTC tests and all on-dynamometer RDE tests according to the criteria specified in the regulation [1].

Vehicle data was logged through the OBD connector with a commercially-available scan tool.

3.3 Emission tests

All tests were done on UK pump-grade gasoline fuel, containing 5% Ethanol.

3.3.1 On-road RDE

All on-road RDE tests were conducted on a route shown to be EMROAD-compliant with more than 10 vehicles. The RDE route commences from the Ricardo site with immediate urban operation that is conducted wholly in 30 and 50 km/h speed-limited zones within the city of Shoreham-by-Sea. Increased urban severity is achieved through moderate hill climbs, inclusion of multiple T-junctions, traffic lights and a rail-crossing so that no artificial stop periods are required. Rural and motorway sections are both out-and-back routes using roundabouts for the turn, with the rural part relatively flat and the motorway one gradually ascending eastbound and descending on the westbound return trip.

Tests were performed in all 4 driving modes and with variations in initial battery State of Charge (SOC), see Table 1. Tests were conducted with a fully charged battery (nominally 100% SOC), depleted battery (nominally 25%) and two intermediate SOC levels (~85% and ~55%). The basic vehicle strategy in the different modes can be understood from the evolution of the SOC over the different RDE tests, see Figure 2.

SOC	Electric	Hybrid	Charge	Sport
100%	*1x	1x	-	1x
85%		1x		
55%	*1x			
25%	1x		1x	1x

*Tests repeated with GPF replacing underfloor TWC

Table 1: Combinations of operation mode and battery State of Charge (SOC) tested on-road

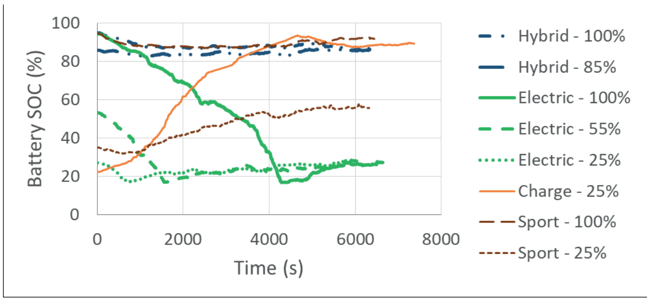

Figure 2: Evolution of battery State of Charge (SOC) during on-road RDE tests.

The first RDE test was performed in Electric mode with a fully charged battery (Electric – 100%). The vehicle initially runs on the electric motor, and the battery SOC decreases during the test until it drops below 20%, after more than 4000 s. The vehicle then starts the Internal Combustion Engine (ICE) to eventually sustain the battery SOC around 25%. The vehicle continuously switches between ICE only, electric motor only, or combined ICE and electric motor operation. The second test in Electric mode was performed the following day, without overnight charge (Electric – 25%). Throughout this test, the vehicle continues to maintain the SOC at ~25%. The third test in Electric mode was done with an intermediate initial SOC of 55% (Electric – 55%). A similar behaviour to the first test was observed: the vehicle runs on the electric motor until the SOC drops below 20%, then acts to sustain the battery level at around 25% for the rest of the test.

In the two Hybrid mode tests, the vehicle sustains the battery SOC at around 85%. The first test was started with a fully-charged battery (Hybrid – 100%). The second test was started the following morning, but without overnight charge (Hybrid – 85%).

The vehicle was also tested in Charge mode, starting with a depleted battery (Charge – 25%). The vehicle completely charges the battery on the ICE, before sustaining the SOC level at around 85% near the end of the test, similar to the Hybrid mode.

The vehicle strategy is however different in the Sport mode. After a start with fully charged battery (Sport – 100%), initial operation is similar to the Hybrid mode, but the vehicle then charges back the battery to 100% during the motorway driving, near the end of the test. When starting with a depleted battery (Sport – 25%), the vehicle increases SOC to near 60%.

Electric mode tests, with initial SOC of 100% and 25%, were repeated with a GPF installed.

