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On-road emissions and energy efficiency assessment of a plug-in hybrid electric vehicle

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Abstract

In order to assess potential benefits brought by the electrification of transport it becomes more and more important to evaluate the performance of hybrid electric vehicles (HEVs) in real-driving conditions, measuring on-road air pollutant emissions and energy efficiency. The present report describes a portable system used at JRC for e-measurements in hybrid and electric vehicles, as an upgrade of the classic PEMS (Portable Emission Measurement System).

Preliminary results of a test campaign conducted on a Euro-6 Plug-in Hybrid Passenger Car (PHEV) equipped with a Flywheel Alternator Starter (FAS) are reported.

The influence of different driving modes as well as of different initial battery state of charge on CO_2 and NOx emissions and energy consumption has been evaluated.

1 Introduction

The Directorate for Energy, Transport and Climate (ETC) of the European Commission's Joint Research Centre (JRC) provides scientific and technical support for policy making in the field of sustainable transport.

Evaluating the performance of hybrid electric vehicles (HEVs) in real-world conditions is of paramount importance in order to assess the environmental benefits brought by the introduction of this new technology with respect to conventional vehicles. This is possible measuring the HEV on-road performance in terms of pollutants emission and energy efficiency. Indeed, energy use directly affects the available driving range, one of the most important parameters for HEVs usability and competitiveness with conventional vehicles. The energy efficiency of all vehicles is affected by several variables, including the use of accessories on-board and ambient temperature. This effect is even larger for HEVs due to their high efficiency and limited driving range compared to conventional vehicles equipped with a single internal combustion engine (ICE).

The present report describes a portable system applied for e-measurements in hybrid vehicles, as an extension of the classic PEMS (Portable Emission Measurement System), and its testing on-board an Euro-6 Plug-in Hybrid Passenger Car (PHEV).

The test campaign has been internally organised by the Sustainable Transport Unit of the Joint Research Centre with the aim to monitor, record and then analyse the behaviour of the tested PHEV in terms of CO_2 and NOx emissions and of electric consumption, evaluating the influence of different driving modes as well as of different initial battery state of charge.

The final purpose of this activity was to contribute to the development of the RDE normative for hybrids and conventional vehicles with new measurement equipment.

2 Vehicle overview

The tested vehicle is a Euro 6 C-segment parallel Plug-In Hybrid (PHEV) available on the European market equipped with a Flywheel Alternator Starter (FAS).

2.1 Driving Modes

Five driving modes are available (see Table I), among which four involve the operation of the ICE. Each driving mode is characterized by a different usage of the electric driving with significant effects on the electric range and on CO_2 emissions.

Pure Electric (E-Mode)	Maximum use of the electric drive
Hybrid	Blends ICE and electric motor to maximize fuel economy.
Hold	The vehicle is driven by the ICE while the High - voltage battery state of charge stays unchanged
Charging	The vehicle is driven by the ICE while the High - voltage battery is charged.
Sport	Offers the full support of both ICE and electric motor to maximize the vehicle's performance.

Table I: PHEV different driving modes.

The pure electric driving mode is the default mode of the vehicle. This means that, once the car is ready to drive, the E-mode is automatically activated. It allows the driver to always drive electrically when the status of the electric system allows it. The operating mode then allows the maximum use of the electric drive. To activate all electric driving the high voltage battery should be sufficiently charged, the vehicle speed should be below 130kmh and the kick-down function is de-activated.

With the hybrid mode the vehicle can be driven electrically at low and medium speeds depending on the charge level of the high voltage battery and the driving resistance. The internal combustion engine is switched off in this instance and it is started during fast accelerations or when the charge in the high voltage battery is too low.

In hold mode the vehicle is driven by the internal combustion engine. The electric motor acts as an alternator and supplies the 12V electrical system. The charge level of the high voltage battery and therefore the electric range remain the same.

In Charging Mode the vehicle is driven by the internal combustion engine, the electrical motor acts as an alternator supplying the 12V electrical system and charging the high voltage battery until it is fully charged.

The Sport Mode allows a dynamic driving, using the internal combustion engine when the driver's acceleration requirements are more demanding [1].

2.2 Internal Combustion Engine

The vehicle is equipped with a gasoline 1.4 l TSI engine (turbocharged straight injection system) which combines direct injection and turbocharging to increase power improving fuel efficiency. TSI engines allow for higher torque at lower RPMs which means more power with less fuel usage.

The maximum output is 110kW at 5000-6000 rpm with a maximum torque of 250Nm at 1600 to 3500 rpm (Figure 1).

