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Fuel and Recharging Effects on Regulated and Unregulated Emissions from a Gasoline and a Diesel Plug-In Hybrid Electric Vehicle

Roland Dauphin Concawe

Joseph Kermani and Philippe Degeilh IFP Energies nouvelles, Institut Carnot

Corrado Fittavolini ENI R&TID R&D, Concawe

Alastair Smith Shell Global Solutions UK, Concawe

Cyrille Callu TotalEnergies OneTech, Concawe

Sofia Chrysafi BP, Concawe

Renate Uitz-Choi Shell Global Solutions Germany, Concawe

Kenneth Kar ExxonMobil

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Abstract

As passenger cars are progressively moving towards more electrification, Plug-in Hybrid Electric Vehicles (PHEVs) may play a greater role. Several questions arise regarding their performance in real-world conditions, their optimal configuration - in terms of battery capacity, fuel and powertrain used - and their pollutant emissions. In this context, two PHEVs complying with Euro 6d standards were evaluated on a chassis-dyno and on-road using the same road profile, complying with RDE requirements. The two vehicles differ only by their powertrain, one being diesel-fueled, and the other being gasoline-fueled. The vehicles were tested under various conditions, including charge depleting and charge sustaining modes (i.e., tests respectively starting with a fully charged battery and a discharged battery), with various fuel compositions including traditional fossil-based fuels, 100% renewable Hydrotreated Vegetable Oil (HVO) and 100% renewable gasoline, blended with 20% v/v ethanol (E20). The vehicle weight was also artificially varied on the chassis-dyno to assess the difference of performance between a PHEV and a Hybrid Electric Vehicle (HEV), having a lower-capacity battery. The set of measurements included fuel and electricity consumptions, CO_2 and regulated pollutant emissions (NOx, CO, HC, PN23, PM) as well as non-regulated pollutant emissions such as PN10, CH_4, NH_3 and N_2O. The results show that the two vehicles have regulated pollutant emissions levels well below the Euro 6d limits under all testing conditions, and unregulated pollutant emissions in the range of Euro 7 proposals. For the PHEVs and operating conditions tested, switching from a traditional fossil-based fuel to a 100% renewable fuel, for both gasoline and Diesel powertrains, does not have statistical significant impact on the pollutant emissions. Regarding fuel and powertrain aspects, it is observed that switching from a gasoline- to a Diesel-PHEV enables a reduction of CO_2 emissions whilst also lowering pollutant emissions except for NH_3 and N_2O. However, on-road tests results show significantly higher fuel consumption than chassis-dyno tests, although being driven on the same test-cycle.

Introduction

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

- The Tank-to-Wheels (TtW) approach focuses only on the tailpipe emissions;
- The Well-to-Wheels (WtW) approach is more complete and considers the GHG emissions related to the production of the energy carriers;

- The Life Cycle Assessment (LCA) approach is holistic and also considers the GHG emissions related to the production of capital goods that are necessary to the transport system (e.g. vehicles, infrastructures of the energy system, etc.).

Obviously, the LCA approach is the most satisfying one as it is the most relevant to climate related issues. Nevertheless, the TtW and WtW approaches should also be considered simultaneously because they are currently regulated in Europe (TtW for the vehicles [3]; WtT with combustion for the fuels according to the renewable energy directive - RED [4]). For example, a solution that would have a high performance in the LCA scope, but a bad performance in the TtW scope would probably face big barriers to its development in the EU market.

In this context, Plug-in Hybrid Electric Vehicles (PHEVs) represent an interesting option as they seem to address the challenges with low GHG emissions at each stage (TtW, WtW and LCA) [5]. Furthermore, they can relieve some of the (time) pressure on the implementation of fast charging infrastructures for Battery Electric Vehicles (BEVs) so as to make their rollout feasible in a shorter timeframe. However, it is believed that the assessments currently available in the literature may require some updates:

- TtW: the OEMs are committed to reducing the TtW CO_2 emissions of passenger cars (in gCO_2/km) by 37.5% in 2030 compared to a 2021 starting point [3]. A 55% reduction compared to 1990 levels is proposed in the fit-for-55 package [6]. It is highly likely that, to reach this target, a high amount of electrification will be necessary, including PHEVs as they generally give CO_2 emissions in the range of ~30 gCO_2/km. As of today, these TtW CO_2 emissions are assessed based on the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). The WLTP does not necessarily consider the real-world emissions of the vehicle, which could affect PHEV credibility in the future for at least the three following reasons:

    1. Some PHEVs are purchased due to tax incentives but are rarely plugged in (especially company cars, which are often provided with a fuel card: a mechanism that unfortunately incentivises not to recharge the vehicles as the drivers rather refuel them “for free”) [7].
    2. Some journeys are much longer than the WLTC over which the CO_2 emissions are assessed. Therefore, it is possible that in some cases, the Internal Combustion Engine (ICE) runs for a larger proportion of the total distance travelled than expected in the regulation. According to German statistical studies [8], only 2 % of daily trips are longer than 100 km, but they account for 26 % of the mileage driven. Similarly, in France, only 1.3 % of the trips are longer than 80 km, but account for 40 % of the total mileage (approximatively. 6000 km/y), including around 50 % of them travelled by car [9]. Therefore, these “rare but long trips” may have a significant impact on the real-world fuel consumption and TtW emissions of PHEVs, which should be assessed properly.
    3. The PHEV has a higher weight than a conventional HEV or pure ICE vehicle - a downside for fuel consumption and CO_2 emissions if not charged.

- WtW and LCA: several WtW and LCA studies, such as those led by Ricardo [10] or by IFPEN [5, 11], rank the PHEV among the best solutions in terms of CO_2 emissions. This is especially true if they use renewable fuels. In some very favourable cases, PHEVs can even have lower CO_2 emissions than BEVs over their life cycle as their battery is smaller - this will of course be highly dependent on the driver’s behaviour in charging the vehicle as well as the carbon intensity of the energy sources. If they have encouraging outcomes for PHEV, these studies do not answer the question of the real ratio of all-electric drive from PHEVs (raised above, also called “Utility Factor”, UF), which may be a limiting factor to the applicability of their conclusions.
- Systemic aspects: more recently, Concawe developed optimal electrification scenarios of passenger cars, aiming at minimizing their WtW CO_2 emissions under constraints of battery availability [12]. They concluded that, under limited battery availability, PHEVs are the preferred option before BEVs to minimize WtW CO_2 emissions of new passenger cars, even under quite conservative utility factors, ranging between 20% and 50%. This result is explained by the fact that, as long as the overall battery availability is limited, it is more efficient to electrify trips by spreading smaller batteries amongst many users who use their full capacity, than by allocating big batteries to few users who generally use only a small share of their full capacity on a daily basis. However, the question remains whether the real-world utility factors are beyond the 20%-50% threshold identified in this study.

Scope and Objectives

If it is understood that PHEVs fueled by renewable fuels and low carbon electricity are an interesting option in terms of CO_2 emissions over their life cycle, this technical option also offers the opportunity to reduce the consumption of liquid fuels. This is particularly interesting in the frame of the outcomes of Concawe’s work published by FuelsEurope [13], which mentions that liquid fuels for road transportation could be 100% low-carbon by 2050, but with a consumption of liquid fuels that would be approximately one third compared to today’s level to be compliant with the GHG emissions trajectory designed by the European Commission in its 1.5 TECH scenario from “A Clean Planet For All” [14]. Hence, to make PHEVs fueled by renewable fuels a viable solution in the long term, they have to prove that they can compete with a third of the consumption of liquid fuels as a first approximation (and still comply with this in real-world operation).

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

In this context, the aim of this study is to assess the energetic performance and emissions of state-of-the-art PHEVs in real-world conditions. More specifically, this study intends to:

1. Provide data on pollutant emissions of PHEVs in real-world conditions and determine if they are relevant solutions to preserve air quality and if the aftertreatment system efficiently manages the particularities of PHEV drive. For this purpose, an experimental campaign was carried out on a chassis dynamometer and on-road on two state-of-the-art PHEVs, and the test protocol focused on real-world driving emissions (RDE). It is the objective of the present article to detail and analyze the related experimental results.
2. Assess life-cycle GHG emissions of PHEVs in real-world conditions, including their sensitivity to the behavior of the driver regarding recharging, to the battery capacity, to the trips distance, to the fuel used (e.g., fossil fuel vs. low carbon renewable fuel) or to the carbon intensity of the electricity mix. This second part of the study was built on the experimental results detailed in this article by using simulations and will be the subject of a separate article.

In more detail, the analysis presented in this article aims to compare:

- Diesel vs. gasoline results: the test protocol includes a Diesel PHEV and a gasoline PHEV;
- Standard vs. renewable fuels: the fuel matrix allows comparing a B7 with a 100% renewable HVO; and the comparison between an E10 and a 100% renewable gasoline, blended with 20% v/v ethanol (E20);
- Full battery mode (charge depleting mode (CD)) vs. empty battery (charge sustaining mode (CS));
- PHEV vs. HEV: by artificially varying the weight of the vehicle on the chassis dyno (equivalent to the weight difference between a HEV and a PHEV), the test protocol allows a comparison of a PHEV with an equivalent non-rechargeable HEV.

Most of the experimental campaign is carried out on a chassis dynamometer, to maximize the repeatability and comparability between all the configurations tested. On-road tests are then conducted to validate the behavior and comparison seen in the first experimental part. Exhaustive measurement equipment is used to assess CO_2 emissions, regulated and non-regulated pollutants emissions (both engine-out and tailpipe), energy consumptions (both fuel and electricity) as well as the electrical services offered (all-electric range and utility factor).

Test Vehicles

As one of the goals of the study is to compare a gasoline PHEV with a Diesel one in a similar configuration, the vehicles selection narrowed to a pair of Mercedes C300de (Diesel) and C300e (gasoline). These two vehicles have the same electrical characteristics (battery, electric machine, architecture), and the powertrain of these two vehicles differ only by the internal combustion engine. In addition, the two gasoline and Diesel engines offer similar drivability (torque and power). Their main characteristics are given in Table 1 and one of the two vehicles is illustrated in Figure 1.

Test Fuels

For each vehicle, two fuels were used:

- A standard fuel, traditionally used for vehicle homologation purposes, and complying with the specifications of the mainstream commercial fuels (EN590 and EN228).

TABLE 1 Main specifications of selected vehicles. (1) In charge sustaining mode, i.e., empty battery at start of test. (2) Weighted between charge depleting mode (i.e. full battery at start of test) and charge sustaining mode, according to the current regulation.

	C300e EQ Power	C300de EQ Power
Regulation	Euro 6d-temp	
Fuel type	Gasoline	Diesel
Test mass [kg]	1885	1970
WLTP CO_2 [g/km]	CS (1): 146 Weighted (2): 31	CS: 140 Weighted: 30.5
Thermal Engine	2.0L 4cyl 155 kW turbo Direct injection	2.0L 4cyl 143 kW turbo Direct injection
Transmission	9-speed automatic transmission	
Battery	13.5 kWh 365V	
Electric motor	90 kW	
Hybridization	P2 parallel hybrid architecture	
Aftertreatment system	2*Three Way Catalyst (TWC) close coupled + Gasoline Particulate Filter (GPF) underfloor	Diesel Oxidation Catalyst (DOC) + Selective Catalyst Reduction Filter (SCRF) + Selective Catalyst Reductor (SCR) close coupled
Mileage [km]	4000	14000

FIGURE 1 Picture of the tested Mercedes C300de EQ Power.

- A 100% renewable biofuel, either complying with an alternative fuel specification (paraffinic diesel, EN15940) or with a possible foreseen specification for E20 (as there exist no specification for E20 today, the authors assumed that a fuel complying with all the EN228 specifications except the oxygen and oxygenates contents would be sensible). It is important to highlight that the vehicles are not homologated with these fuels, and that these fuels are tested for research purpose only. Long-term compliance with these fuels would require further research work. In this instance:

1. The 100% renewable paraffinic diesel is a hydrotreated vegetable oil (HVO);
2. The 100% renewable gasoline blended with 20% v/v ethanol (E20) is produced using fermentation and an alcohol-to-gasoline process, using grains, residues and wastes as feedstock, and reduces GHG emissions by 66% compared to a fossil according to the supplier. A C14 analysis performed on the fuel confirmed its biogenic origin.

The main fuel properties are given in Table 2.

Experimental Programme on Chassis Dynamometer

Vehicle Instrumentation and Measurement Systems

Table 3 details the equipment used on each vehicle during the laboratory campaign, illustrated in Figure 2. The measurements spanned engine-out and tailpipe regulated and unregulated emissions, CO_2 (and more generally GHG) emissions, fuel and electrical consumption, and some temperatures.

The devices for measuring regulated emissions are part of the permanent equipment of the test bench: CO_2, NO / NO_2, CO, HC, PM and PN. The measurements of THC, CH_4, CO, CO_2, and NOx are carried out by a Horiba MEXA 7000 analyzer. The particulates in mass are determined by CVS and samples on filter and weightings. The particulates in number (with a diameter greater than 10 nm) are determined by a SPCS. An additional particle counter CPC-100 was implemented for counting particles greater than 23 nm, so that simultaneous counting of particles between 10 and 23 nm is possible. Finally, the measurements of NO, NO_2, N_2O and NH_3 are measured by a Horiba QCL (MEXA-ONE-QL-NX) analyzer.

The use of a gas analyzer induces gas sampling that can have an impact on the vehicle's aftertreatment system.

TABLE 3 Chassis Dyno instrumentation and measurement systems.

	Measurement
Engine-out	Raw sample - HORIBA MEXA (CO_2, CO, NOx, NO, NO_2, CH_4, THC, NMHC)
	HORIBA QCL (NH_3, N_2O, NO, NO_2)
	CPC-100 (PN23)
	SPCS 110 (PN10)
Tailpipe	CVS - HORIBA MEXA (CO_2, CO, NOx, NO, NO_2, CH_4, THC, NMHC)
	HORIBA QCL (NH_3, N_2O, NO, NO_2)
	CPC-100 (PN23)
	SCPS 110 (PN10)
	PM by filter weighting
	DMS500 (particle size distribution)
Fuel consumption	Carbon balance on tailpipe emissions
Electrical consumption	HIOKI 3390 (current clamp on high-voltage (HV) direct current (DC) cable between battery and inverter
	Current clamp on low-voltage (LV) battery)
Aftertreatment system	AdBlue consumption when urea SCR is used thanks to instrumentation of the injector control signals (number of pulses and Ti), urea Pressure and a characterization of the injector
Temperature	Engine-out
	TWC or DOC inlet
	DPF or GPF inlet and outlet
	Sump
	Coolant
Additional bench measurements	Exhaust flow
	Ambient temperature, pressure, and humidity
	Roller power
	Vehicle speed
	Engine speed

TABLE 2 Key properties of test fuels.

		Standard		Renewable	
Property	Method	EN590	EN228-E10	HVO	E20
Density [kg/L]	EN ISO 12185	0.834	0.748	0.764	0.762
Lower Heating Value [MJ/kg]	ASTM D 240/ASTM D3338 mod/GC calculated	42.13	41.40	44.16	39.78
Carbon content [%m/m]	ASTM D 5291/ASTM D3343 mod/GC calculated	85.8	83.1	84.62	79.4
Hydrogen content [%m/m]	ASTM D 5291/ASTM D3343/GC calculated	13.5	13.4	15.38	13.4
Oxygen content [%m/m]	MO238LA2008/EN 14078/GC calculated	0.7	3.5	0	7.2
Total aromatics	EN 12916/IP 391 mod/NF M 07-086/EN ISO 22854	22.2 %m/m	26.7 %v/v	0.1 %m/m	28.7 %v/v
Cetane number / RON-MON [-]	EN ISO 5165/5164/5163/ASTM D6890	52.5	97.0-85.9	78.2	99.4-88.0
Final boiling point [°C]	EN ISO 3405/ASTM D86	354.1	180.2	302.5	201.7

FIGURE 2 Picture of the chassis dyno setup with one of the tested vehicle.