An RDE trip is defined by a number of boundary conditions defined within the regulation [1]. Together these create a multi-dimensional RDE space within which a huge number of possible valid RDE routes can exist. All data in this study are considered valid within the RDE boundary conditions. Figure 3 illustrates where the RDE data measured fit within the environmental boundary conditions. The dots represent the average temperature and altitude during each on-road RDE test. The box around the dots visualises all the conditions observed during the tests. Driving dynamics observed and characterised by the two parameters vxa_{pos} (vehicle speed multiplied by positive acceleration) and RPA (relative positive acceleration), are illustrated in Figure 4. Although the tests were done near sea level, the severity from altitude accumulation during the RDE route on the road reaches 940 m/100 km (the regulatory boundary is 1200 m/100 km).

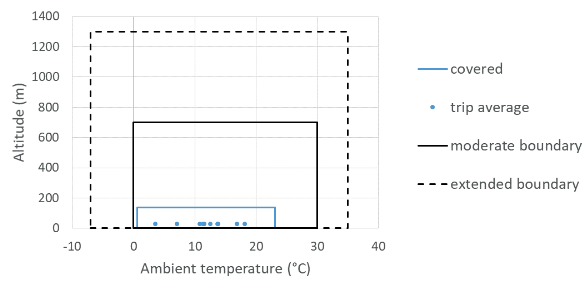

Figure 3: All on-road RDE data is within the moderate environmental boundary condition.

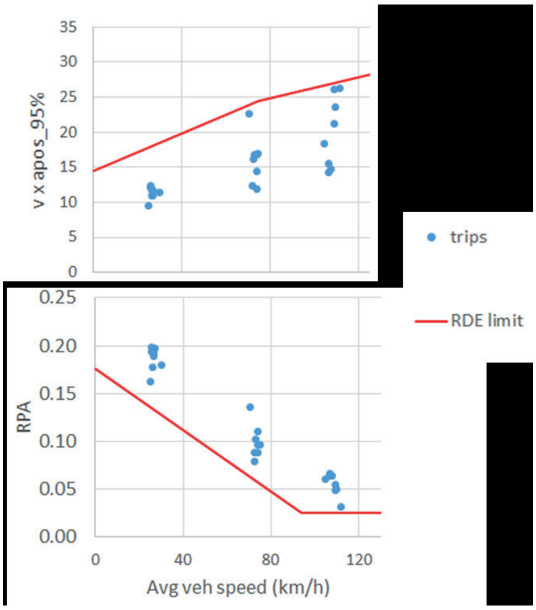

Figure 4: vxa_{pos} and RPA values observed during on-road RDE testing

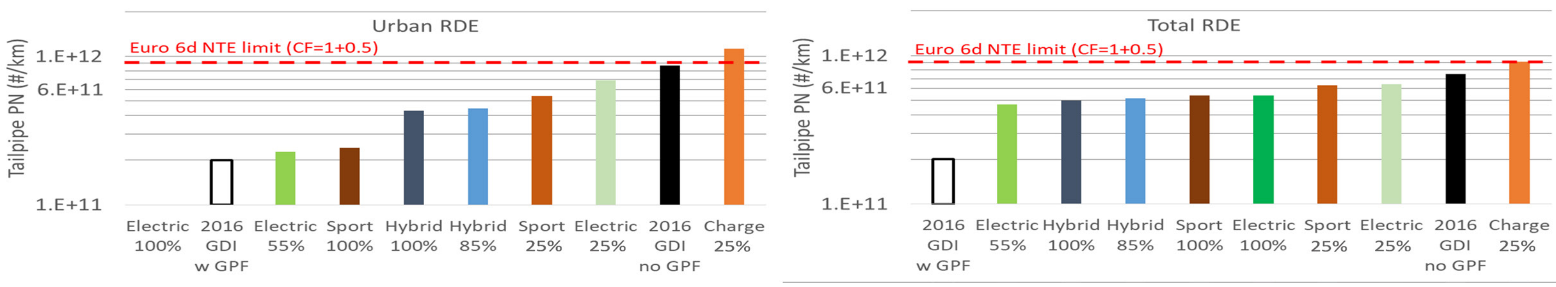

Figure 5: Urban and total RDE PN emissions

3.3.2 On-dyno RDE

On-dyno RDE tests were conducted with the aim of expanding the range of RDE test severities experienced by the vehicle during the on-road tests. For certification purpose, a valid test is required on a single route only, but since this route may not present the most severe challenge possible within the RDE space, the creation of more demanding RDE tests that can be conducted on a chassis dynamometer is desirable. The process to derive the on-dyno RDE tests was developed during a previous test programme of a GDI vehicle [2]. In summary, severitized RDE (SRDE) tests were obtained based in three steps, starting from a reference on-road speed trace:

1. vxa_{pos} was made more severe by taking the speed vs. time trace of the reference on-road trip and modifying it to increase each acceleration within the trip. The three values of vxa_{pos} for the urban, rural and motorway parts were shifted close to the upper boundary.
2. The dyno load was changed to shift the characteristic CO2 curve in EMROAD in between the -25% and +25% lines which is the range expected for normal driving.
3. The ambient temperature of the test cell was controlled down to 0 °C or -7 °C while the test was run.

For the PHEV test programme, each SRDE test was conducted with a combination of those 3 steps: at the boundary for vxa_{pos}, with such dyno load increased movethat the characteristic CO2 curve was up to the +25% line, and at 0°C ambient temperature.

All combinations of operation mode and battery SOC from Table 1 were tested for SRDE, except for the Hybrid mode with an initial SOC of 85%. The Electric mode with an initial SOC of 100% and the Sport mode with an SOC of 25% were repeated with the GPF for the Severitized RDE tests on the chassis dyno.

4. Results and discussion

Results are compared to those from the previous test programme on a directly-comparable GDI vehicle [2], labelled as "2016 GDI". That programme also contained tests with the OEM exhaust vehicle configuration, without GPF, and with a GPF retrofitted in underfloor position.

4.1 PN emissions

Urban and total RDE PN emissions of all the on-road RDE PHEV tests are plotted in Figure 5, sorted in ascending order. The on-road results of the 2016 GDI programme, with and without GPF are added for reference. The lowest urban RDE PN result is measured in Electric mode with a fully-charged battery (Electric – 100%). However, the total RDE PN result in this condition is placed in the middle of the measured values, even though the ICE was not operating during the urban part of the trip. It can be seen in Figure 6 that this occurs because of the PN spike as the ICE starts in the middle of the trip. The start-event brings the final PN emissions to the same level as in the other modes, e.g. the Hybrid – 100% curve that is also plotted.

The PN emissions in the other conditions lay between the range of emissions from the 2016 GDI car without and with GPF, from $2{\cdot}10^{11}$ to $7{\cdot}10^{11}$ particles/km. The highest PN emission were measured in the Charge mode when starting with depleted battery (Charge – 25%). The urban RDE PN emission reaches $1{\cdot}10^{12}$ particles/km, while the total RDE PN emission stay below $9{\cdot}10^{11}$ particles/km. Figure 6 shows that this is mainly caused by the PN spike almost immediately after the start of the test (the test commenced in Electric mode for the first ~300 m). The further accumulation of PN emission is similar to the other test conditions, although the load on the ICE is higher during most of the trip when it is charging the battery back to its maximum level.

Figure 7 shows the impact of the GPF for the Electric – 100% and Electric – 25% tests. PN emissions are controlled to below $2{\cdot}10^{11}$ particles/km, similar to the effect observed with the 2016 GDI car.

Figure 8 compares the on-road RDE and on-dyno Severitized RDE results in selected modes. The tests in the OEM exhaust configuration are plotted on the right, those with GPF on the left. All urban and total PN emissions in the original configuration, without a GPF, exceed $9{\cdot}10^{11}$ particles/km during the Severitized RDE tests. As seen with the 2016 GDI testing, PN emissions with the GPF are controlled to below $6{\cdot}10^{11}$ particles/km, the Euro 6c limit.

4.2 NOx emissions

Ascending urban and total RDE NOx emissions from all on-road tests are plotted in Figure 9. 2016 GDI NOx emissions are in the middle of the range of the PHEV emissions. Urban NOx emissions reach ~60 mg/km, while total NOx emissions do not exceed 30 mg/km. Zero urban NOx tailpipe emissions are measured in Electric mode when the battery is fully charged (Electric – 100%). The value plotted is not exactly zero, as there is low-speed (<60kph) data from the rural and motorway sections which is allocated to the calculated urban section through the speed-binning data analysis in the RDE procedure. A fully charged battery at the start consistently results in the lowest NOx emissions. The highest NOx emissions were