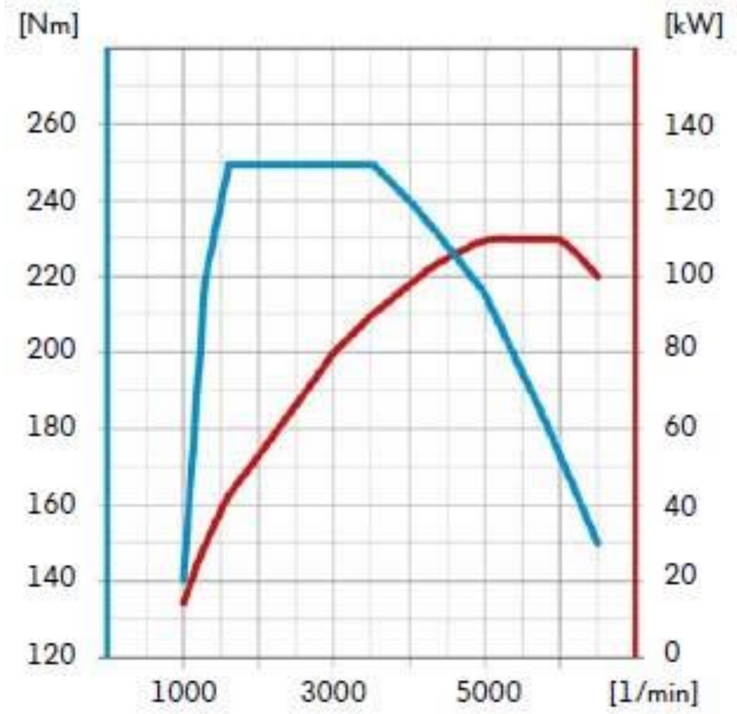


Figure 1: ICE Torque and power diagram. (Picture from https://www.alientech-tools.com/golf-gte-hybrid/)

2.3 Electric Drive

The electric drive uses a permanent magnet synchronous motor. It is located between the TSI engine and the six-speed dual clutch gearbox. It can act as the sole drive for the vehicle or in combination with the combustion engine. It also performs the tasks of the starter and alternator. In Figure 2 it is shown the torque and power diagram, while in Figure 3 there is an overview of the hybrid module design.

Technical Data	
Max output	75kW
Max torque	330Nm
Max motor speed	7000rpm

Table II: Electrical motor main features.

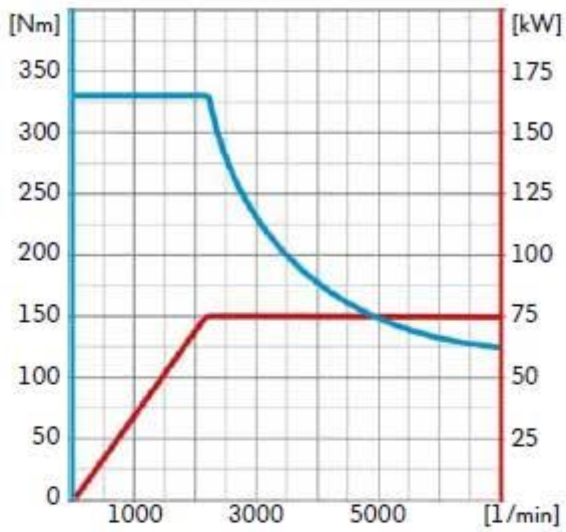


Figure 2: Electrical motor configuration; torque and power diagram (Picture from https://www.alientech-tools.com/golf-gte-hybrid/)