Artificial flows are induced when the engine is turned off and can cause changes in temperature and gas composition conditions. These phenomena can then influence the thermal deactivation dynamics of the catalysts or modify the storage of oxygen in the catalyst blocks. These impacts are greater in the case of PHEVs, with long engine-off phases. To avoid these effects and to limit the intrusiveness of gas sampling on the vehicle's behavior, the sampling rates of the gas analyzers are switched off when the engine speed is below its idle speed.

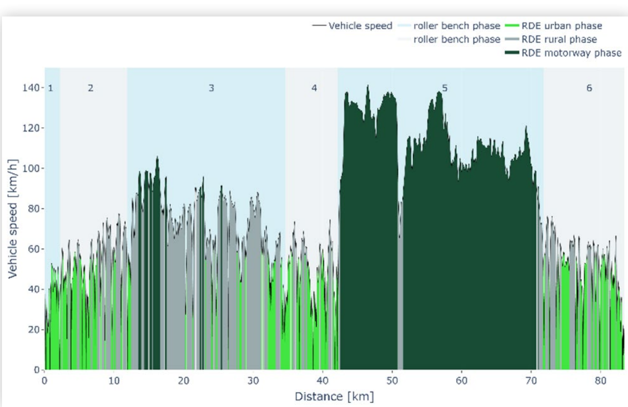
RDE Test Cycle Reproduced on Chassis Dyno

The cycle operated at the test bench was derived from a previous RDE test driven on-road and compliant with the RDE WP3 and WP4 requirements [15, 16]. Figure 3 depicts the vehicle speed as a function of distance driven with chassis dyno phases and RDE phases (urban, rural and motorway) as stipulated by the RDE regulation. The cycle is cut into 3 categories based on the vehicle speed: the urban phase gathered the events where the vehicle speed is lower than 60 km/h (included), the rural phase between 60km/h and 90km/h (included) and the motorway phase above 90km/h. The chassis dyno phases are driven by the equipment capabilities, in this case, the volume of the sampling bags. The volume of the gas trapped can be reduced to the sampling duration because of the constant volume sampling (CVS) system. On the equipment used for the PHEV testing, the sampling bags could be used for a maximum of 1322 seconds. As the RDE cycle total duration is approximately of 5600 seconds, the choice made was to use 6 bags. The first bag is focused on the beginning of the test, the firsts kilometers, the second phase is mainly composed of urban conditions, the third one with mainly rural condition, the fourth phase is mainly urban, the fifth one mainly motorway and the last (sixth) phase is also mainly urban conditions.

The RDE trip is also defined by its drivability. To assess and categorize the driving behavior, two main indicators are used: the 95th percentile of v*apos,, i.e., the 95th percentile of vehicle speed x (acceleration >= 0.1m/s2) for each RDE phase, and the Relative Positive Acceleration (RPA), i.e., the sum of vehicle speed x (acceleration $\geq 0.1 m/s^2$) / distance driven (in km) for each RDE phase. Those indicators are constrained by the RDE regulation.

Figure 4 and Figure 5 show those drivability indicators 95th percentile of v*apos and RPA respectively in relation to the RDE boundaries. More information about the compliance with RDE criteria can be found in Appendix 1.

FIGURE 3 Vehicle speed profile with chassis dyno and RDE (urban, rural, motorway) phases.



Road Load

Road laws are needed to assess the energy required to propel the vehicle. The driving resistance force is given through a speed polynomial based on masses and dimensionless coefficients registered in the next table for all vehicle configurations.

$$F_{wheel} = Inertia.g.(F0 + F1.v) + F2.v^2$$

Table 4 shows the road load coefficients used at the test bed. Those coefficients are issued from C300e certification coefficients in Vehicle Low configuration. They were chosen because they are closer to real masses and show less difference between the Diesel and gasoline vehicles. The choice of a unique set of coefficients was made to simplify the comparison.

In order to simulate the resistance behavior of a not off-vehicle chargeable hybrid electric vehicle (NOVC-HEV, later

FIGURE 4 V*apos on RDE reference cycle on roller test bench, by urban, rural, motorway phases and over total cycle, compared to RDE boundary.

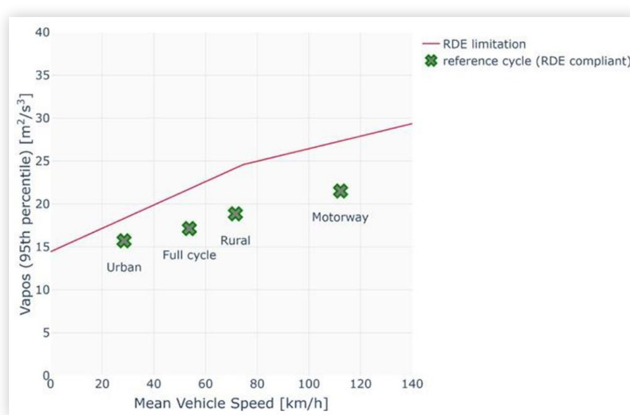


FIGURE 5 Relative Positive Acceleration (RPA) on RDE reference cycle on roller test bench, by urban, rural, motorway phases and over the whole cycle, compared to RDE boundary.

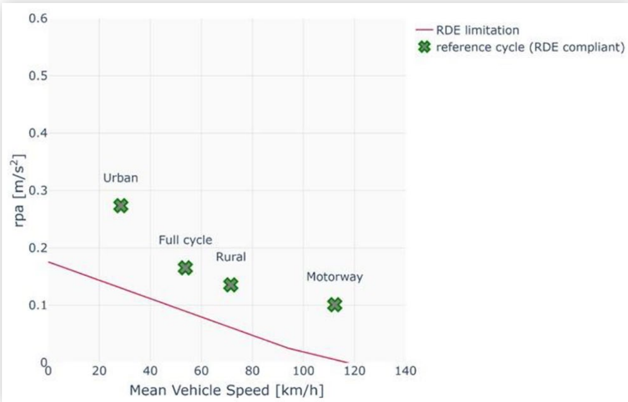


TABLE 4 Tested vehicles road laws.

	PHEV Diesel	HEV Diesel	PHEV Gasoline	HEV Gasoline
inertia [kg]	1970	1850	1885	1765
F0 [N]	134.8			
F1 [N/(km/h)]	0.561			
F2 [N/(km/h)^2]	0.02762			

referred as "HEV") compared to an off-vehicle chargeable hybrid electric vehicle (OVC-HEV, later referred as "PHEV"), a market research was performed with vehicle models that are commercialized in both HEV and PHEV configurations. The difference between the vehicles mass was assessed to be around 120 kg. This hypothesis was also validated by the estimation of the mass of the components of the HEV and the PHEV, i.e. mainly a gap due to a reduced battery size and no onboard charging equipment. The hypothesis that externally both PHEV and HEV are identical led to the use of the same F0, F1 and F2 road load coefficients.

Test Matrix

Both vehicles were tested with two fuels, standard and renewable ones, and three testing conditions, charged (CD - Charge Depleting), uncharged (CS - Charge Sustaining) and uncharged using a reduced weight (CS HEV) to simulate the configuration of a hypothetic (non-plug-in) hybrid electric vehicle. Each test was repeated three times to assess and ensure good repeatability. To avoid biases due to the timeline of tests and configuration changes, the proposed test matrix is based upon three main test blocks with the standard fuels and three blocks performed with the renewable fuels. An extra test block was added for further evaluation of the renewable fuels with a battery conditioning that is uncharged (CS). In addition, a configuration was chosen as reference to monitor the repeatability of the vehicle during the test campaign. Tests identified as invalid at the time of running were repeated in-sequence whereas those identified later as non-conforming were repeated in a position in the sequence subject to the constraint of avoiding successive tests on the same configuration. The actual test order deviated from the planned test order due to operational requirements. Table 5 shows the initial test matrix.

The driving cycles were long enough to ensure a full depletion of the battery (as illustrated in Figure 13), and therefore a transition from CD to CS. Furthermore, to ensure that the CS cycles start with a fully depleted battery and a consistent state of charge, they were preceded by a "normal" RDE cycle (at the end of which the battery is already well depleted) followed by a steady state driving in all-electric mode at 50 km/h until the engine finally starts (the steady state driving at 50 km/h is likely to be the driving conditions in which the ECU will maximize the all-electric drive, and therefore battery depletion).

The tested Diesel vehicle went through a DPF regeneration that required some extra test to regenerate the soot cake. The test in which the regeneration occurred as well as the following conditioning tests were omitted from the analysis (Note that according to the current regulation, a test where a DPF regeneration occurs is non-valid. However, a test performed right after the DPF regeneration, when the soot cake is not fully regenerated, is valid. The reason why

TABLE 5 Test matrix for tests performed on the chassis dyno.

	Vehicle	Fuel	Battery	Mass	Repeat
Block 1	C300de	EN590	CD	PHEV	1
	C300e	E10	CD	PHEV	1
	C300e	E10	CS	PHEV	1
	C300de	EN590	CS	PHEV	1
	C300de	EN590	CS	HEV	1
	C300e	E10	CS	HEV	1
	C300de	EN590	CD	PHEV	2
	C300e	E10	CD	PHEV	2
Block 2	C300de	EN15940	CD	PHEV	1
	C300e	E20	CD	PHEV	1
Block 3	C300e	E10	CS	PHEV	2
	C300de	EN590	CS	PHEV	2
	C300de	EN590	CS	HEV	2
	C300e	E10	CS	HEV	2
	C300de	EN590	CD	PHEV	3
	C300e	E10	CD	PHEV	3
Block 4	C300de	EN15940	CD	PHEV	2
	C300e	E20	CD	PHEV	2
Block 5	C300e	E10	CS	HEV	3
	C300de	EN590	CS	HEV	3
	C300de	EN590	CS	PHEV	3
	C300e	E10	CS	PHEV	3
	C300de	EN590	CD	PHEV	4
	C300e	E10	CD	PHEV	4
Block 6	C300de	EN15940	CD	PHEV	3
	C300e	E20	CD	PHEV	3
Extra	C300e	E20	CS	PHEV	1
	C300de	EN15940	CS	PHEV	1
	C300de	EN15940	CS	PHEV	2
	C300e	E20	CS	PHEV	2

we decided to omit these results from the analysis is related to repeatability issues: tests performed right after DPF regeneration generally have higher particulate emissions, which is detrimental to repeatability. In the context of this study, whose purpose is to compare different vehicles and fuels configurations, a fairly good repeatability was needed, which led to omit these tests which would have looked like outliers and would have limited the extent of the conclusions regarding the comparison of the configurations). The statistical analysis was carried out on all remaining data declared valid by the test facility. Statistical outlier testing was performed, and no significant outliers were identified for further omission following this.

Correction Factor

For tests performed in charge sustaining (CS) mode, a correction factor may be applied to compensate for the actual difference of state of charge (SOC) of the battery between the beginning and the end of the test, so that results are displayed at iso-SOC. The calculation of this correction factor follows the following steps.

If the variation of energy stored in the battery had to be produced by the combustion engine:

$$\Delta E_{elec}[Wh] = \eta_{elec} \times \eta_{thermal} \times \Delta E_{fuel}[Wh]$$

Where,

- ΔE_{elec} is the variation of electrical energy stored in the battery during the test.
- η_{elec} is the mean electrical efficiency (from the shaft to the battery). Based on the calibrated simulators (not detailed in this article), it is set to 77% (motor 87%, inverter 90%, battery 98%).
- $\eta_{thermal}$ is the mean thermal efficiency (from the fuel to the shaft). Based on the calibrated simulators, it is set to 35% for Diesel and 33% for gasoline.
- ΔE_{fuel} is the theoretical delta of fuel energy needed to produce ΔE_{elec}.

Therefore,

$$\Delta E_{fuel}[Wh] = \frac{\Delta E_{elec}}{\eta_{thermal} \times \eta_{elec}}$$

$$= \frac{(SOC_{CS,end} - SOC_{CS,ini}) \times Battery\ capacity[Wh]}{\eta_{thermal} \times \eta_{elec}}$$

Furthermore, the thermal energy consumption measured over the cycle is:

$$E_{fuel}[Wh] = FC[L] \times Fuel\ density\left[\frac{g}{L}\right] \times Fuel\ LHV\left[\frac{kJ}{kg}\right] \times \frac{1}{3.6}$$

Finally, the correction factor is determined as follows, along with the corrected consumption and CO2 emission values:

$$Correction\ factor = 1 - \frac{\Delta E_{fuel}}{E_{fuel}}$$

$$FC_{corrected}\left[\frac{L}{100km}\right] = Correction\ factor \times FC\left[\frac{L}{100km}\right]$$

$$CO_{2\,corrected}\left[\frac{g}{km}\right] = Correction\ factor \times CO_2\left[\frac{g}{km}\right]$$

Thus, if the vehicle performs a partial recharge of the battery during the CS test, its fuel consumption will be corrected downwards. Conversely, if it uses energy from the battery and partially discharges it during this CS test, its consumption will be corrected upwards.

Experimental Programme On-Road

Vehicle Instrumentation and Measurement Systems

Part of the instrumentation is similar to what was used during the chassis dyno tests: measurement of the battery output current, on-board diagnostic (OBD) information, urea consumption for the Diesel vehicle. Regarding the pollutants and greenhouse gases emissions, their measurement was performed with a portable emissions measurement system (PEMS) as detailed in Table 6 and illustrated in Figure 6.

TABLE 6 On-road vehicle instrumentation and measurement systems.

	Measure
Tailpipe	HORIBA OBS-ONE GS (CO_2, CO, NOx, NO, NO_2)
	HORIBA OBS-ONE PN (PN23)
Fuel consumption	Carbon balance on tailpipe emissions
Electrical consumption	HIOKI 3390 (current clamp on HV DC cable between battery and inverter
	Current clamp on LV battery)
AFTS	AdBlue consumption when urea SCR is used thanks to instrumentation of the injector control signals (number of pulses and Ti), urea Pressure and a characterization of the injector
Temperature	Engine-out
	TWC/DOC inlet
	DPF/GPF inlet and outlet
	Sump
	Coolant
Additional measurements	Exhaust Flow Meter (EFM)
	Ambient temperature, pressure and humidity (PEMS weather station)
	Vehicle speed (from PEMS Global Positioning System (GPS))
	Engine speed

FIGURE 6 Vehicle setup for on-road tests, with PEMS equipment.

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RDE Cycle On-Road

The itinerary is the same as the driving cycle performed at the chassis dyno, but the speed profile as well as the aggressiveness indicator differs from what was performed at the test bed due to traffic conditions causing different driveability factors (V*apos and RPA, see Figure 7, Figure 8 and Figure 9). Only RDE compliant tests were kept in the analysis presented in the following.

FIGURE 7 Vehicle speed profiles measured during on-road tests compared to the RDE cycle performed on the chassis dyno.

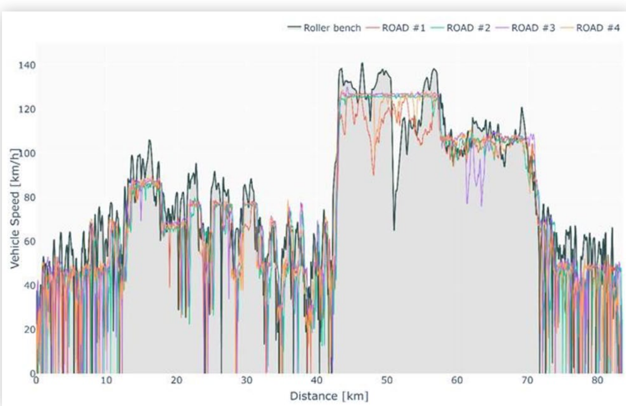

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FIGURE 8 V*apos measured during on-road-tests compared to RDE boundaries.