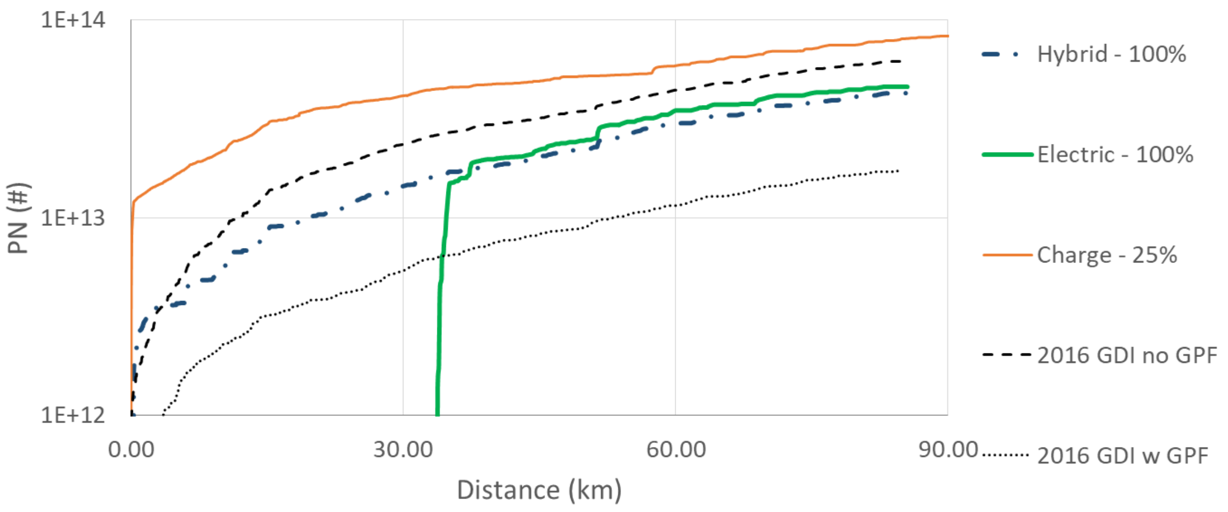

Figure 6: Cumulative PN emission.