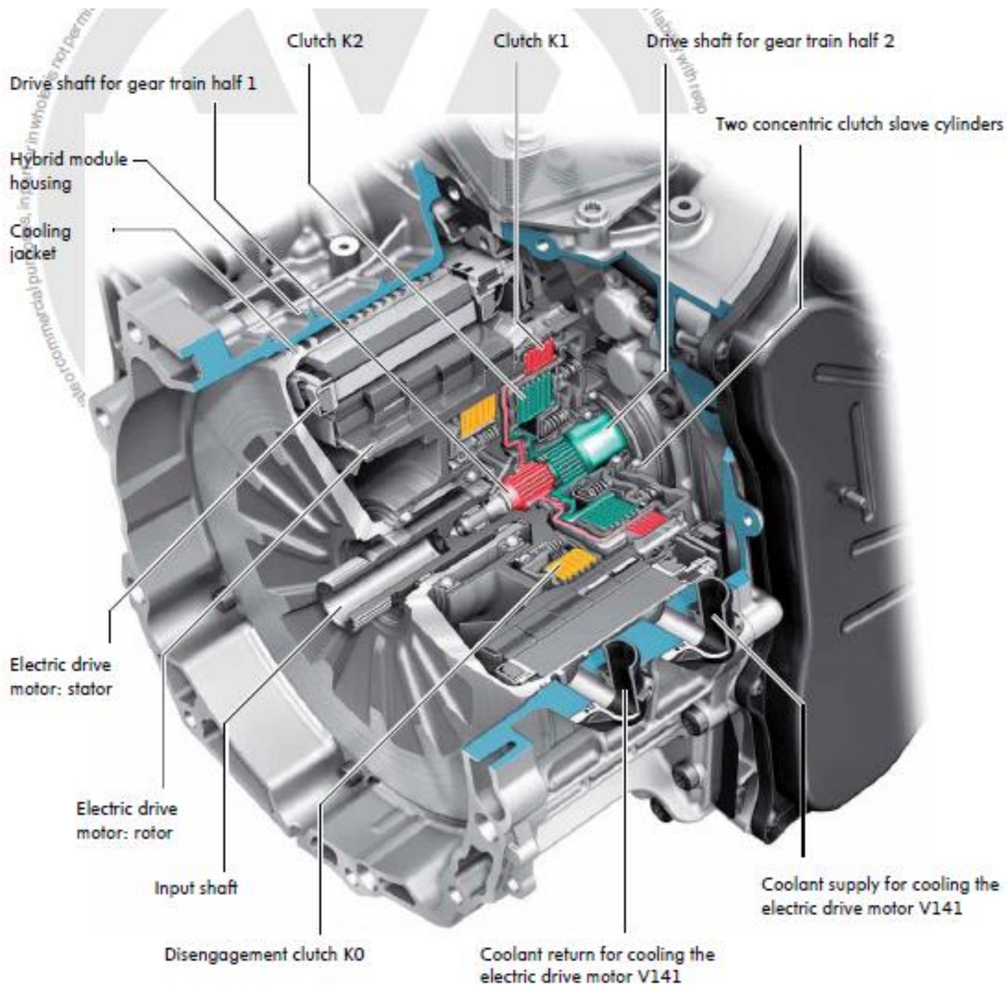


Figure 3: Hybrid module design overview (Picture from http://qualityservicemanual.com/725/volkswagen-audi-skoda-self-study-programme-sspservice-training-collection)

3 Test set up

3.1 Electrical Instrumentation Layout

The vehicle was equipped with four Hioki current clamps placed on the high voltage battery positive and negative cables, on the potential equalization line and on the charging cable, as shown in Figure 4 and in Table III below.

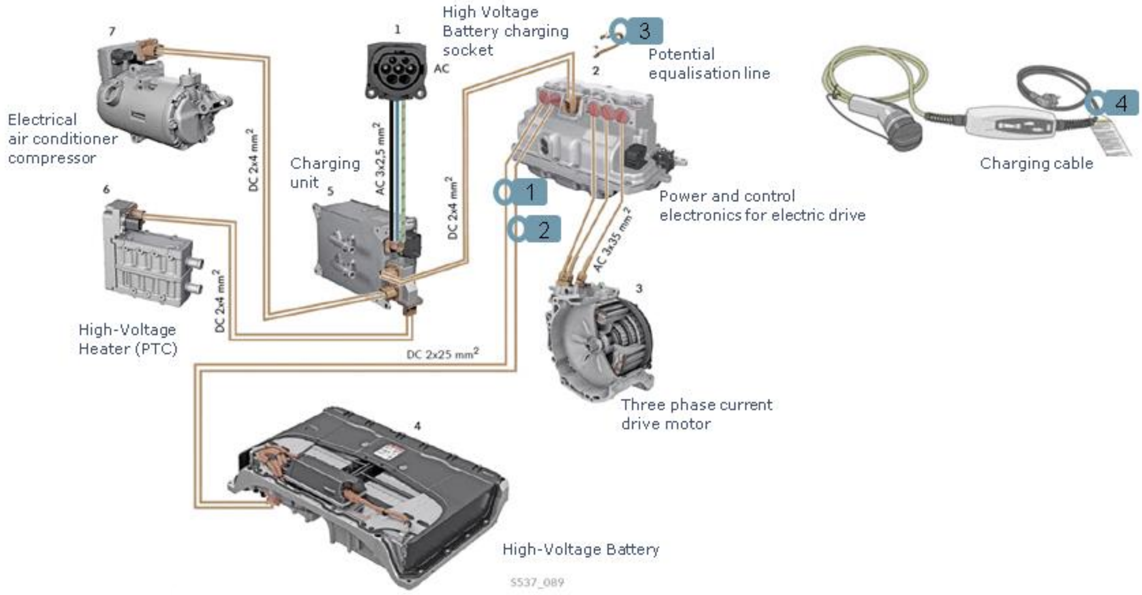


Figure 4: High voltage connections and current clamps sample points.

SAMPLE POINTS		
#	Channel	Measurements
1	HV Battery (-)	[A] and [V]
2	HV Battery (+)	[A] and [V]
3	Potential equalisation line	[A] and [V]
4	Charger	[A] and [V]

Table III: Current clamps sample points.

The high voltage from the battery was measured by means of a power analyser HIOKI3390 powered by an independent power supply system composed of a 12V battery and an inverter.

In order to guarantee driver’s and operators’ safety, a box with a relay and fuses was placed between the battery and the instrument (Figure 5).