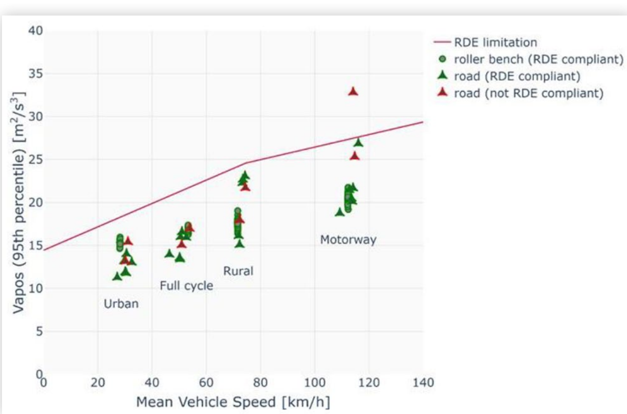

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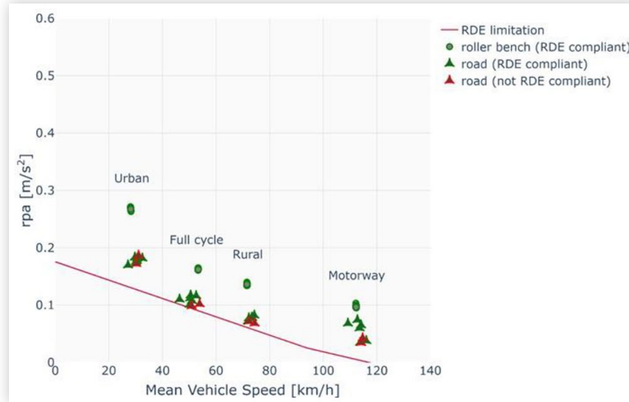
FIGURE 9 Relative Positive Acceleration measured during on-road tests compared to RDE boundaries.



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Test Matrix

As Table 7 shows, only one repetition was made for the two battery modes with the reference fuel. As the RDE compliance condition was not always respected and some hardware failed, the final test matrix was different from the one below and was finally populated with more tests and more repeats.

Results Obtained in Laboratory Conditions

Key results from the RDE tests performed on the chassis dyno are described in this section and the full results are tabulated in Appendices 2 and 3. Where shown on charts, error bars denote the 68 % confidence intervals (i.e. +/- the standard deviation) and the number of test repeats on which the mean values are calculated is indicated at the bottom of each bar. In the following figures using the format of Figure 10 in this section, the comparisons between the average values obtained on the RDE cycle for the different configurations are shown as follows:

- E10 vs E20 (used in the gasoline PHEV) vs B7 vs HVO (used in the Diesel PHEV).
- In the following configurations: Charge Depleting mode (CD), Charge Sustaining mode (CS) and HEV CS mode.

TABLE 7 Test matrix for tests performed on-road.

Vehicle	Fuel	Battery	Mass	Repeat
C300de	EN590	CD	PHEV	1
C300e	E10	CD	PHEV	1
C300e	E10	CS	PHEV	1
C300de	EN590	CS	PHEV	1

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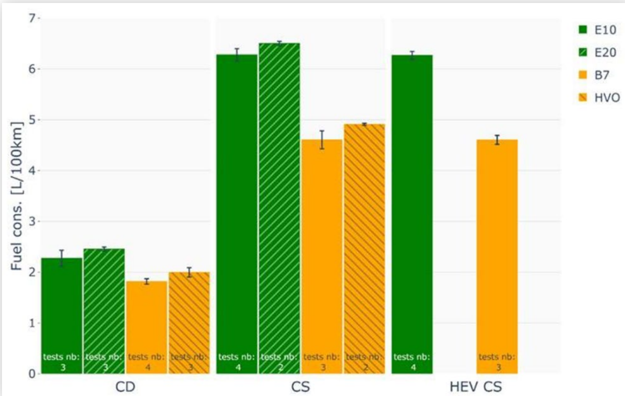
FIGURE 10 Comparison of Volumetric Fuel Consumption [L/100km] measured on RDE cycles on chassis dyno for each fuel and mode.



Volumetric Fuel Consumption

Figure 10 shows the evolution of fuel consumption in all the tested configurations. The volumetric fuel consumption is calculated thanks to the fuel properties, the CO_2, HC and CO emissions in mass. The Diesel PHEV using B7 shows lower volumetric fuel consumption compared to the gasoline PHEV using E10: -20.1% in CD and -26.7% in CS. This finding is consistent with the literature [17] and explained by the better efficiency of compression ignition engines and by the higher density of B7 compared to E10, leading to a higher energy density by volume.

When applying the correction factors (Figure 11), the gap between the gasoline PHEV using E10 and the Diesel PHEV using B7 in CS increases to -32.6%. It because the Diesel vehicle showed a higher partial battery recharge than the gasoline vehicle during the CS tests.

Switching to renewable fuels leads to a higher volumetric fuel consumption, both for the gasoline and the Diesel vehicles: + 4.5 % for E20 compared to E10 in CS and + 8.4 % for HVO compared to B7 in CS, after applying the correction factors. This is due to the lower energy density by volume of these renewable fuels: a lower density for HVO compared to B7 (despite a higher energy density by mass) and a higher oxygen content for E20 compared to E10.

No significant impact of the HEV versus PHEV configuration was detected for either the Diesel or gasoline vehicle. This is a rather surprising result given that one would normally expect a significantly lighter vehicle (-120 kg) to result in lower energy consumption. Quite logically, the HEV vehicle with 120kg less weight needs less energy for the same driving cycle: it consumes 0.53 kWh/100km less positive energy at the wheel compared to the PHEV vehicle. It is compensated by the fact that, on hybrid vehicles in general, part of the kinetic energy delivered to the vehicle is recovered during regenerative braking. Thus, the PHEV vehicle, with its 120kg more, recovers 0.22 kWh/100km more to its battery compared to the HEV vehicle. This compensation explains why vehicles with regenerative braking (HEV, PHEV, BEV) are therefore less sensitive to mass variations compared to conventional vehicles. However, it does not explain the total lack of mass sensitivity established experimentally.

Electrical Consumption and Utility Factor

Figure 12 shows the net electrical energy consumed for each configuration on the RDE cycles. Here, it is particularly relevant to focus on consumption in charge depleting mode. Indeed, electrical consumption in charge sustaining mode is only the result of marginal variations of SOC between the start and the end of the cycle. These consumptions have no practical significance, insofar as there is no external electrical energy to consume in this mode which is, by definition, a mode of maintaining the charge level. Moreover, these "parasitic" consumptions are reduced to zero by determining the corrected fuel consumptions and CO_2 emissions in CS, as detailed above.

Thus, regarding the CD cases, the Diesel PHEV fuelled with B7 consumes 9.4% less electrical energy than the gasoline PHEV fuelled with E10. As the battery, i.e. the "electric energy tank", is identical between the two models, it means that the SOC at the end of the RDE in the case of

FIGURE 11 Comparison of corrected Volumetric Fuel Consumption [L/100km] measured on RDE cycles on chassis dyno for each fuel and mode.

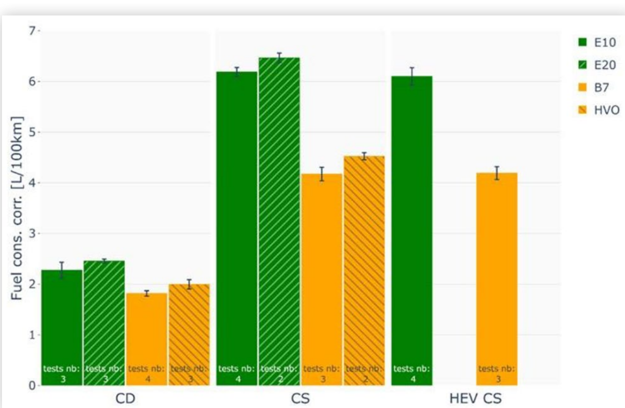
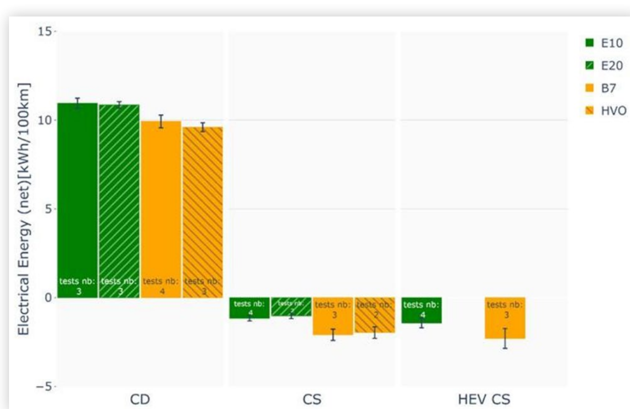


FIGURE 12 Comparison of Electrical consumption [kWh/100km] measured on RDE cycles on chassis dyno for each fuel and mode.



the B7 PHEV CD is systematically higher than for the E10 PHEV CD RDE. The difference can be explained by a difference of calibration on the electric versus thermal use between the petrol and Diesel PHEV, specifically around the motorway driving. The Diesel vehicle seems to use its thermal engine at an earlier stage, which reduces the use of electricity. Furthermore, at the end of the driving, the battery of the Diesel vehicle seems to recharge more, explaining the reduced net electrical consumption compared to the gasoline one (see Figure 13). It could also be explained by a difference of behaviour between the two vehicles history as they are second-hand vehicles. Switching from standard (E10 and B7) to renewable fuels (E20 and HVO) has no significant impact on the CD electrical consumption.

Figure 14 shows the utility factors, i.e., the percentage of distance driven in all-electric mode. The Diesel PHEV fuelled with B7 shows 8.8% lower electric driving mode in CD and 20.7% less in CS compared to E10. This behaviour can be linked to a difference in calibration between the gasoline and Diesel PHEV, as the thermal engine efficiencies differ and the fuel properties are in favour of the Diesel vehicle, the electric usage may decrease [18]. This behaviour is consistent with the analysis made on the electrical consumption. Switching from standard (E10 and B7) to renewable fuels (E20 and HVO) has no significant impact on the UF, neither in CS nor in CD. Likewise, HEV demonstrated UF similar to PHEV ones in CS, for both the gasoline and the Diesel vehicles.

FIGURE 13 Comparison of Battery State of Charge [%] in depleting mode on RDE cycles on chassis dyno for the Diesel PHEV (B7) and the gasoline PHEV (E10).

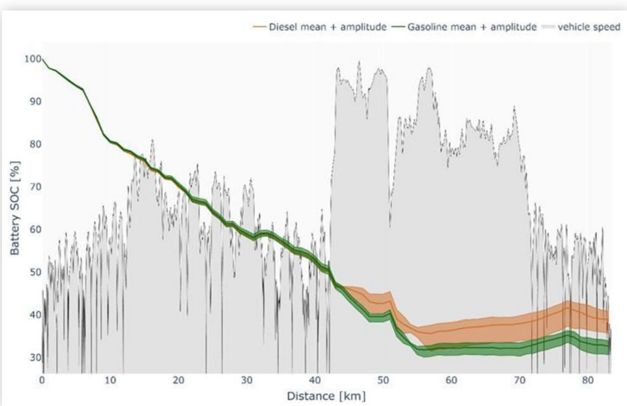
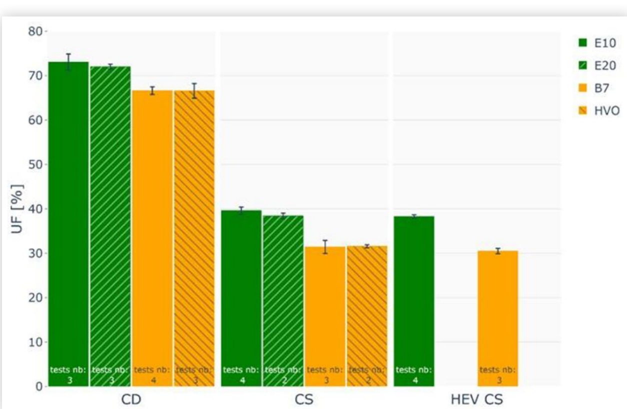


FIGURE 14 Comparison of Utility factor [%] measured on RDE cycles on chassis dyno for each fuel and mode.



Carbon Dioxide (CO_2) and GHG Emissions

Tailpipe CO_2 emissions differences between E10, E20, B7 and HVO are shown in Figure 15. In charge sustaining mode, the Diesel technology shows a reduction of 15.5 % of CO_2 emissions (22.3 % when CO_2 is corrected to return to iso-SOC CS condition, see Figure 16) compared to the gasoline one. This is consistent with the statements made above on volumetric fuel consumption, and the CO_2 emission factors of the respective fuels.

Using renewable fuels, E20 does not significantly change the CO_2 emissions compared to E10. On the contrary, HVO shows lower CO_2 emissions by 3.6 % (2.0 % when corrected) compared to B7 in charge sustaining mode, thanks to its lower CO_2 emission factor.

FIGURE 15 Comparison of tailpipe CO_2 emissions [g/km] measured on RDE cycles on chassis dyno for each fuel and mode.

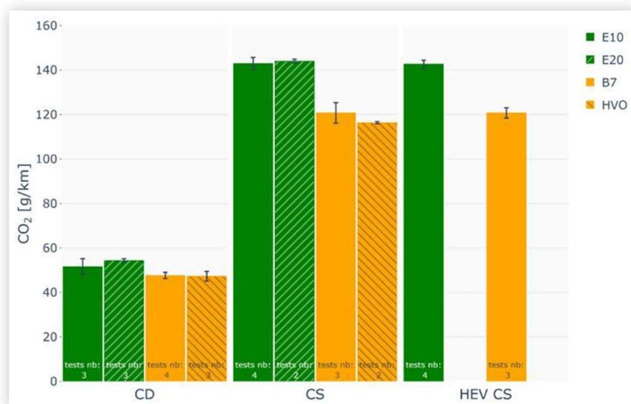
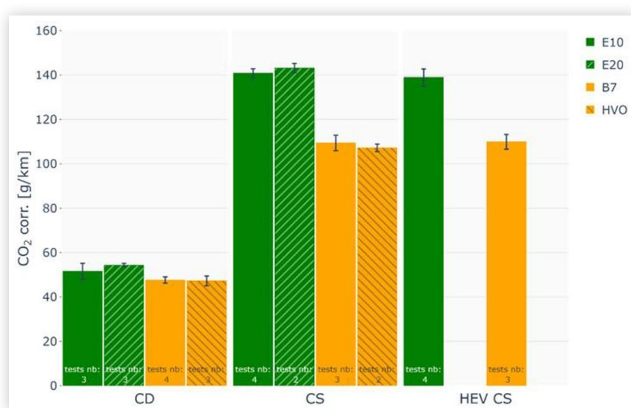


FIGURE 16 Comparison of corrected tailpipe CO_2 emissions [g/km] measured on RDE cycles on chassis dyno for each fuel and mode.



Reducing the mass of the vehicle, i.e. HEV mode, does not impact the CO_2 emissions, for gasoline, as well as for Diesel. Similarly to the volumetric fuel consumption, it is quite a surprising result.

Adding the non-regulated greenhouse gases (CH_4, N_2O) emissions to the CO_2 emissions leads to an increase of total GHG compared to CO_2 only by around 3% in Diesel and 0.8% in gasoline. The main contributor to this CO_2 equivalent increase is the N_2O, because of its high GWP and because almost no CH_4 is released at the tailpipe. As more N_2O is emitted by the Diesel PHEV, the -22.3% CO_2 emissions gap that was quantified between gasoline and Diesel vehicles is reduced to -20.5% considering total GHG emissions. More details on the non-CO_2 GHG emissions is provided in the Appendix 4.