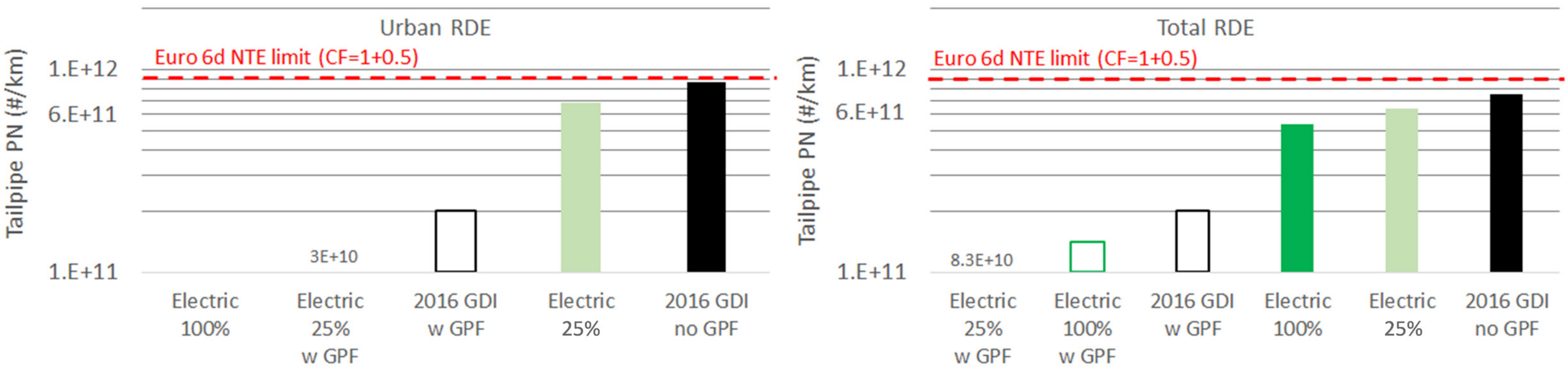

Figure 7: Urban and total RDE PN emissions without and with GPF

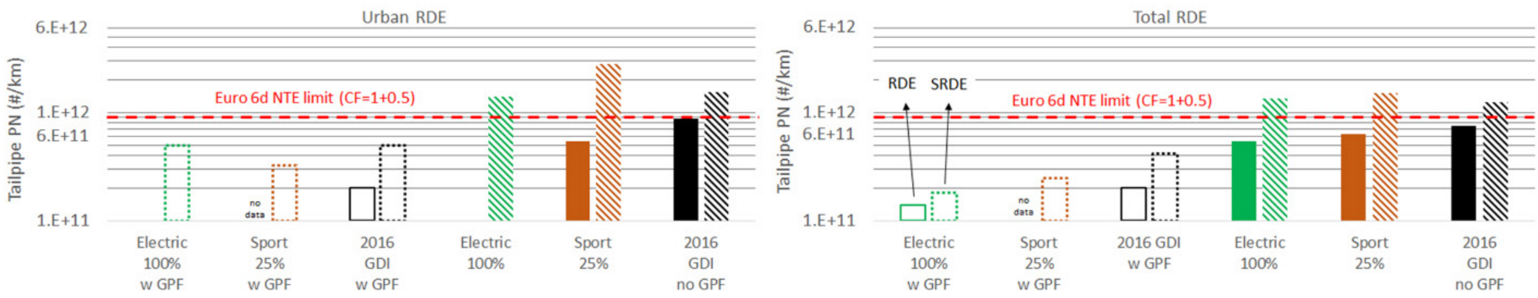

Figure 8: Urban and total Severitized RDE PN emissions

recorded in Electric mode with the intermediate battery SOC (Electric – 55%). As Figure 10 shows, this is caused by the NOx spike generated at ICE start, when the three-way catalysts have not yet reached their light-off temperature. The accumulation of NOx emissions during the rest of the trip is similar to that of the fully charged tests.

The impact of the Severitized RDE is shown in Figure 11 for urban NOx, where all emissions are below 60 mg/km. In contrast to PN, NOx emissions do not systematically increase when RDE conditions are severitized. In Electric mode, with fully charged battery (Electric – 100%), the increased load experienced in the SRDE reduces the electric range and the ICE starts during the urban part in of the test. As a consequence, urban RDE NOx emissions in these conditions are similar to the other tests. Observations are similar for the total RDE and Severitized total RDE emissions, which are not shown.

The cumulative NOx plotted in Figure 12 confirms that the NOx emissions are mainly determined by the peak generated by cold-start. Following ICE start accumulation of NOx emissions during the rest of the test is very similar in RDE in all modes, and from both RDE and SRDE. Interestingly, Electric mode with fully charged battery results in the highest NOx