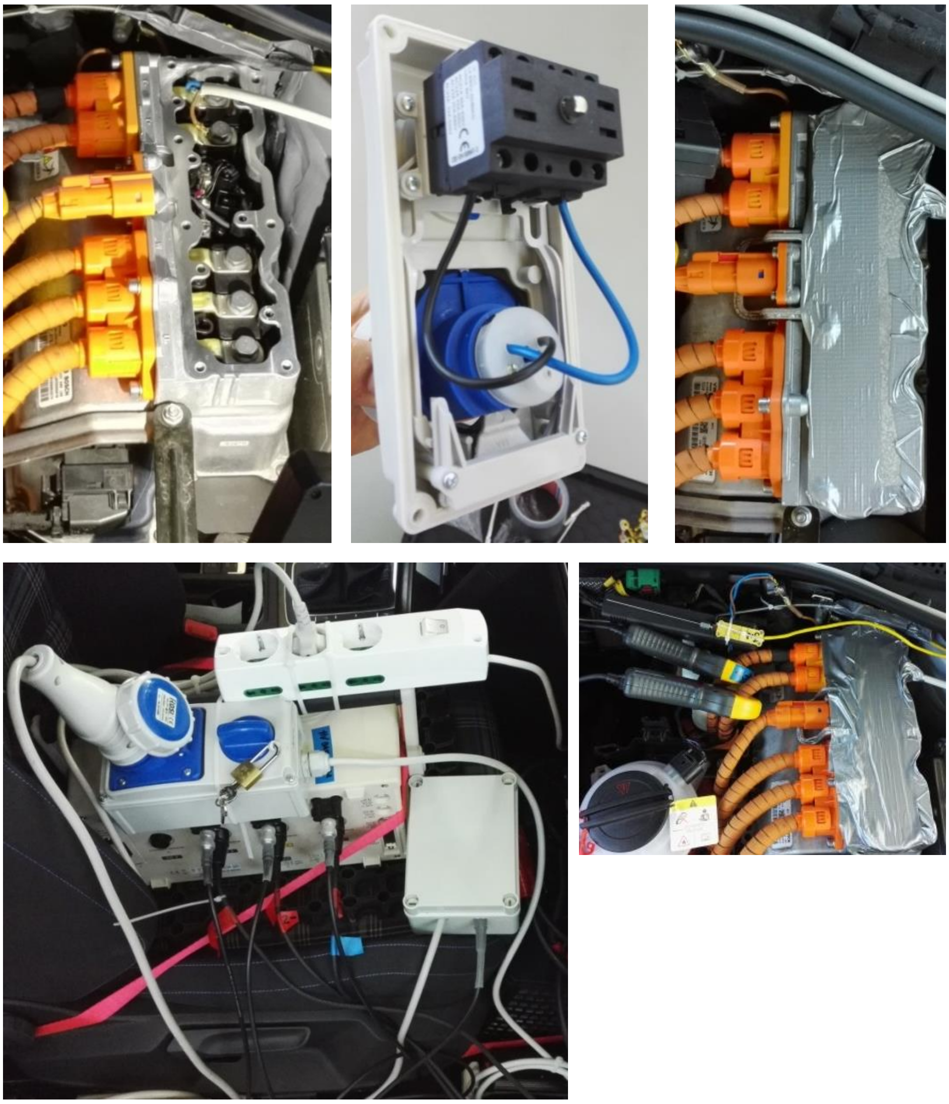


Figure 5: High voltage safety box and measurement set up.

As detailed in the vehicle's manual [1], the high voltage cable for the battery, power electronics and the electric drive motor features double insulation and a single-pole design (Figure 6).

The battery regulation control unit transmits a test voltage while the high voltage vehicle is in use. The test voltage is 500V and has a very low current.

If all high voltage components and wires are correctly insulated and shielded, the control unit calculates and compares the previously set total resistance of the high voltage system. If the insulation of a wire is damaged externally, the insulation resistance will change and consequently the control unit will detect an insulation fault due to this change in resistance.

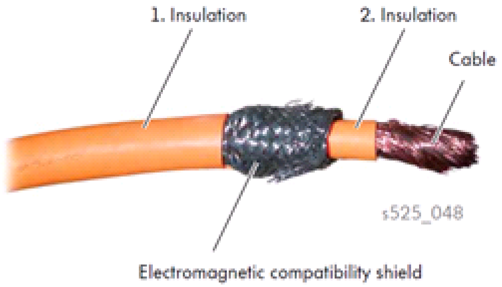
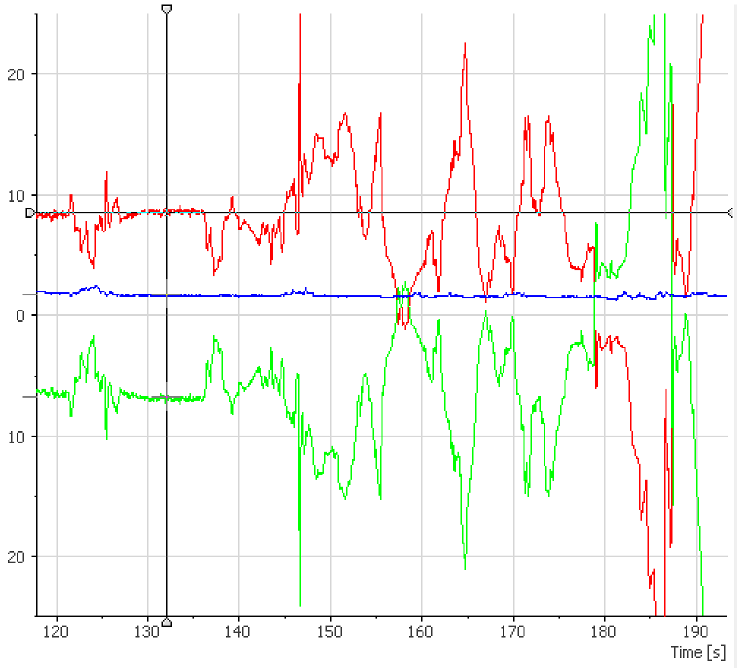