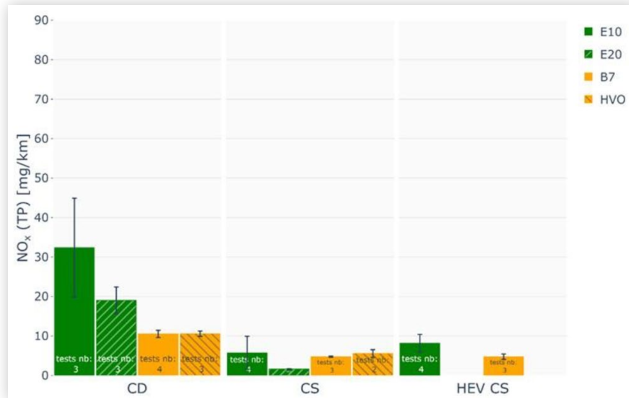
Oxides of Nitrogen (NOx) Emissions

As expected from the literature [19, 20], the Diesel engine using exhaust gas recirculation (EGR) emits less engine-out NOx than the stoichiometric gasoline one: around 80% less both in CS and CD (Figure 17). At the tailpipe (Figure 18), the first observation is that both B7 and E10 vehicles have very low emissions level in CS mode, below 10 mg/km, bearing in mind that the Euro6d limits for NOx emissions are 60 mg/km for gasoline and 80 mg/km for Diesel. In CD mode, the gasoline PHEV has higher NOx emissions than the Diesel one, mostly due to the cold start of the engine during the motorway phase.

Switching to renewable fuels has no significant impact on the engine-out NOx emission levels. At the tailpipe, HVO does not have a significant effect on NOx emissions compared to B7, when E20 shows a reduction of tailpipe NOx emissions compared to E10, both in CD and CS mode. Changing from PHEV to HEV has no significant impact on the engine-out and tailpipe NOx emission levels.

As the very low NOx tailpipe level could foreshadow, the NOx aftertreatment system (AFTS), i.e., the three-way catalyst for the gasoline PHEV and the SCR for Diesel PHEV, demonstrates high conversion efficiencies, over 95% in CS mode, as shown in Figure 19. Despite higher engine-out NOx emissions, E20 shows lower tailpipe NOx compared to E10 in CD and in CS, de facto improving the AFTS conversion efficiency. HVO does not impact NOx AFTS conversion efficiency compared to B7, nor does HEV compared to PHEV.

FIGURE 18 Comparison of tailpipe NOx emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.



Particulate Mass and Particle Number Emissions

Engine-out particle emissions are globally higher for the Diesel PHEV compared to the gasoline PHEV, for both PN23 (Figure 20) and PN10 (Figure 21). This finding is in line with the well-known behavior of Compression Ignited engine compared to Spark Ignited engines (diffusion flame vs premixed flame). The Diesel PHEV fueled with B7 emits almost 200 times more PN23 engine-out compared to the gasoline PHEV fueled with E10 in CS mode and around 50 times more for PN10. Compared to E10, E20 tends to increase by a factor of 4.4 engine-out PN23 and by 3.6 engine-out PN10 in CS mode.

FIGURE 17 Comparison of engine-out NOx emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.

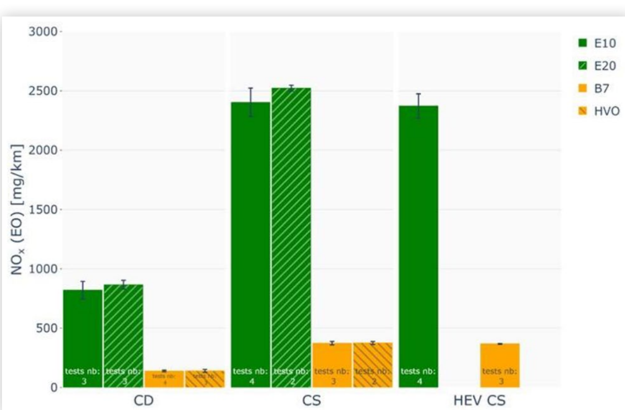


FIGURE 19 Comparison of NOx AFTS conversion efficiency [%] measured on RDE cycles on chassis dyno for each fuel and mode.

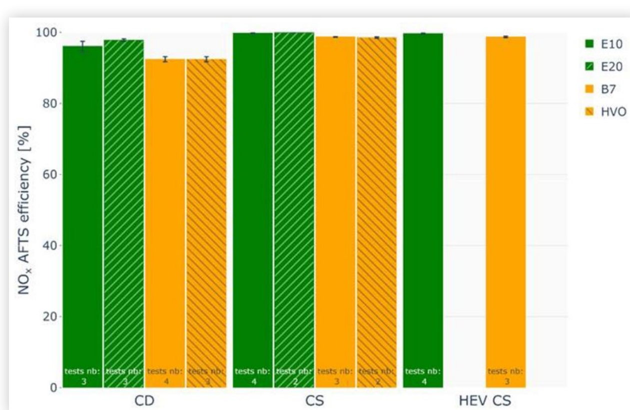
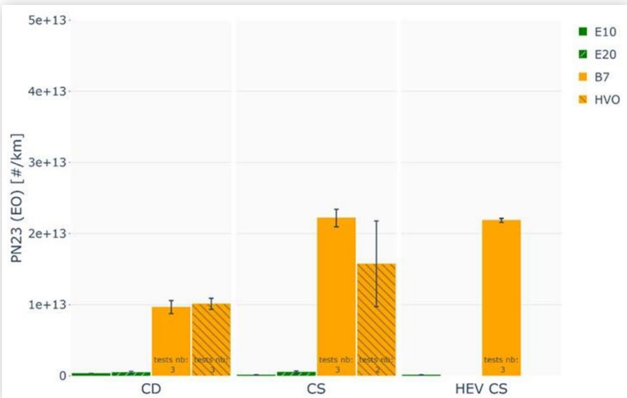


FIGURE 20 Comparison of engine-out PN23 emissions [#/km] measured on RDE cycles on chassis dyno for each fuel and mode.



At the tailpipe, and as expected from the literature [21, 22], the gasoline PHEV emits more PN23 (Figure 22) or PN10 (Figure 23) than the Diesel PHEV. In CS mode, the gasoline PHEV fueled with E10 emits around 480% more particle compared to the Diesel PHEV fueled with B7, regardless of the cut diameter considered at 10 or 23 nm. E20 or HVO have no significant impact on tailpipe PN23 or PN10 compared to E10 or B7, nor the HEV configuration compared to PHEV. In all the tested configurations, the tailpipe PN emissions are far below the Euro 6d limits (6.10^{11} #/km).

Figure 24 and Figure 25 show the PN filter efficiency, i.e., GPF for the gasoline PHEV and DPF for the Diesel PHEV. The DPF efficiencies are higher than the GPF ones, in agreement with the existing literature [21, 22]. HVO does not have a significant impact on the DPF efficiency, nor the HEV configuration for PN23 or PN10 filtration. As on the one hand, E20 tends to increase engine-out PN23 and PN10 compared to E10, and on the other hand, E20 tailpipe PN23 or PN10 are similar to E10 ones, the GPF filtration efficiencies with E20 are higher than with E10. HEV configuration does not impact the GPF filtration efficiency.

FIGURE 21 Comparison of engine-out PN10 emissions [#/km] measured on RDE cycles on chassis dyno for each fuel and mode.

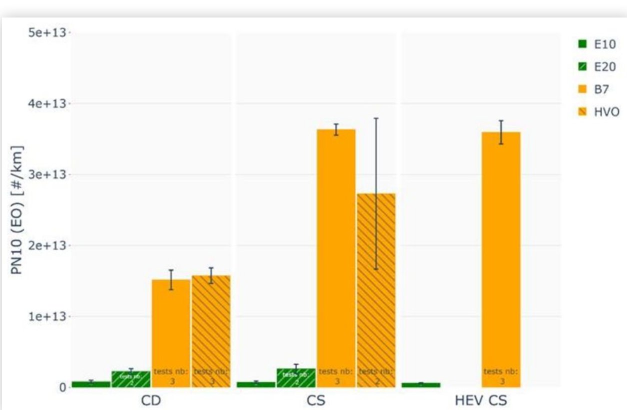


FIGURE 22 Comparison of tailpipe PN23 emissions [#/km] measured on RDE cycles on chassis dyno for each fuel and mode.

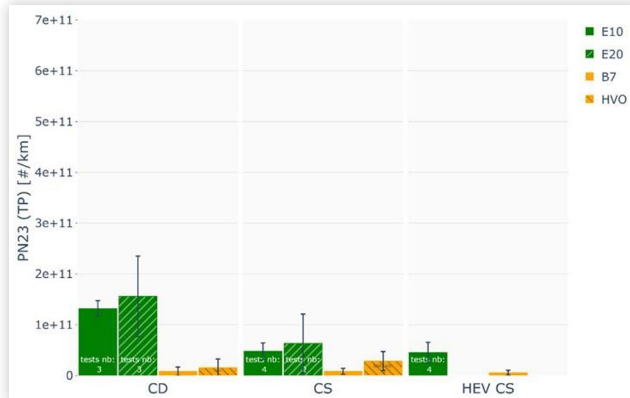


FIGURE 23 Comparison of tailpipe PN10 emissions [#/km] measured on RDE cycles on chassis dyno for each fuel and mode.

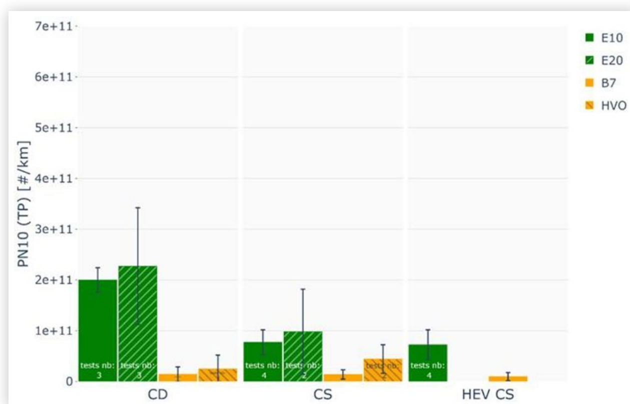


FIGURE 24 Comparison of PN23 efficiency [%] measured on RDE cycles on chassis dyno for each fuel and mode.

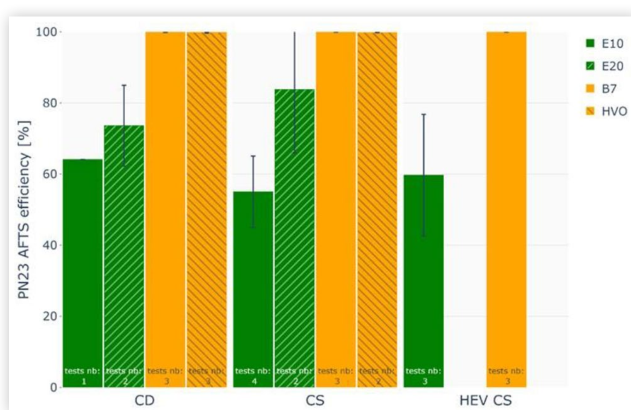


FIGURE 25 Comparison of PN10 efficiency [%] measured on RDE cycles on chassis dyno for each fuel and mode.

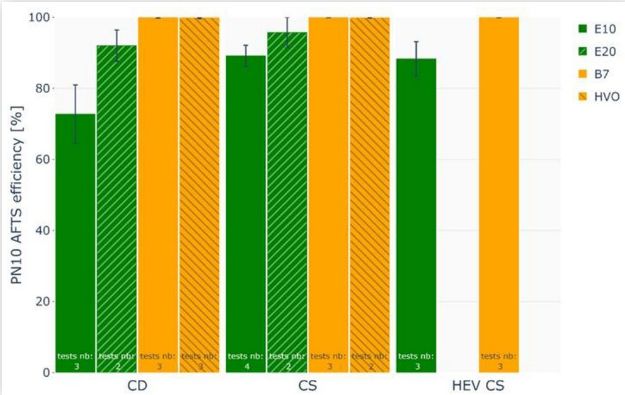


FIGURE 27 Spectrum of Tailpipe PN emissions measured with DMS500 - RDE test cycle, roller test bench, CS mode, gasoline vehicle, E10.

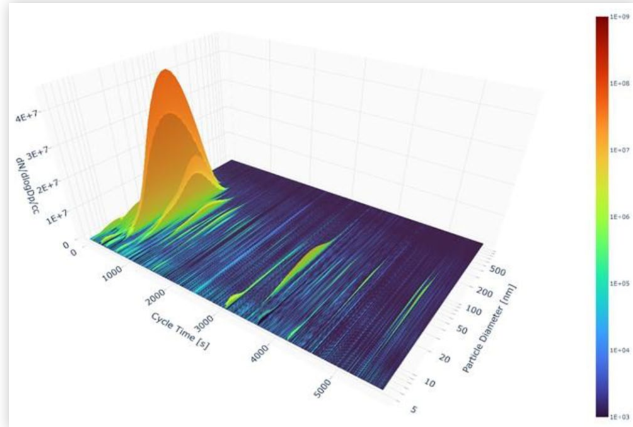


Figure 26 and Figure 27 show DMS500 measurement results at the tailpipe for a representative cycle with B7 and E10 respectively. As shown previously, levels for E10 are higher than for B7. The DMS500 device makes it possible to evaluate the particle size distribution at each moment of the test. The particles have larger diameters for gasoline than for Diesel. This is due to the filtration technology used, and the sensitivity of engine performance to the back pressure of the gasoline powertrain which induces the need to manage a trade-off between filtration efficiency and fuel consumption. Also, B7 emissions are mainly located around the engine start. E10 emissions are higher at engine start and are sensitive to the driving behavior and enrichment phases (motorway insertion, around 3500s in Figure 27).

Figure 28 shows PM emissions at the tailpipe. These values are to be compared with Euro 6d limit of 4.5 mg/km. Both vehicles show very low level of particulate matter in mass.

FIGURE 28 Comparison of tailpipe PM emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.

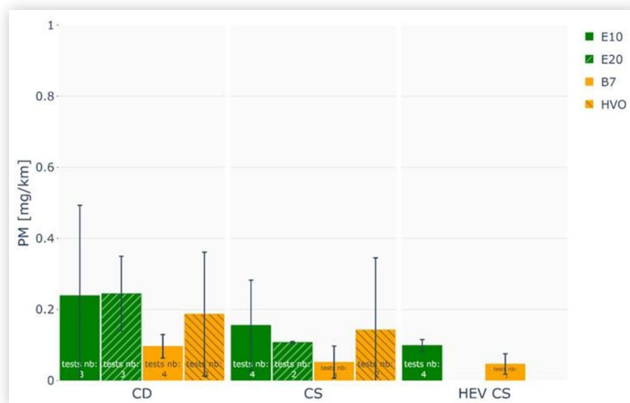
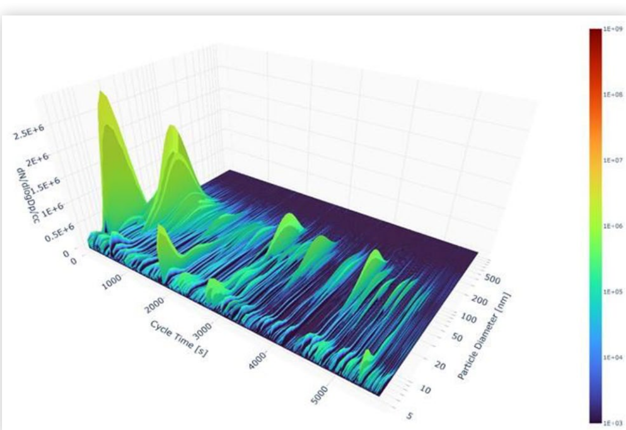


FIGURE 26 Spectrum of tailpipe PN emissions measured with DMS500 - RDE test cycle, roller test bench, CS mode, Diesel vehicle, B7.



Carbon Monoxide (CO) Emissions

The Diesel PHEV fuelled with B7 emits 92% less engine-out CO emissions than the gasoline PHEV fuelled with E10 in CS mode (Figure 29). E20 does not have any impact on CO engine-out emissions compared to E10, when HVO tends to reduce engine-out CO emissions by 24% compared to B7 in CS. HEV does not affect engine-out CO emissions, neither for gasoline nor for Diesel vehicles.