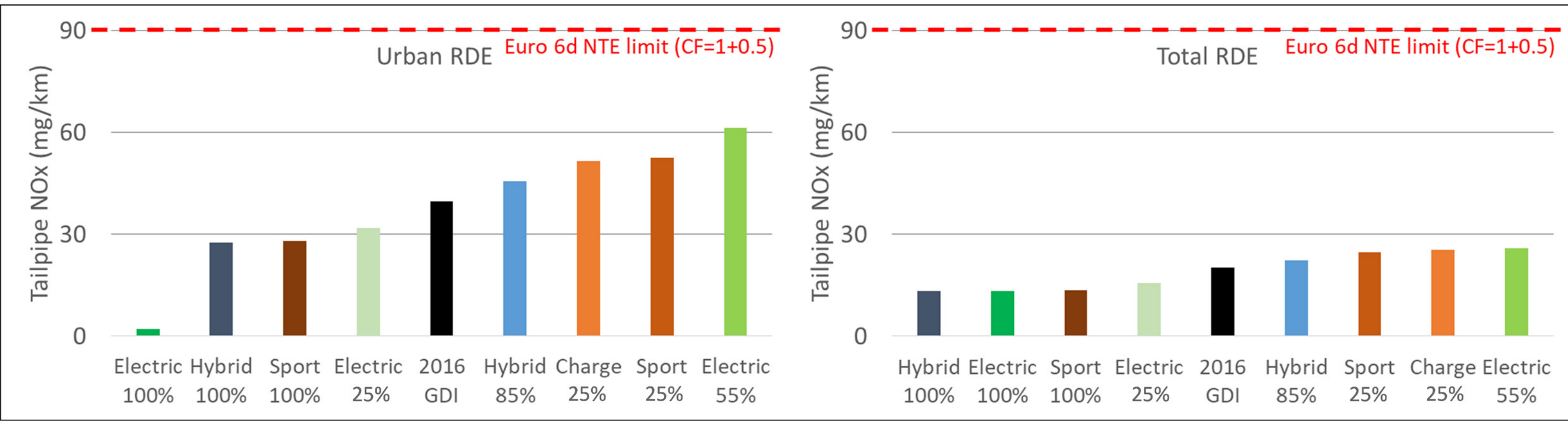

Figure 9: Urban and total RDE NOx emissions

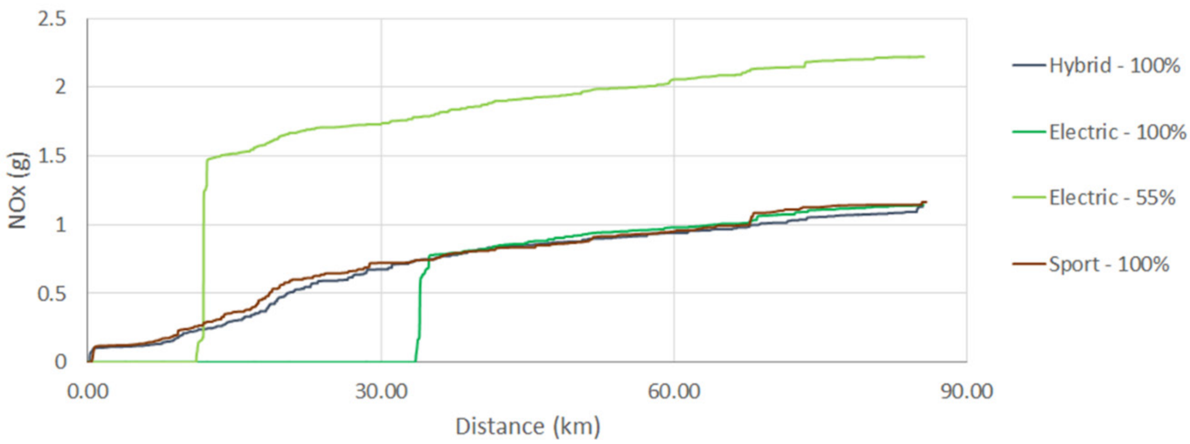

Figure 10: Cumulative NOx emissions

emissions under the SRDE conditions, because it produces the highest cold-start NOx breakthrough. NOx emissions in Electric mode with intermediate battery SOC (Electric – 55%) are lower during the SRDE test compared to the RDE test because of a lower cold-start peak. This difference may be due to differences in the instantaneous load demand on the ICE at the point of engine start.

A combination of effects influence the NOx peak at the initial start of the ICE and not enough data was measured to investigate this in detail. Figure 13 and Figure 14 illustrate this for the Electric - 55% RDE and Severitized RDE test respectively. The engine-out temperature, vehicle speed and ICE status (on or off) are plotted. Although the start of the ICE is during an acceleration in the Severitized RDE test (Figure 14 at 6.75 km), the initial NOx peak is lower than during the on-road RDE test where the start of the ICE is during a small deceleration (Figure 13 at 11.1 km). The duration of the NOx peak in Figure 12 is 1.5 km for the Electric - 55% RDE test and 1.75 km for the Severitized RDE test.

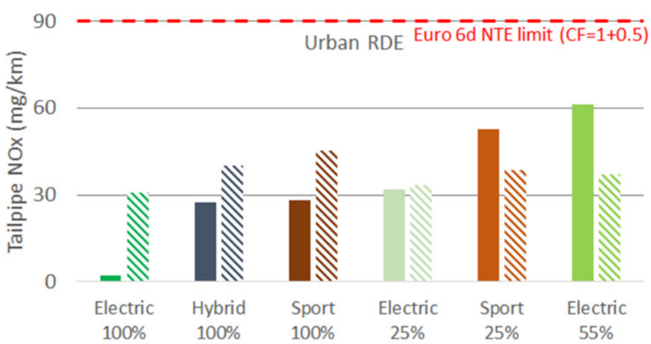

Figure 11: Urban Severitized RDE NOx emissions

4.3 CO_2 emissions

Urban and total CO2 emissions are plotted in Figure 13. The effects of the different operating modes are more straightforward with CO2 than with pollutant emissions. Driving in Electric mode consistently results in the lowest CO2 emissions, and CO2 emissions increase when the initial battery SOC is lower. Driving in Sport or Charge mode with an empty battery at the start results in significantly higher CO2 emissions as there is a high load on the ICE when it is recharging the battery.