Figure 6: High voltage cable section.

The current clamps have been placed around the high voltage wires coming from the battery without excluding the insulation. For this reason, current [A] measurements from High Voltage battery cables differ around 1~2 A between the positive and negative lines due to the current flow through the wire shield for insulation monitoring (Figure 7).



channel	time [s]	Current [A]
$Idc_1(-)$	132.15	8.52
$Idc_2(+)$	132.15	-6.82
Added	132.15	1.7

Figure 7: Current values on positive and negative cables from the HV battery.

Furthermore VCDS, a Windows-based Diagnostic Software (Ross-Tech) that emulates the functions of the dealers' proprietary scan tools, was used to acquire different data from on-board vehicle diagnostics (OBD) port.

High voltage battery current, state of charge (SoC), coolant temperature, fuel consumption, internal combustion engine speed, intake manifold temperature have been recorded using this software.

Errors in the determination of the current have a great impact in the calculation of the total current and power integration [Ah] and [Wh].

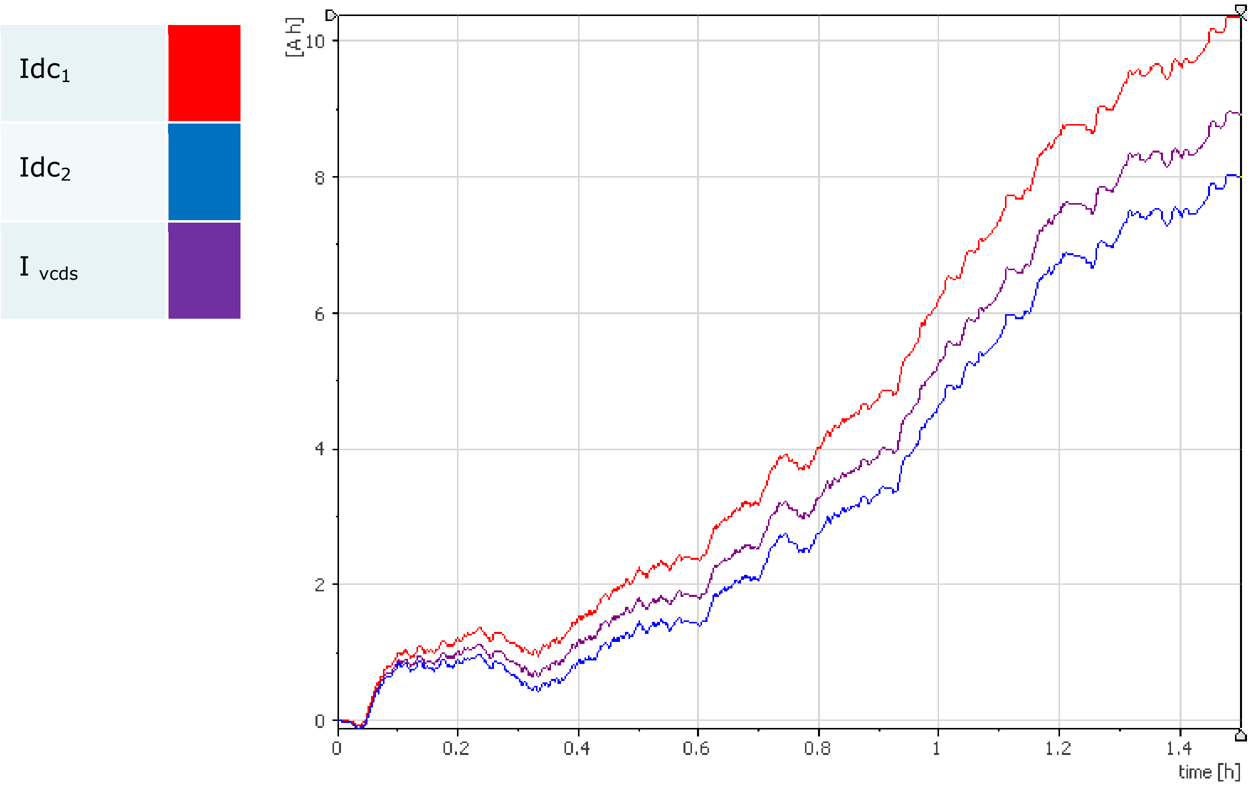


Figure 8: Currents on positive and negative cables from HV battery and current recorded by VCDS software.