At the tailpipe (Figure 30), the Diesel and gasoline PHEVs show very low emission levels in CS mode, below 60 mg/km for E10/E20 (compared to the Euro 6d limit of 1000 mg/km), and below 10 mg/km for B7/HVO (compared to Euro 6d limits of 500 mg/km). The tailpipe CO emissions of the gasoline PHEV fuelled with E10 are higher than those of the Diesel PHEV fuelled by B7, by around 300% in CS mode, with B7 emissions of less than 8mg/km. HVO tends to reduce by 59% the tailpipe CO emissions compared to B7 in CS whereas E20 increases tailpipe CO emissions by 113% compared to E10.

FIGURE 29 Comparison of engine-out CO emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.

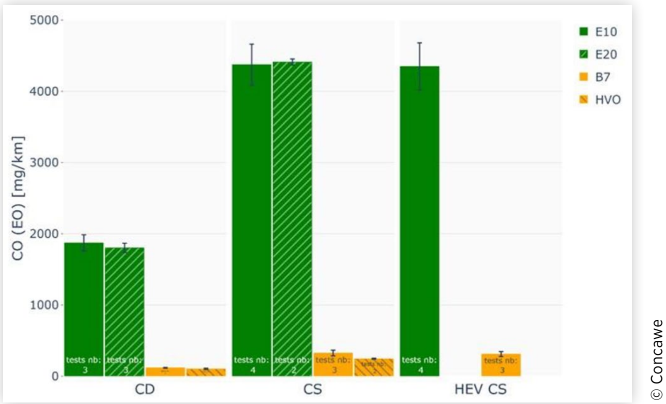


FIGURE 30 Comparison of tailpipe CO emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.

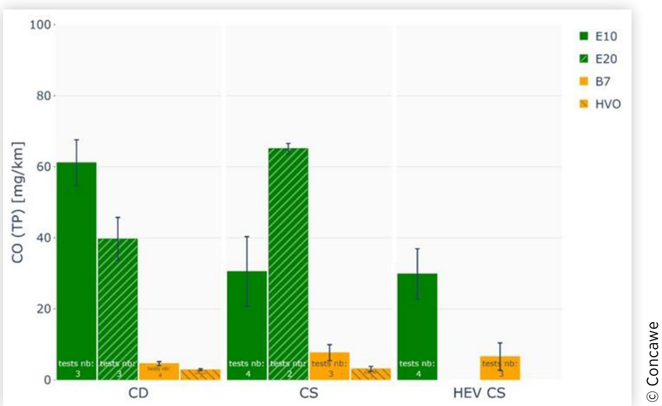


Figure 31 exhibits CO AFTS conversion efficiency, i.e. three-way catalyst for the gasoline PHEV and DOC for the Diesel PHEV. Three-way catalyst and DOC show similarly high conversion efficiencies. Neither E20, nor HVO, nor HEV configuration have any impact on the CO conversion efficiencies.

Hydrocarbons (THC) Emissions

Figure 32 shows THC engine-out emissions. The Diesel PHEV fueled with B7 shows 89 % lower engine-out THC emissions compared to the gasoline PHEV fueled with E10 in CS. E20 shows 45 % higher engine-out THC emissions compared to E10 in CS. HVO (compared to B7) and HEV (compared to PHEV) configuration have no significant effect on the engine-out THC emissions.

Figure 33 shows the THC tailpipe emissions. Very low tailpipe THC emissions performed by the gasoline PHEV and the Diesel PHEV are observed, below 10 mg/km in both fuel types, compared to a Euro 6d limit of 100 mg/km for gasoline vehicles and 90 mg/km (170-80) for Diesel vehicles. The tailpipe

FIGURE 31 Comparison of CO AFTS conversion efficiency [%] measured on RDE cycles on chassis dyno for each fuel and mode.

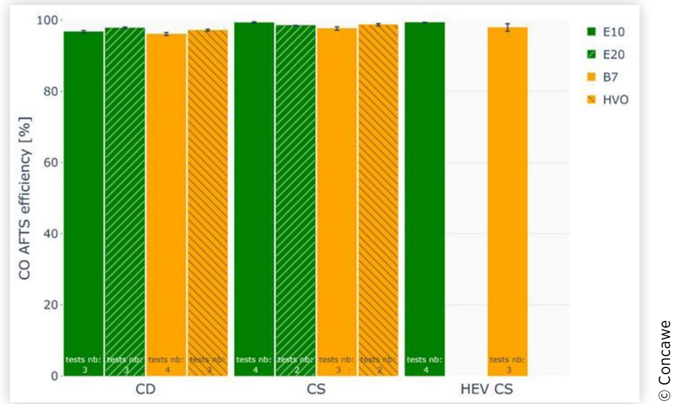


FIGURE 32 Comparison of engine-out THC emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.

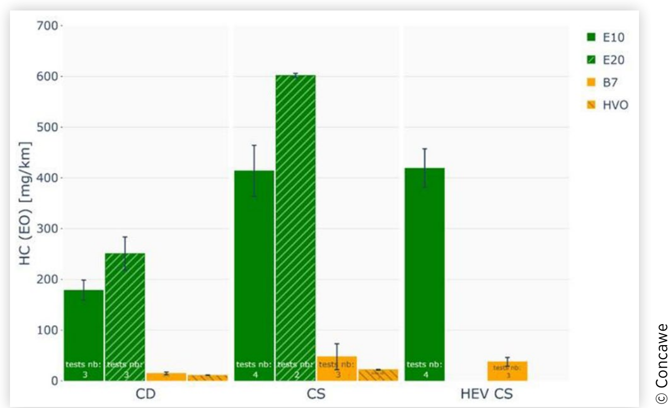
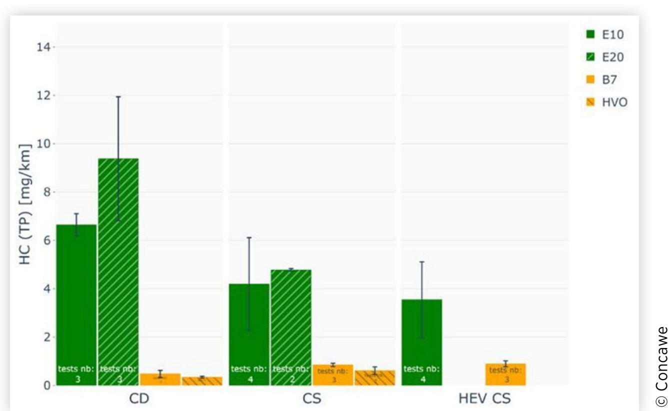


FIGURE 33 Comparison of tailpipe THC emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.



THC emissions of the Diesel PHEV fueled with B7 are 80 % lower than the ones of the gasoline PHEV fueled with E10 in CS.

Figure 34 exhibits THC AFTS conversion efficiency, i.e. three-way catalyst for the gasoline PHEV and DOC for the Diesel PHEV. Both technologies show similar conversion efficiencies, above 95 % in CS. Neither E20 (compared to E10), nor HVO (compared to B7), nor HEV (compared to PHEV) configuration have any impact on the THC conversion efficiencies.

Ammonia (NH_3) Emissions

Figure 35 and Figure 36 illustrate respectively engine-out and tailpipe NH_3 emissions. As expected, no NH_3 is emitted at the engine-out of both the gasoline PHEV and the Diesel PHEV. At the tailpipe, the Diesel PHEV shows an increase of the NH3 released, due to the NOx aftertreatment technology that is urea-based. Most of the NH_3 is released during the motorway phase of the RDE, as the urea injector instrumentation confirms (see Figure 37). The typical behavior observed is that NH_3 slip occurs when a threshold of temperature, and probably gas hourly space velocity (GHSV) is crossed. Those conditions are met when driving on motorway.

FIGURE 34 Comparison of THC AFTS efficiency [%] measured on RDE cycles on chassis dyno for each fuel and mode.

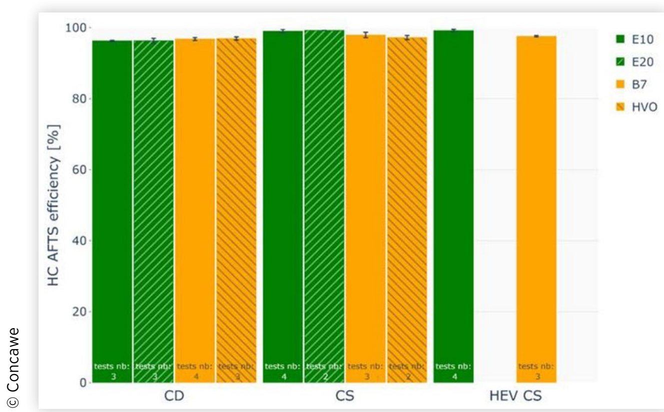


FIGURE 35 Comparison of Engine-out NH_3 emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.

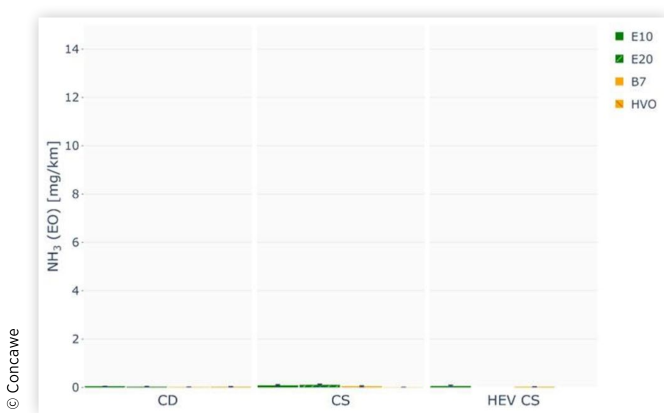


FIGURE 36 Comparison of Tailpipe NH3 emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.

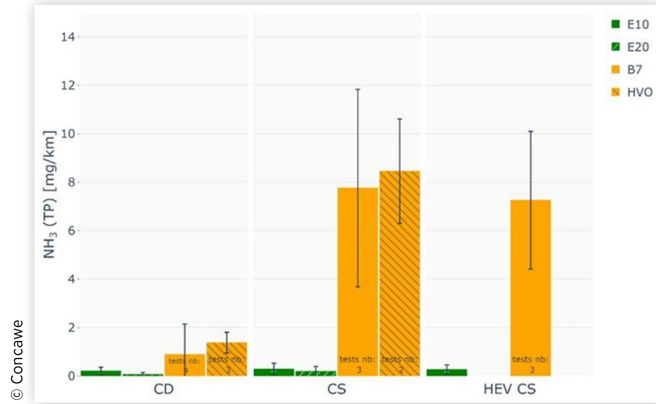
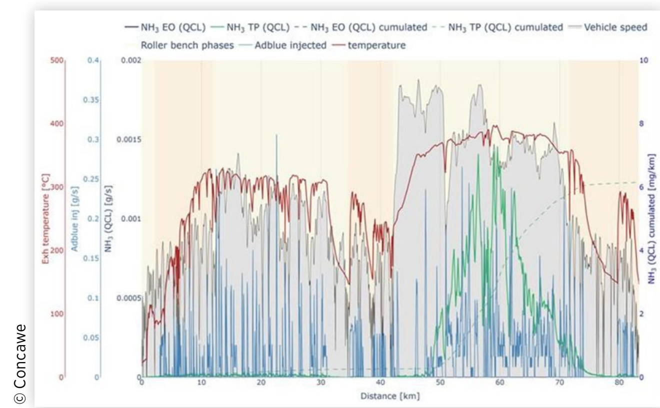


FIGURE 37 Distance-based evolution of AdBlue injection, exhaust gas temperature and NH3 emissions (EO and TP) along an RDE cycle.



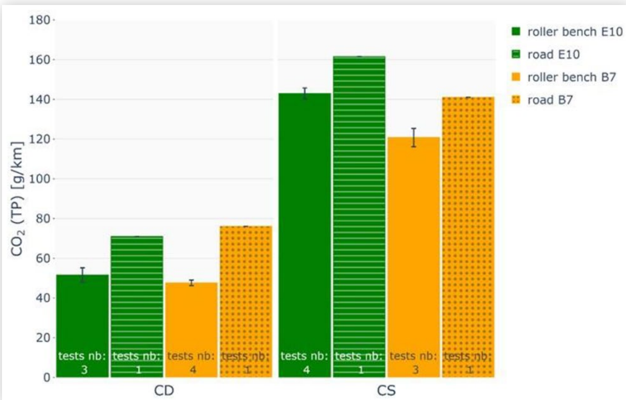
Results Obtained On-Road

The key results from the RDE performed on-road are described in this section and are compared to the tests performed on the chassis dyno. The full results are tabulated in the Appendices 2 and 3. Where shown on charts, error bars denote the 68% confidence intervals (i.e. =/- the standard deviation) and the number of test repeats on which the mean values are calculated is indicated at the bottom of each bar. Even though only one test per configuration was expected for the road tests, some tests that were not fully valid (e.g. one measurement missing among the full set of measurements) were included in the analysis when sensible to improve the statistical relevance of the results.

Carbon Dioxide (CO_2) Emissions

Figure 38 shows the emissions of CO_2 on-road compared to the emissions measured on the roller test bed with the same vehicle under close conditions. Higher CO_2 emissions, about +17% for B7 PHEV in CS (+28.9% when corrected) and +13% for E10

FIGURE 38 Comparison of tailpipe CO_2 emissions [g/km] measured on RDE on-road and chassis dyno tests for each fuel and mode.



PHEV in CS (+13.5% when corrected), are observed for the on-road tests despite milder driving conditions. These gaps were assessed by using calibrated vehicle simulators (not shown in this article), and it was concluded that there was a discrepancy between the "real-world" road law and the roller test bed road law which explains the stated difference on CO_2 emissions.

Volumetric Fuel Consumption

Figure 39 illustrates the volumetric fuel consumption that is computed from the carbon balance, i.e., the CO_2, HC and CO emissions. The trends are therefore similar to the CO_2 emissions, i.e. the fuel consumption is higher on-road than on the chassis dyno, with 17% higher fuel consumption for B7 PHEV in CS mode (29.1% when corrected) and 13% for E10 PHEV in CS mode (13.6% when corrected).

Electrical Consumption and Utility Factor

Figure 40 shows the electrical energy consumption over the entire RDE and Figure 42 exhibits the utility factor. The

FIGURE 39 Comparison of volumetric fuel consumption [L/100km] measured on RDE on-road and chassis dyno tests for each fuel and mode.

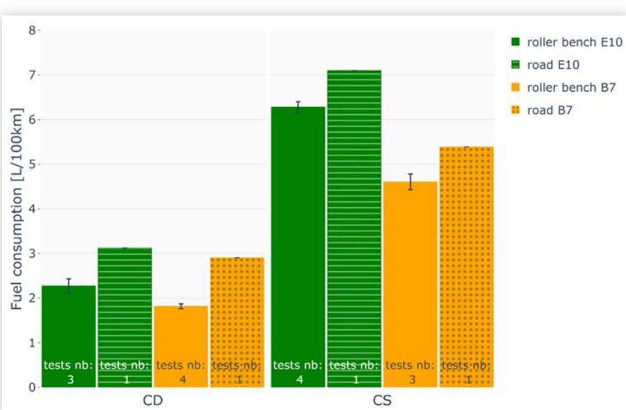


FIGURE 40 Comparison of electrical consumption [kWh/100km] measured on RDE on-road and chassis dyno tests for each fuel and mode.