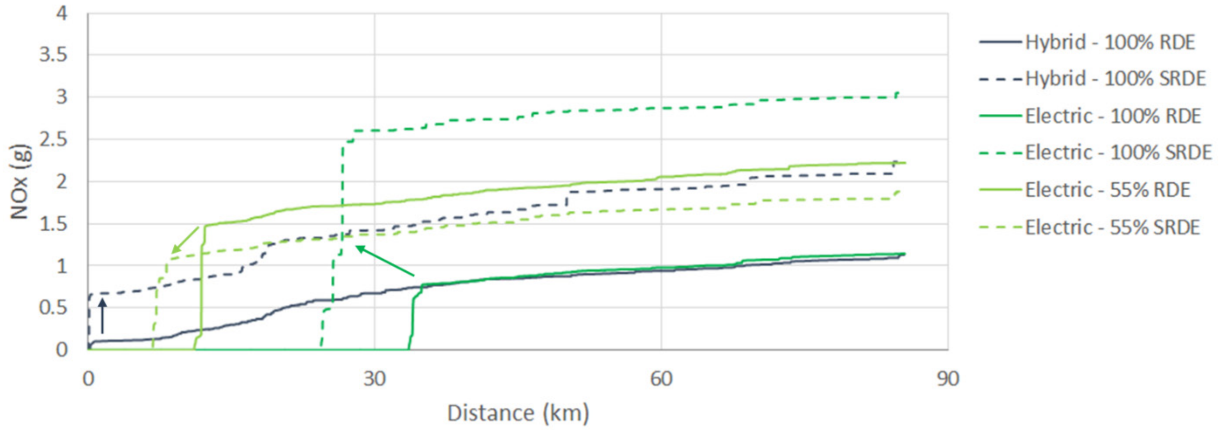

Figure 12: Cumulative NOx emissions of RDE and Severitized RDE tests

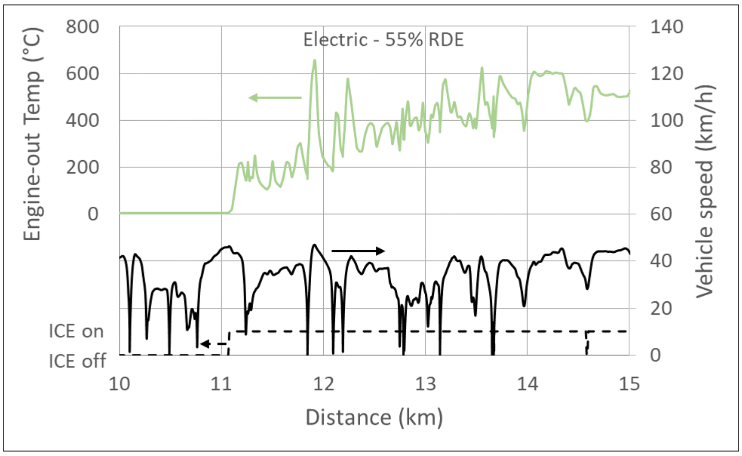

Figure 13: Engine-out temperature, vehicle speed and ICE status during the Electric–55% RDE test.

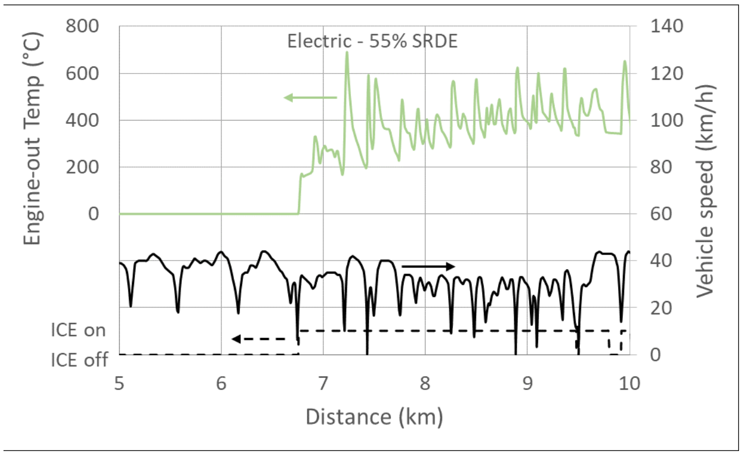

Figure 14: Engine-out temperature, vehicle speed and ICE status during the Electric–55% Severitized RDE test.