The chart in Figure 8 shows the deviation in current integration when using ECU values (I_{vcds}) and direct measurement with clamps on HV battery cables (Id_1 and Id_2).

3.2 New PEMS device for emissions testing

Emission measurements, GPS and weather station data were acquired by means of a portable emmission measurement system device (PEMS) for Real Driving Emissions testing of passenger cars (Figure 9), which allow exact test execution according to European RDE legislative requirements (Reg. 427, 646/2016 and 2017/1154).

The gas analyser has been connected to the tailpipe through a $3_{1/2}$ inches double adaptor, a reducer and a $2_{1/2}$ inches flowmeter. It is able to record and to align data from different devices and sensors such as current probes and termocouples. Thermocouples Type K have been placed to record the temperature of the engine oil. The zeroing and gas calibration have been been performed with pure N_2 gas and certified reference cylinders (Figure 10).

Figure 9: M.O.V.E. Portable Emission Measurement system with its System Control Unit.

Figure 10: Positioning of GPS & weather station, of the flowmeter and of thermocouples.

4 Test campaign

The test campaign was conducted on the Esperia route (

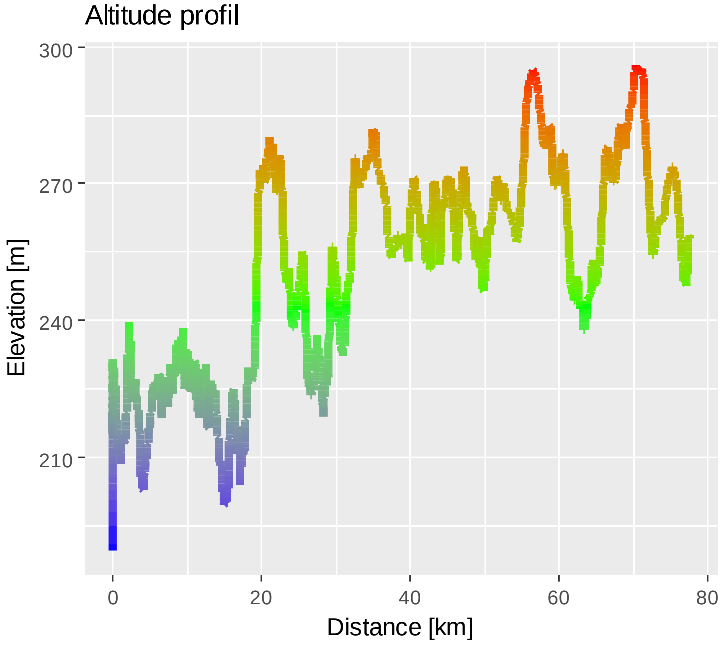


Figure 11), in compliance with the RDE3 (Real Driving Emissions) Regulation 2017/1154 (7.7.2017)[2]-[3] trip requirements, (with the exception of the requirement of 12 km of urban distance driven with ICE on operation for one test): distance shares for urban portion between 29% and 44%; for rural and motorway portions, 23% and 43%; altitude difference between the start and end point not exceeding 100meters;cumulative altitude gain below 1200 m per 100 km on urban and total trip.

The trip starts with the urban portion of at least 16km which has been driven on urban roads with a speed limit of 60 km/h or less, followed by the rural (speed between 60 and 90 km/h) and the motorway (speed over 90 km/h). During the motorway section, vehicle's velocity has been kept above 100 km/h for at least 5 minutes [2]-[3].

In order to minimize the effects on the results, the driver and his driving style has been the same for every test independently from the selected driving mode.