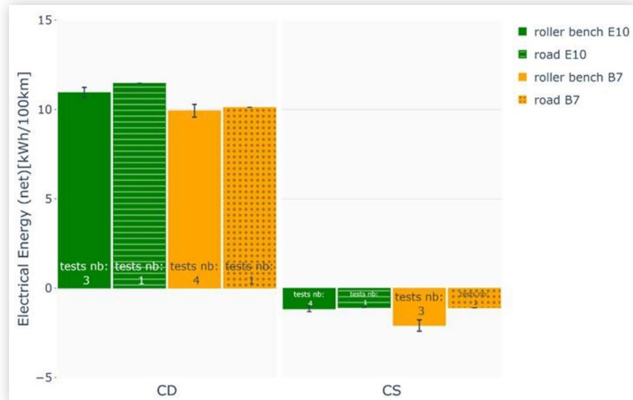


FIGURE 41 Illustration of the battery SOC [%] evolution on road test in charge depleting mode.

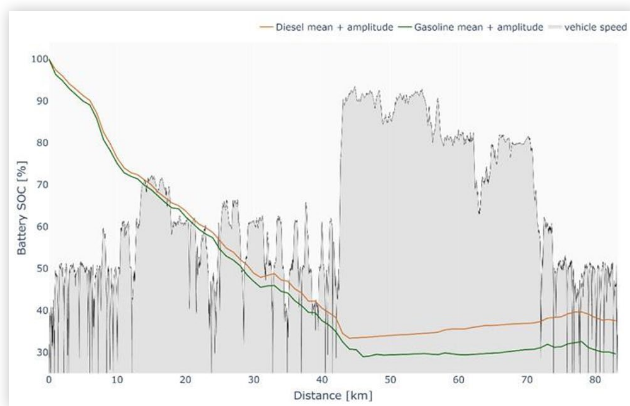
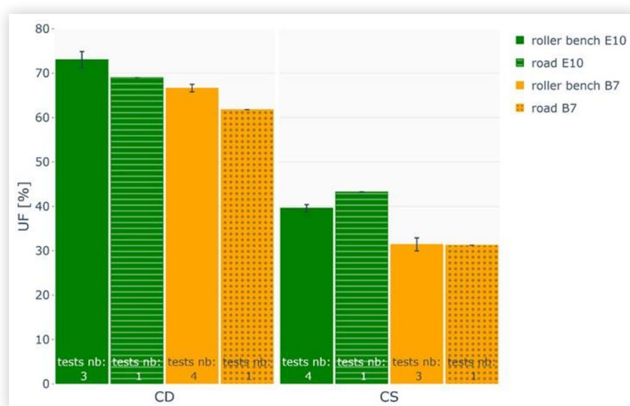


FIGURE 42 Comparison of Utility Factor [%] measured on RDE on-road and chassis dyno tests for each fuel and mode.



aforementioned assumption that the "road" road law is more demanding than the "bench" road law seems to be verified, as a lower UF with a higher electrical energy consumed means higher energy used over the whole driving cycle. For the Diesel PHEV, the lower electrical energy and UF, as stated in the previous section, can be explained by a better efficiency of the thermal engine moving the sweet spot optimization compared to the gasoline PHEV, and still improving the CO_2 emissions.

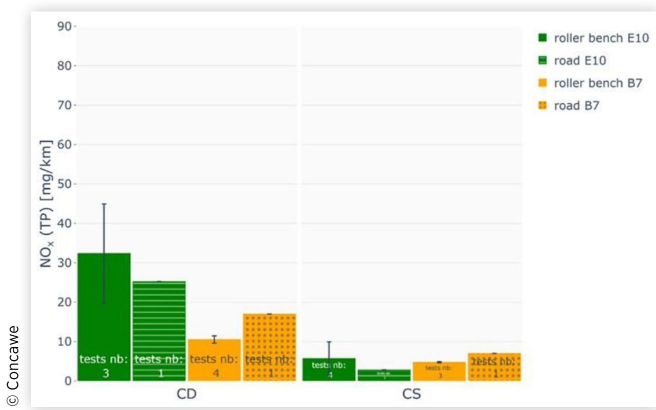
Oxides of Nitrogen (NOx) Emissions

Figure 43 shows the emissions of NOx. The difference between on-road tests and roller test bed tests can be explained by the difference in terms of driveability, modifying the number of accelerations and their level hence the peaks of NOx during the cycle. Even with those differences, the levels of NOx emissions remain low.

Particle Number Emissions

Figure 44 shows the PN23 emissions. The same observation as for the NOx emissions can explain what is observed on the PN23 emissions. For the gasoline PHEV in CD mode, a difference in the moment when the engine starts can lead to a big difference in PN emissions due to high peaks of PN emissions right after the engine starts. Still, the emissions remain below the Euro 6d limits.

FIGURE 43 Comparison of tailpipe NOx emissions [mg/km] measured on RDE on-road and chassis dyno tests for each fuel and mode.



Carbon Monoxide (CO) Emissions

Figure 45 shows the emissions of CO at the tailpipe. The trend that emerges is that "on-road" CO are often higher than CO emissions measured in laboratory conditions. Still the level remains low compared to the Euro 6d levels. This can be due to a difference of AFTS efficiency and/or differences of the load profile.

Conclusions

Two Euro 6d PHEVs were selected to allow a relevant comparison between gasoline and Diesel internal combustion engines. These vehicles were tested on a chassis dynamometer and on-road, both with standard and renewable fuels, in charge depleting and charge sustaining mode.

The two PHEVs show low regulated (well below Euro 6d limits) and non-regulated (in the range of Euro 7 proposals) pollutant emissions. The Diesel PHEV allows, compared to the gasoline one, a reduction of TtW CO_2 emissions of up to 22.3% (and a reduction of 20.5% of TtW GHG emissions) in charge sustaining mode, and a reduction of pollutant emissions except for NH_3 and N_2O. The distance where the vehicle switched to CS mode on the RDE driven (i.e. the all-electric range) was around 54 km, close to the 57 km homologated on WLTP.

Regarding the gasoline PHEV, switching from a standard E10 fuel to a 100% renewable gasoline blended with 20% v/v ethanol (E20) fuel does not have a significant impact on the pollutant tailpipe emissions under the conditions of this study, neither on TtW CO_2 emissions. However, it implies a higher volumetric fuel consumption (+4.5% on CS). With the Diesel PHEV, switching from a standard B7 fuel to a 100% renewable HVO fuel does not have any significant effect on the pollutant tailpipe emissions under the tested conditions. It decreases by

FIGURE 44 Comparison of tailpipe PN23 emissions [#/km] measured on RDE on-road and chassis dyno tests for each fuel and mode.

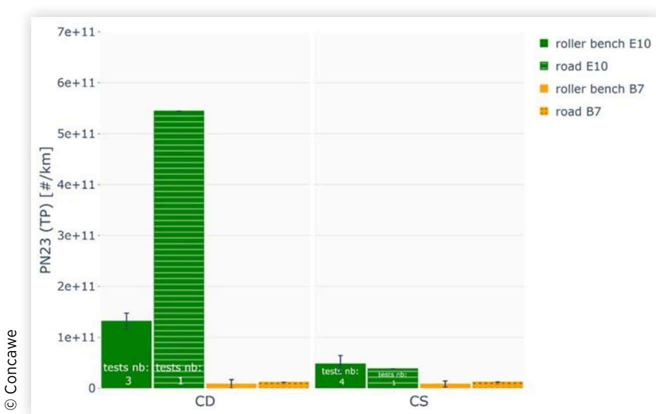
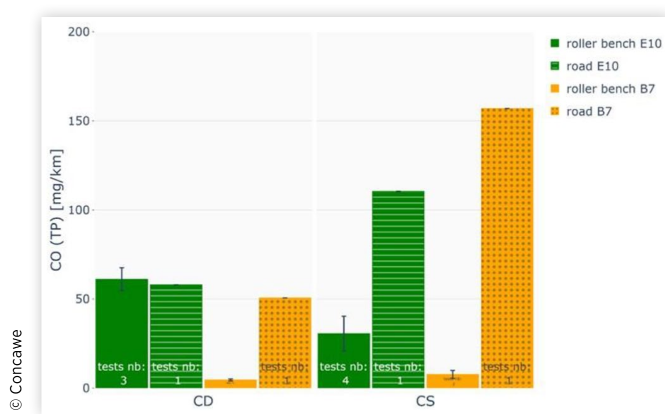


FIGURE 45 Comparison of tailpipe CO emissions [mg/km] measured on RDE on-road and chassis dyno tests for each fuel and mode.



2.0% the TtW CO_2 emissions and increases the volumetric fuel consumption by 8.4% on CS.

Reducing the mass of the vehicle surprisingly does not change the consumption or the pollutant emissions: despite weighing 120 kg less, the HEV configuration presents results in emissions and energy consumption very close to the PHEV configuration in CS mode.

The measurements performed on-road show higher fuel consumption and CO_2 emissions. In CS mode, the Diesel vehicle showed a 29% higher fuel consumption and CO_2 emissions on the road compared to the laboratory tests. The gasoline vehicle showed a difference of 13.6%. This gap was investigated using a calibrated simulator (not shown in this article) and explained by a different road law between the roller test bed and the on-road.

Perspectives

The data generated in this study, from RDE driving in the laboratory and on-road, will allow to calibrate a vehicle simulator. It will aim at extending the findings to more varied conditions: trip distance, driving profile, ambient temperature, battery capacity, recharging frequency, etc. By combining these different parameters extensively, statistically representative use cases can be generated and evaluated regarding their fuel and electricity consumption, utility factor and CO_2 emissions. This will be the subject of another article.

Furthermore, TtW CO_2 emissions do not offer a complete picture of the GHG emissions emitted during the life of a vehicle. For this, a broader analysis of the vehicle's life cycle must be determined by considering not only the TtW emissions of the vehicle during its use, but also the WtT emissions related to the energy sources (electricity and fuel productions) and finally the production and end of life of the vehicle itself, including the battery. This assessment is based on many parameters: the CO_2 intensity of electricity production, the CO_2 WtT emissions of different fuel production pathways, the CO_2 emissions related to the production of the vehicles, particularly the battery, the lifetime of the vehicles, etc. These LCA and WtT aspects will be the subject of future work. Additionally, given the quantity of assumptions and their variability, a dynamic LCA GHG tool will be developed, allowing to configure any possible combinations of parameters and to compare PHEVs life-cycle emissions with other levels of vehicle electrification: HEVs and BEVs.

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Contact Information

Roland Dauphin
fuels@concawe.eu

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Definitions/Abbreviations

AFTS - Aftertreatment System
BEV - Battery Electric Vehicle
Bx - Diesel fuel containing max. x% v/v of FAME
CD - Charge Depleting
CH_4 - Methane
CI - Compression Ignition
CN - Cetane Number
CO - Carbon monoxide
CO_2(eq) - Carbon dioxide (equivalent)
CPC - Condensation Particle Counter
CR - Compression Ratio
CS - Charge Sustaining
CVS - Constant Volume Sampling
DOC - Diesel Oxidation Catalyst
DPF - Diesel Particulate Filter
Ex - Gasoline containing max. x% v/v of ethanol
EFM - Exhaust Flow Meter
EGR - Exhaust Gas Recirculation
FAME - Fatty Acid Methyl Ester
FBP - Final Boiling Point
FC - Fuel Consumption
GHG - Greenhouse Gas(es)
GPF - Gasoline Particulate Filter
GPS - Global Positioning System
GWP - Global Warming Potential
(T)HC - (Total) Hydrocarbons
HEV - Hybrid Electric Vehicle
HV - High Voltage
HVO - Hydrotreated Vegetable Oil
ICE - Internal Combustion Engine
IPCC - Intergovernmental Panel on Climate Change
LCA - Life-Cycle Assessment
LV - Low Voltage
NH_3 - Ammonia
N_2O - Nitrous Oxide
NOVC-HEV - Not Off-Vehicle Charging Hybrid Electric Vehicles, simply called HEVs
NO_x - Oxides of Nitrogen
OBD - On-board Diagnostics
OEM - Original Equipment Manufacturer
OVC-HEV - Off-Vehicle Charging Hybrid Electric Vehicles, simply called PHEVs
P2 - Hybrid configuration where the electric machine is integrated between the internal combustion engine and the transmission
PEMS - Portable Emissions Measurement System
PHEV - Plug-in Electric Vehicle
PM - Particulate Matter/Mass
PN - Particle Number
PNx - Particulate Number with a diameter greater than x nm
RDE - Real Driving Emissions

RED - Renewable Energy Directive

RPA - Relative Positive Acceleration

SCR(F) - Selective Catalytic Reduction (with a soot Filter)

SI - Spark Ignition

SoC - State of Charge

TtW - Tank to Wheels

TWC - Three-Way Catalyst

$V*A_{pos}$ - Driving dynamic parameter, velocity x positive acceleration

UF - Utility Factor, i.e. % of distance driven in all-electric mode

WLTC - Worldwide harmonized Light-duty Test Cycle

WLTP - Worldwide Harmonized Light Vehicles Test Procedure

WtT - Well to Tank

WtW - Well to Wheels

Appendix 1: Compliance of the Chassis Dyno Driving Cycle with RDE Criteria

TABLE 8 Compliance of the chassis dyno driving cycle with RDE criteria.

	Limit	Cycle
Trip duration [min]	[90, 120]	93
Total distance [km]	48 <	83.4
cold start stop time [s]	< 90	52
cold start mean speed [km/h]	[15, 40]	23.7
cold start max speed [km/h]	60	53
urban share [%]	[19, 44]	30.8
urban distance [km]	16<	25.7
urban mean speed [km/h]	[15, 40]	28.5
urban rpa [#]	150 < (WP3), 100 < (WP4)	1125
urban cumulated positive altitude [m/100km]	< 1200	560
urban stop time share [%]	[6, 30]	13.7
stop duration (max) [s]	< 300	69
stop number (>10s) [#]	2 <	27
rural share [%]	[23, 43]	31.9
rural distance [km]	16<	26.7
rural rpa [#]	150 < (WP3), 100 < (WP4)	488
motorway share [%]	[23, 43]	37.2
motorway distance [km]	16<	31.1
high speed > 100 duration [min]	5 <	13
high speed 145 share [%]	< 3	0
motorway rpa [#]	150 < (WP3), 100 < (WP4)	325
motorway maximum speed [km/h]	[110, 160]	141
total cumulated positive altitude [m/100km]	< 1200	620
elevation difference [m]	[-100, 100]	0
elevation max [m]	< 700	180

Appendix 2: Tabulated Results

TABLE 9 Energy and CO_2 mean values.

					FC	FC corr*	CO_2	CO_2 corr*	GHG	GHG corr*	UF	EC	EC+	EC-
					L/100km	*L/100km*	*g/km*	*g/km*	*g CO_2 eq /km*	*g CO_2 eq /km*	*%*	*kWh/ 100km*	*kWh/ 100km*	*kWh/ 100km*
							CVS		CVS CO_2 + N_2O + CH_4	CVS corr* CO_2 + N_2O + CH_4				
C300 de	**Chassis dyno**	**B7**	**PHEV**	**CD**	1.8	1.8	48	48	49	49	67	10	16	-6
				CS	4.6	4.2	121	109	124	113	31	-2	5	-7
			HEV	**CS**	4.6	4.2	121	110	124	113	30	-2	5	-7
		HVO	**PHEV**	**CD**	2.0	2.0	47	47	49	49	67	10	15	-6
				CS	4.9	4.5	116	107	120	111	32	-2	5	-7
	Road	**B7**	**PHEV**	**CD**	2.9	2.9	76	76			62	10	15	-5
				CS	5.4	5.4	141	141			31	-1	5	-6
C300 e	**Chassis dyno**	**E10**	**PHEV**	**CD**	2.3	2.3	52	52	52	52	73	11	16	-5
				CS	6.3	6.2	143	141	144	142	40	-1	6	-7
			HEV	**CS**	6.3	6.1	143	139	144	140	38	-1	5	-6
		E20	**PHEV**	**CD**	2.5	2.5	54	54	55	55	72	11	16	-5
				CS	6.5	6.5	144	143	145	144	38	-1	5	-6
	Road	**E10**	**PHEV**	**CD**	3.1	3.1	71	71			69	11	15	-4
				CS	7.1	7.0	162	160			43	-1	5	-6

TABLE 10 Regulated pollutant emissions mean values.