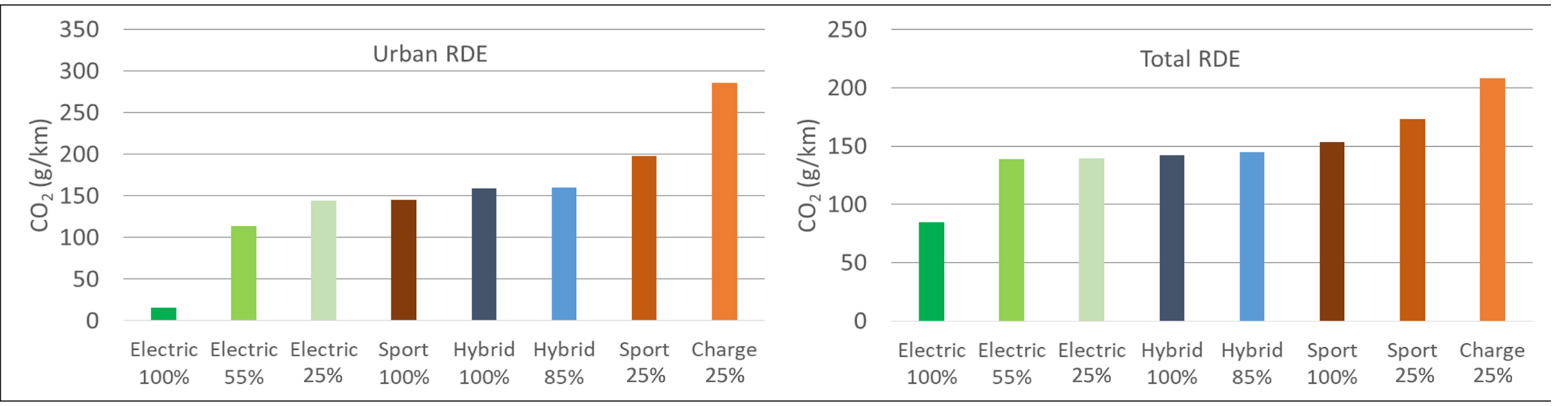

Figure 15: Urban and total RDE CO2 emissions.

5. Conclusion

This paper investigated the Real-Driving Emissions of a gasoline Plug-In Hybrid Electric Vehicle (PHEV). Tests were performed both on the road and also on the chassis dyno to explore the impact of the RDE boundary conditions on emissions. Different combinations of vehicle's operation modes (Electric, Hybrid, Sport and Charge) and initial battery State of Charge (SOC) were evaluated. Results were also contrasted with emissions from a comparable, reference GDI vehicle tested during a previous programme.

The PHEV tested delivers zero tailpipe emission in urban areas, within the electric range, when it was driven in electric mode and if the battery had been fully charged. Outside of these conditions, higher emissions than a reference Gasoline Direct Injection car were observed.

Considering both RDE and SRDE tests, NOx results were all below the Euro 6d NTE limit. Without a GPF, PN emissions were also below the Euro 6d NTE limit, except for the test in Charge mode.

It was shown that the different combinations of driving modes and initial battery SOC do not have an obviously predictable impact on tailpipe pollutant emissions. These data show that the urban RDE NOx emissions of this vehicle can be highest in Electric mode when the battery has not been fully recharged prior to the test drive. It was demonstrated that the timing of the cold start of the Internal Combustion Engine (ICE) during the RDE trip strongly impacted NOx and PN emissions. The high PN spikes were nevertheless well controlled in those tests that were repeated with a GPF.

References

[1] 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 6).

[2] Demuynck, J., et al., Real-World Emissions Measurements of a Gasoline Direct Injection Vehicle without and with a Gasoline Particulate Filter, SAE Technical Paper 2017-01-0985, 2017, doi:10.4271/2017-01-0985.