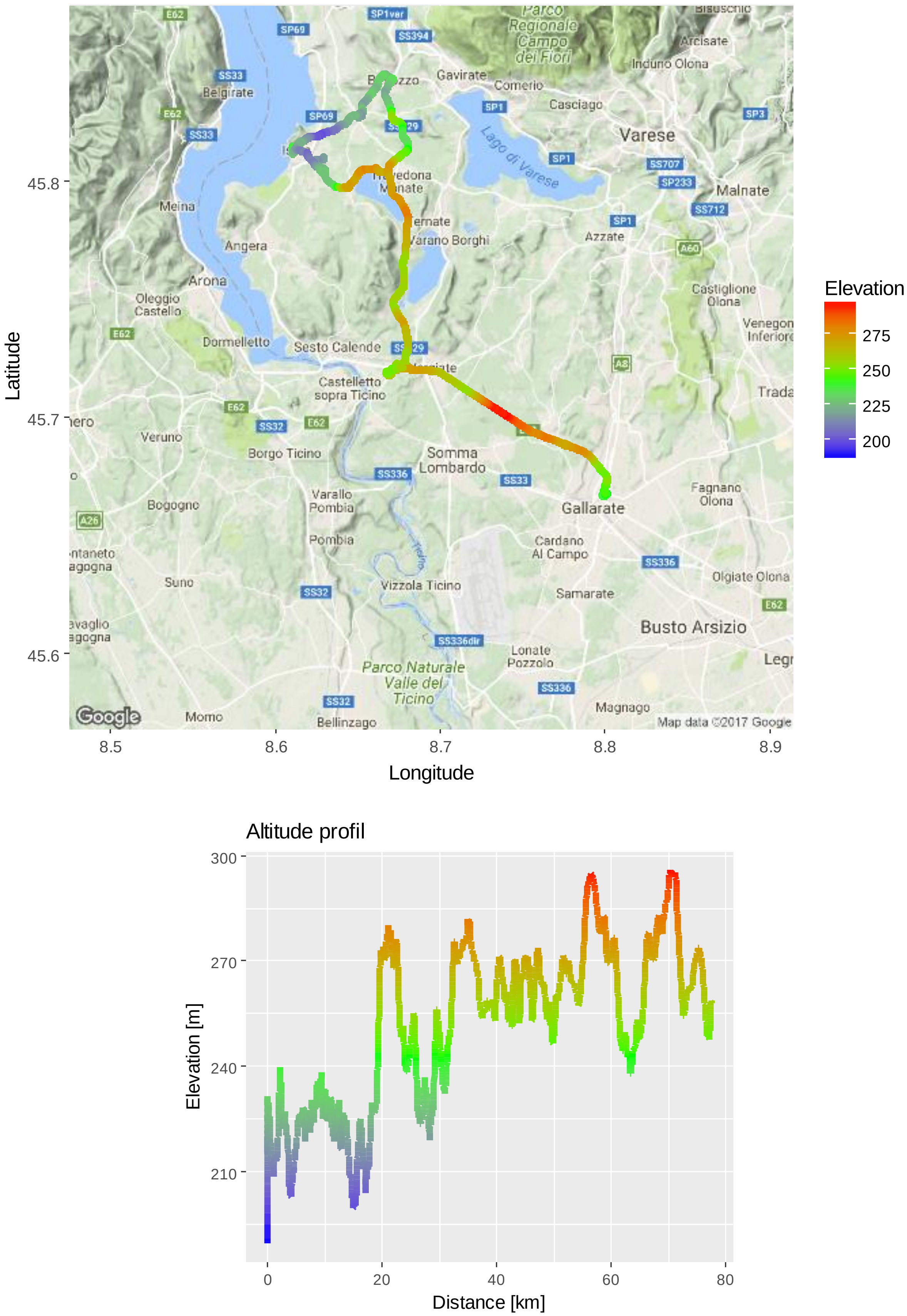


Figure 11: Esperia geographic coordinates.

Data are recorded from different devices and sensors ensuring data time alignment.

It is worth stressing that data alignment between several instruments is usually a source of uncertainty during data processing. For this reason the current of the HV battery has been measured with two different clamps on the same cable, one connected to an analogue input of the portable device for emissions measurements and the other connected to the HIOKI power analyser. Fast and reliable data post processing has been made with dedicated software.

5 Tests results

Driving Modes impact on CO_2 emissions [grams] and energy consumption [Wh] (over time and over distance) were analysed under charge depleting (CD, initial state of the HV Battery: Full) and charge sustaining (CS, initial state of the HV Battery: Empty) driving conditions. Table IV: Summary of the tests results reports a summary of the tests results.

Date	Legend	Mode	SoC	Dist. [Km]	Dur. [s]	Av Speed [Km/h]	CO_2 [g]	CO_2 [g/km]	WP [Wh]	WP [Wh/km]
13/09/16	CS	Sport	EMPTY	77.84	5975	46.97	14336.87	184.19	3354	43.09
15/09/16	CS	**Charge**	EMPTY	77.65	*6154*	*45.42*	*18690.16*	***240.70***	*6531*	*84.10*
16/09/16	CS	Hold	EMPTY	77.70	5423	51.82	12977.33	167.02	938.5	12.08
27/09/16	CS	Hybrid	EMPTY	78.32	5838	48.38	12585.35	160.75	813.5	10.39
28/09/16	CD	Hybrid	FULL	78.35	5714	49.57	7489.85	96.31	-5391	-68.80
29/09/16	CD	Sport	FULL	78.31	6059	47.32	12586.28	160.79	-34	-0.43

Date	Legend	Mode	Ambient Temperature [degC]	NOx [mg/km] Total trip	NOx [mg/km] Urban trip	NOx [g] Total trip	NOx [g] Urban Trip
13/09/16	CS	Sport	26.71	8.3	12.82	0.75	0.49
15/09/16	CS	**Charge**	23.12	11.4	14.6	1.37	0.99
16/09/16	CS	Hold	17.62	18.2	29.7	1.48	0.96
27/09/16	CS	Hybrid	20.33	11.9	17.5	0.95	0.58
28/09/16	CD	Hybrid	20.33	ICE distance on Urban<12km (Not RDE3 compliant)		1.08	0.34
29/09/16	CD	Sport	21.03	12.8	21.6	1.02	0.65

Table IV: Summary of the tests results

Graphs in Figure 12 show the electric energy consumption from the HV battery and the CO_2 emissions (grams) for each test as a function of time and as a function of the driven distance for charge depleting (HV battery fully charged) and charge sustaining (HV battery discharged) operations. Different total durations of tests are due to traffic conditions, unexpected stops and average speed.