					NOx			CO			HC			SPN23			SPN10			PM
					EO	TP	AFTS Eff	EO	TP	AFTS Eff	EO	TP	AFTS Eff	EO	TP	AFTS Eff	EO	TP	AFTS Eff	TP
					mg/km	*mg/ km*	*%*	*mg/km*	*mg/ km*	*%*	*mg/ km*	*mg/ km*	*%*	*nb/km*	*nb/km*	*%*	*nb/km*	*nb/km*	*%*	*mg/km*
					raw gases	raw gases		raw gases	raw gases		raw gases	raw gases		raw gases	raw gases		raw gases	raw gases		soot filter weight
C300 de	**Chassis dyno**	**B7**	**PHEV**	**CD**	139.1	10.5	92.4	117.9	4.6	96.1	14.7	0.5	96.8	9.7E+12	8.3E+09	99.9	1.5E+13	1.4E+10	99.9	0.1
				CS	373.3	4.8	98.7	324.9	7.7	97.7	47.5	0.9	97.9	2.2E+13	8.2E+09	100.0	3.6E+13	1.4E+10	100.0	0.1
			HEV	**CS**	367.1	4.7	98.7	310.7	6.6	98.0	37.5	0.9	97.6	2.2E+13	5.5E+09	100.0	3.6E+13	9.5E+09	100.0	0.0
		HVO	**PHEV**	**CD**	140.0	10.6	92.4	102.7	2.9	97.2	11.1	0.3	96.9	1.0E+13	1.5E+10	99.8	1.6E+13	2.4E+10	99.8	0.2
				CS	374.6	5.6	98.5	245.5	3.1	98.7	21.8	0.6	97.2	1.6E+13	2.8E+10	99.8	2.7E+13	4.4E+10	99.8	0.1
	Road	**B7**	**PHEV**	**CD**		17.0			50.6						1.2E+10					
				CS		7.0			157.0						1.2E+10					
C300 e	**Chassis dyno**	**E10**	**PHEV**	**CD**	819.9	32.4	96.1	1871.3	61.1	96.7	178.7	6.6	96.3	3.4E+11	1.3E+11	64.1	7.8E+11	2.0E+11	72.7	0.2
				CS	2403.2	5.7	99.8	4372.6	30.5	99.3	413.9	4.2	99.0	1.1E+11	4.8E+10	55.0	7.2E+11	7.7E+10	89.2	0.2
			HEV	**CS**	2372.3	8.2	99.7	4349.2	29.9	99.3	419.2	3.5	99.2	1.1E+11	4.5E+10	59.7	6.1E+11	7.2E+10	88.2	0.1
		E20	**PHEV**	**CD**	865.7	19.0	97.8	1801.4	39.7	97.8	250.9	9.4	96.3	4.6E+11	1.6E+11	73.6	2.2E+12	2.3E+11	92.0	0.2
				CS	2522.7	1.6	99.9	4410.7	65.1	98.5	601.8	4.8	99.2	4.9E+11	6.3E+10	83.8	2.6E+12	9.8E+10	95.7	0.1
	Road	**E10**	**PHEV**	**CD**		25.2			58.0						5.4E+11					
				CS		2.8			110.5						3.8E+10					

TABLE 11 GHG and unregulated pollutant emissions mean values.

					CH_4				NH_3		N_2O			AdBlue
					EO	TP	AFTS Eff	TP	EO	TP	EO	TP	TP	
					mg/km	*mg/km*	*%*	*g CO_2eq / km*	*mg/km*	*mg/km*	*mg/km*	*mg/km*	*g CO_2eq / km*	*L/1000km*
					raw gases	raw gases		raw gases	raw gases	raw gases	raw gases	raw gases	raw gases	calculation from command signal
C300 de	**Chassis dyno**	**B7**	**PHEV**	**CD**	0.3	0.1	55.5	0.0	0.0	0.9	0.6	4.7	1.2	0.3
				CS	0.8	0.2	65.6	0.0	0.0	7.8	0.9	12.8	3.4	0.9
			HEV	**CS**	0.7	0.5	25.5	0.0	0.0	7.3	0.9	12.7	3.4	0.9
		HVO	**PHEV**	**CD**	0.2	0.1	56.2	0.0	0.0	1.4	0.5	5.4	1.4	0.3
				CS	0.6	0.3	49.4	0.0	0.0	8.5	0.9	12.9	3.4	0.8
	Road	**B7**	**PHEV**	**CD**										0.0
				CS										1.0
C300 e	**Chassis dyno**	**E10**	**PHEV**	**CD**	6.7	0.7	89.7	0.0	0.0	0.2	1.0	1.7	0.5	
				CS	14.0	0.3	97.9	0.0	0.1	0.3	2.7	4.0	1.0	
			HEV	**CS**	13.9	0.3	98.1	0.0	0.0	0.3	2.7	3.9	1.0	
		E20	**PHEV**	**CD**	9.1	0.9	90.6	0.0	0.0	0.1	1.0	1.9	0.5	
				CS	18.4	0.6	96.8	0.0	0.1	0.2	2.8	3.1	0.8	
	Road	**E10**	**PHEV**	**CD**										
				CS										

Appendix 3: Relative gaps between tested configurations

The tables below show the relative differences between the different tested configurations. The cells are colored when the differences are greater than the sum of the standard deviations. The cells in red show a degradation and the ones in green an improvement.

TABLE 12 Configuration relative differences expressed in % for charge depleting mode on the whole RDE cycle.

		Gaps				
		B7 to HVO (CD mode)	E10 to E20 (CD mode)	E10 to B7 (CD mode)	Lab to road (B7 CD)	Lab to road (E10 CD)
		rel [%]	rel [%]	rel [%]	rel [%]	rel [%]
FC		9.87	8.06	-20.09	59.87	37.31
FC_{corr}		9.87	8.06	-20.09	59.87	37.31
CO_2	CVS	-0.73	5.29	-7.68	59.75	37.60
$CO_{2,corr}$		-0.73	5.29	-7.68	59.75	37.60
GHG		-0.33	5.36	-6.15		
UF	share of distance engine off	-0.08	-1.40	-8.80	-7.27	-5.56
E Wheel net	Vreal	-0.01	-0.06	-0.35	-3.42	-7.79
E Wheel +	Vreal	-0.14	-0.09	1.80	-13.67	-19.11
E Wheel -	Vreal	-0.34	-0.13	5.26	-29.24	-37.26
EC		-3.24	-0.89	-9.37	1.94	4.72
EC+		-1.74	-1.82	-3.00	-5.98	-4.79
EC-		0.85	-3.78	10.46	-19.73	-24.92
NOx EO	raw gases	0.65	5.59	-83.03		
NOx TP	raw gases	0.50	-41.19	-67.52	61.48	-22.07
NOx Eff		-0.01	1.82	-3.77		
NOx TP	CVS	-2.91	-33.49	-72.29		
CO EO	raw gases	-12.90	-3.74	-93.70		
CO TP	raw gases	-36.67	-35.05	-92.50	1003.72	-5.13
CO Eff		1.09	1.11	-0.64		
CO TP	CVS	-33.13	-48.22	-92.89		
HC EO	raw gases	-24.40	40.38	-91.76		
HC TP	raw gases	-28.97	41.13	-92.80		
HC Eff		0.14	0.03	0.55		
HC TP	CVS	-17.95	43.95	-94.69		
SPN23 EO	raw gases	4.81	36.82	2751.99		
SPN23 TP	raw gases	83.30	18.36	-93.69	38.84	313.26
SPN23 Eff		-0.07	14.82	55.88		
SPN23 TP	CVS					
SPN10 EO	raw gases	3.95	187.41	1845.30		
SPN10 TP	raw gases	72.67	13.60	-92.90		
SPN10 Eff		-0.06	26.50	37.34		
SPN10 TP	CVS	71.05	12.78	-93.00		
PM	soot filter weight	94.04	2.42	-59.63		
CH_4 EO	raw gases	-24.31	34.70	-96.25		
CH_4 TP	raw gases	-33.44	24.85	-84.45		
CH_4 Eff		1.33	0.97	-38.16		
CH_4 TP	CVS	-35.39	26.75	-59.11		
CH_4 TP (CO_2eq)	raw gases	-33.44	24.85	-84.45		
	CVS	-35.39	26.75	-59.11		
NH_3 EO	raw gases	62.67	-55.54	-80.16		
NH_3 TP	raw gases	55.26	-67.89	331.14		
NH_3 Eff						
NH_3 TP	CVS					
N_2O EO	raw gases	-18.12	2.25	-32.59		
N_2O TP	raw gases	15.01	11.79	169.41		
N_2O Eff						
N_2O TP	CVS					
N_2O TP (CO_2eq)	raw gases	15.01	11.79	169.41		
	CVS					
Urea	calculation for command signal	-2.22				

TABLE 13 Configuration relative differences expressed in % for charge sustaining mode on the whole RDE cycle.

		Gaps**						
		B7 to HVO (CS mode)	E10 to E20 (CS mode)	E10 to B7 (CS mode)	PHEV to HEV (B7)	PHEV to HEV (E10)	Lab to road (B7 CS)	Lab to road (E10 CS)
		rel [%]	rel [%]	rel [%]	rel [%]	rel [%]	rel [%]	rel [%]
FC		6.64	3.55	-26.66	-0.03	-0.18	16.97	13.06
FC_{corr}*		8.43	4.50	-32.55	0.46	-1.38	29.10	13.56
CO_2	CVS	-3.65	0.73	-15.51	-0.02	-0.18	16.79	13.00
$CO_{2,corr}$*		-2.03	1.64	-22.30	0.46	-1.39	28.90	13.50
GHG		-1.94	1.48	-20.48	0.43	-1.39		
UF	share of distance engine off	0.48	-2.98	-20.65	-2.94	-3.34	-0.55	9.25
E Wheel net	Vreal	-0.03	-0.08	-0.34	0.37	0.34	-3.82	-4.82
E Wheel +	Vreal	-0.44	-0.22	2.04	-3.08	-3.28	-13.89	-16.85
E Wheel -	Vreal	-1.05	-0.45	5.87	-8.31	-9.10	-29.12	-36.19
EC		-5.94	-12.14	80.15	9.84	23.06	-47.17	-7.10
EC+		-0.65	-4.21	-11.32	-6.41	-8.79	4.05	-6.76
EC-		-2.24	-5.59	4.59	-1.54	-3.25	-11.30	-6.82
NOx EO	raw gases	0.35	4.97	-84.47	-1.68	-1.29		
NOx TP	raw gases	16.49	-71.51	-16.50	-0.47	42.75	46.71	-50.36
NOx Eff		-0.20	0.17	-1.05	-0.01	-0.11		
NOx TP	CVS	1.91	-63.54	-31.70	-13.52	30.39		
CO EO	raw gases	-24.44	0.87	-92.57	-4.35	-0.54		
CO TP	raw gases	-59.06	113.29	-74.82	-14.34	-2.17	1941.20	261.65
CO Eff		1.08	-0.78	-1.65	0.30	0.02		
CO TP	CVS	-42.21	94.35	-65.29	-10.27	5.70		
HC EO	raw gases	-54.03	45.41	-88.52	-21.16	1.28		
HC TP	raw gases	-28.04	13.91	-79.73	5.29	-15.54		
HC Eff		-0.75	0.22	-1.05	-0.37	0.18		
HC TP	CVS	-32.14	9.25	-86.67	24.57	1.98		
SPN23 EO	raw gases	-29.01	341.43	19806.15	-1.49	1.66		
SPN23 TP	raw gases	246.03	32.97	-82.75	-32.71	-5.24	48.43	-19.49
SPN23 Eff		-0.13	52.27	81.67	0.01	8.46		
SPN23 TP	CVS							
SPN10 EO	raw gases	-24.87	260.43	4915.88	-1.03	-16.25		
SPN10 TP	raw gases	221.25	26.94	-82.21	-30.74	-6.34		
SPN10 Eff		-0.12	7.36	12.12	0.01	-1.02		
SPN10 TP	CVS	219.23	26.66	-82.22	-31.07	-5.76		
PM	soot filter weight	177.10	-30.78	-66.77	-9.97	-36.55		
CH_4 EO	raw gases	-26.16	31.11	-94.57	-8.70	-1.01		
CH_4 TP	raw gases	17.69	96.64	-15.93	106.46	-12.99		
CH_4 Eff		-24.70	-1.08	-33.02	-61.07	0.25		
CH_4 TP	CVS	-40.19	29.11	-5.18	63.54	10.20		
CH_4 TP (CO_2eq)	raw gases	17.69	96.64	-15.93	106.46	-12.99		
	CVS	-40.19	29.11	-5.18	63.54	10.20		
NH_3 EO	raw gases	-96.34	19.98	-52.80	-42.47	-39.12		
NH_3 TP	raw gases	8.99	-31.78	2611.66	-6.48	-6.50		
NH_3 Eff								
NH_3 TP	CVS							
N_2O EO	raw gases	6.50	1.20	-68.45	5.77	-1.39		
N_2O TP	raw gases	0.74	-21.04	223.44	-0.83	-2.35		
N_2O Eff								
N_2O TP	CVS							
N_2O TP (CO_2eq)	raw gases	0.74	-21.04	223.44	-0.83	-2.35		
	CVS							
Urea	calculation for command signal	-6.08			-2.53		13.88	

Appendix 4: Non-CO_2 GHG emissions

As a reminder, CH_4 and N_2O are greenhouse gases having global warming potential (GWP) significantly higher than CO_2. Estimations from the fifth assessment report (AR5) of the IPCC (Intergovernmental Panel on Climate Change) define a GWP of 28 for CH_4 and 265 for N_2O for a hundred-year time horizon. Thus, despite emissions levels generally three orders of magnitude below CO_2 emissions, these emissions have to be considered for a proper assessment of TtW greenhouse gases emissions.

Adding non-regulated greenhouse gases leads to an increase of total GHG compared to CO_2 only by around 3% in Diesel and 0.8% in gasoline (Figure 46). The main contributor to this CO_2 equivalent increase is N_2O, because of its high GWP and because almost no CH_4 is released at the tailpipe. As more N_2O is emitted by the Diesel PHEV, the -22.3% CO_2 emissions gap that was quantified between gasoline and Diesel vehicles is reduced to -20.5% considering total GHG emissions.

Details of N_2O and CH_4 emissions, both engine-out and tailpipe, to underline the origin of these, are presented below.

Concerning tailpipe CH_4 emissions (Figure 48), both Diesel and gasoline vehicles show similarly low levels, around 0.3 mg/km, representing less than 10 mg of CO_2 equivalent / km. Engine-out (Figure 47), the gasoline engine emits significant amounts of CH_4 whereas levels of the Diesel one are low, around 1 mg/km. E20 demonstrates higher engine-out CH_4 emissions compared to E10, respectively +34% in CD and +31% in CS. This finding is similar to the one established for total HC (see above). As mentioned before, these emissions are anyway converted by the after-treatment system since they are very low at the tailpipe.

Concerning engine-out N_2O emissions (Figure 49), E10 emissions are 217 % higher than B7 in CS mode but the observed trend is inverted at the tailpipe (Figure 50): the E10 tailpipe N_2O emissions are not increased by the aftertreatment system (AFTS), whereas B7 tailpipe N_2O emissions are sensibly impacted by the AFTS and are 3 times higher than E10 emissions. This is expected to be due to reactions occurring in the SCR. Even if the emissions levels seem low it represents up to 3 g of CO_2 equivalent / km (12 mg of N_2O /km).

FIGURE 46 Comparison of tailpipe greenhouse gases emissions [g CO_2eq/km] measured on RDE cycles on chassis dyno for each fuel and mode.

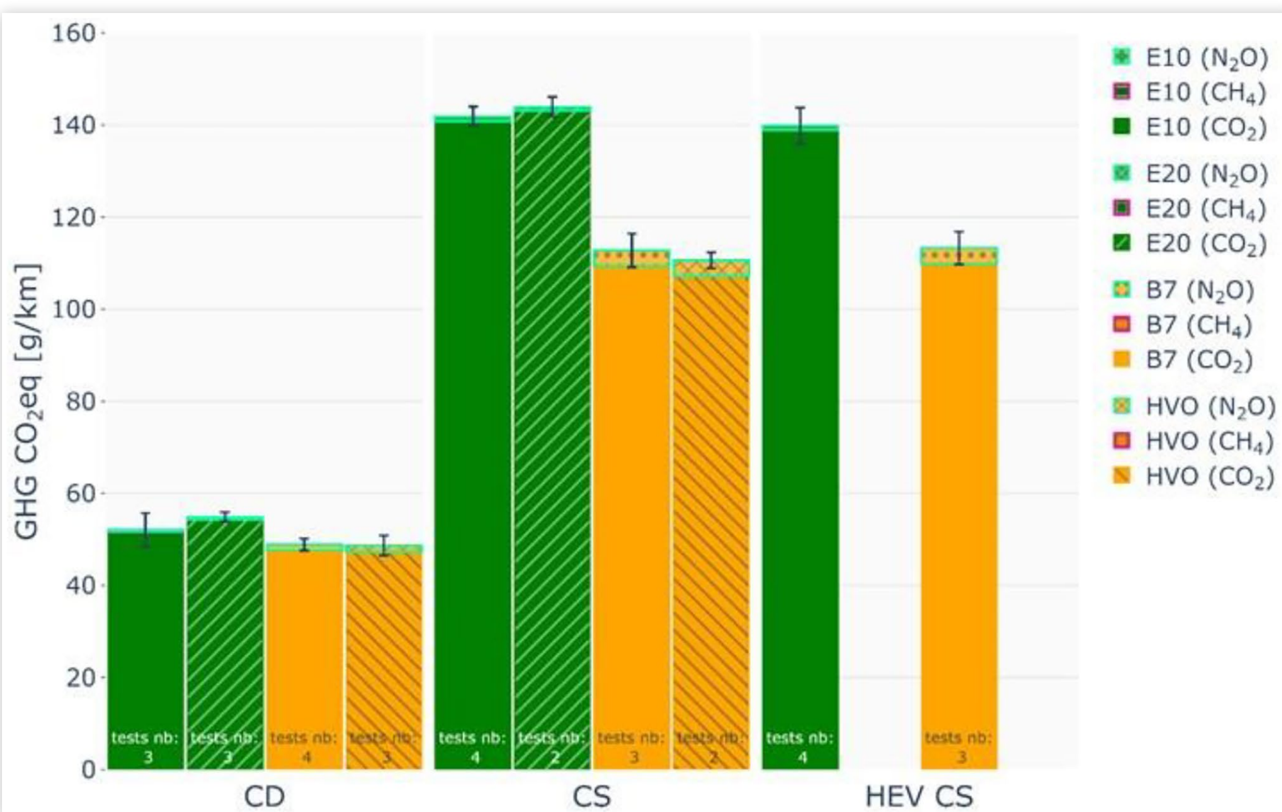


FIGURE 47 Comparison of engine-out CH_4 emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.

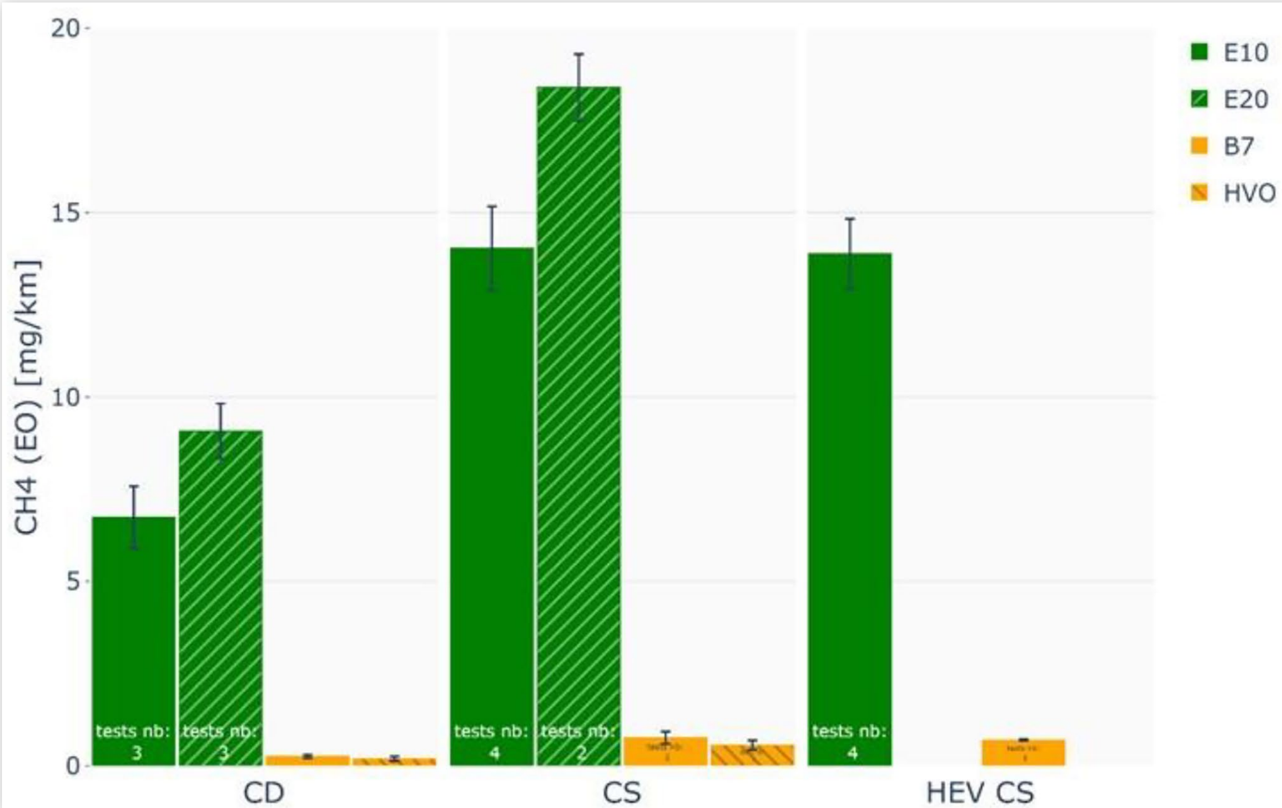


FIGURE 48 Comparison of tailpipe CH_4 emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.

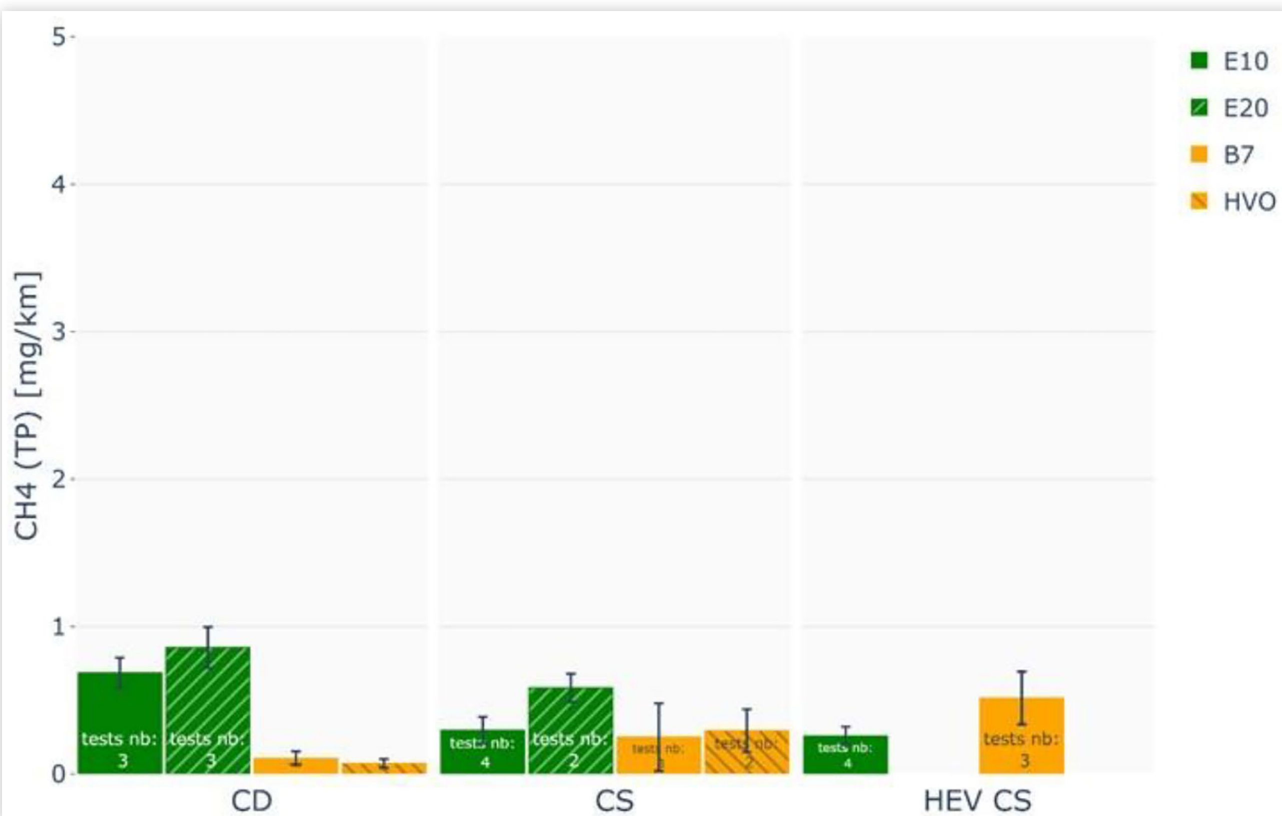


FIGURE 49 Comparison of engine-out N_2O emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.

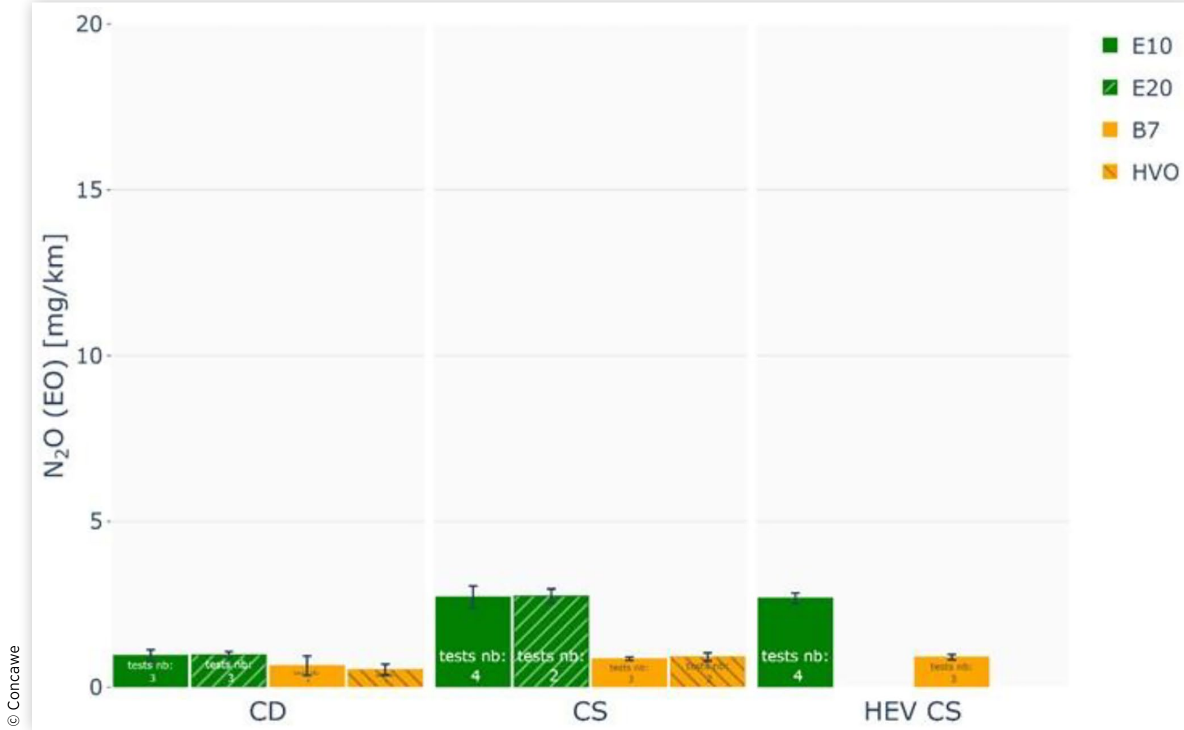
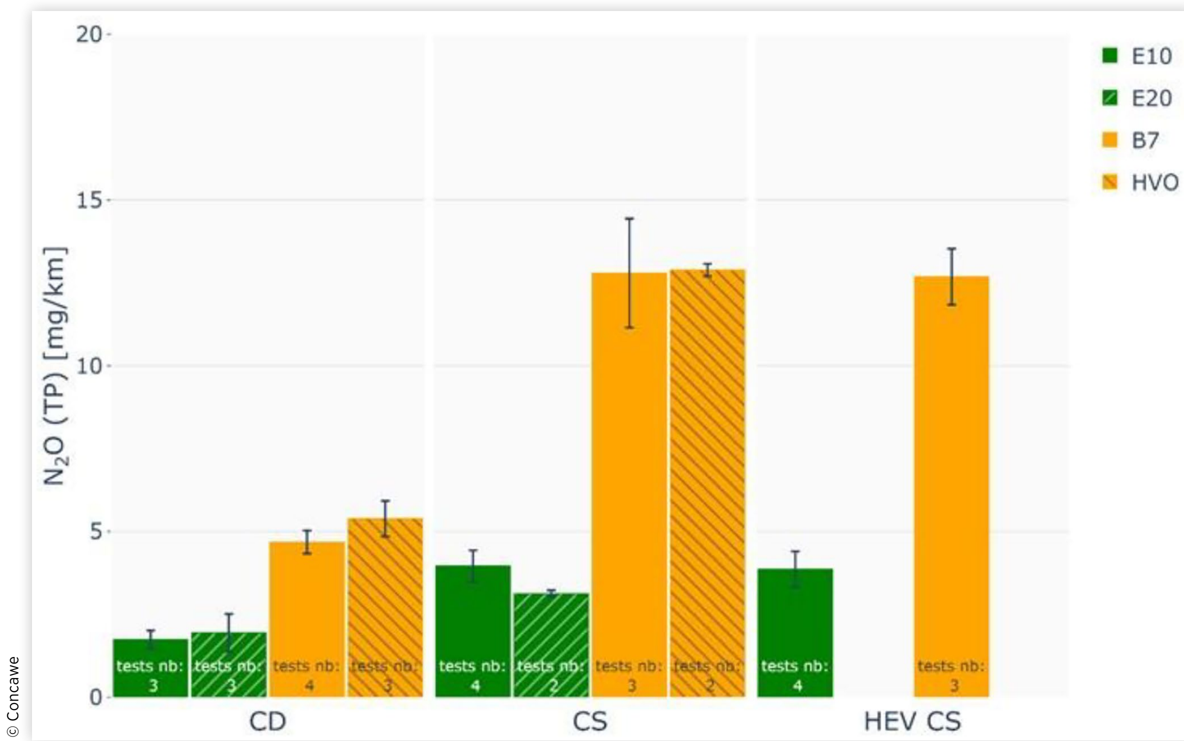


FIGURE 50 Comparison of tailpipe N2O emissions [mg/km] measured on RDE cycles on chassis dyno for each fuel and mode.



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