Negative values of energy consumption indicate that the vehicle is discharging its high voltage battery (charge depleting test). Positive values of energy consumption indicate that the high voltage battery has been charged during the driving (charge sustaining test).

It has to be underlined that, at the time of the test campaign, the RDE3 Regulation 2017/1154 (7.7.2017) hadn't come into force yet, so the trip requirements refer to the previous version of the regulation. However the data analysis done after the introduction of the RDE3 shows that all the considered tests reported in Table IV are compliant with the trip requirements of RDE3, except for one amongst them, performed in Hybrid mode charge depleting condition on 28th of September.

In particular this test is not compliant with the requirement introduced in RDE3 related to the portion of 12Km that should be driven with the internal combustion engine working during the urban phase. This verification was done checking the rpm registered from the

ECU and the exhaust flow rate. As stated in Appendix 4-Point 5 of Regulation 2017/1154, the ICE is considered active when the engine speed is above 50 rpm and the exhaust mass flow rate is less than 3 kg/h.

Distance-specific NOx emissions (Table IV) were calculated following Appendix 7c of Regulation 2017/1154. The reference WLTC CO_2 on charge-sustaining of the vehicle is 157.91 gCO_2/km. NOx emissions of all trips, with independence of the driving mode and battery initial SoC are below the RDE Not to Exceed limit for NOx (EURO6 limit * 2.1 conformity factor = 126 mg NOx/km), both on the total trip and in the urban trip. The distance-specific NOx emissions are similar on trips operated in CS and CD.

Note that particle number was not measured on-road during this campaign.

The charge sustaining test in Charge mode (Figure 13) corresponds to the highest value of CO_2 emissions (240.70 g/km). In this condition the vehicle uses the ICE at any circumstances to recharge the battery. The ICE idles even during traffic stops to recharge the battery and it is only switched OFF during deceleration phases or when driving downhill. Once the HV battery is fully charged, the vehicle runs only on ICE, getting no support from the electric drive.

The charge sustaining test on Sport mode (Figure 14) differs from Hybrid and Hold modes tests in the final HV SoC, which is considerably higher in Sport mode due to the contribution of the ICE, resulting in higher values of emitted CO_2.

In charge sustaining tests on Hybrid and Hold modes (Figure 16 & Figure 15) instead, the vehicle behaves basically in the same way. The HV battery is slightly charged in order to support the vehicle when starting from rest. Total CO_2 emissions are similar to those obtained for charge depleting on sport mode, but the energy balance of the HV battery is positive for Hybrid and Hold modes (i.e. the battery is recharged).

For charge depleting test in Sport mode (Figure 17) the vehicle relies basically on the ICE. During the urban phase some extra support is taken from the HV battery but it is recovered on the rural phase. During the motorway phase no power is taken from the HV battery. This strategy results on reaching the end of the test with the battery fully charged.

During charge depleting test with Hybrid mode (Figure 18) the vehicle uses extensively the electric drive, behaving almost as in pure electric mode. This case corresponds to the lowest value of CO_2 emissions (96.31 g/km) and a complete depletion of the HV battery (5391Wh). The internal combustion engine remains practically inactive as long as the state of charge of the HV battery allows it. Once the SoC is too low the ICE starts.

As already mentioned, the worst case in terms of emissions is the charge sustaining test in *Charge mode,* where the CO_2 emission is 240.70 g/km (Table IV), due to the fact that the vehicle uses the ICE at any circumstances to recharge the battery.

It is possible to estimate the CO_2 produced by the ICE working as a generator to recharge the battery during the Charging mode CS. Considering the charge depleting test in *Sport mode*, where the contribution of the HV battery is almost negligible (-34Wh) and the emission of CO_2 is 160.79 g/km, the difference between the two modes results in 79.91 g/km. Hence, in Charge mode the total CO_2 emissions needed to recharge 6531 Wh is 6103.88 CO2g, which means a production of 0.935 CO_2 g/Wh.

Considering the best case in terms of emissions (charge depleting on hybrid mode 96.31 g/km) and the CD Sport mode (160.79 g/km of CO2), the difference results in 64.48 g/km of CO_2 "saved" due to the contribution of the HV battery. It represented an amount of 5096.43g of CO_2 which was reduced by using 5391 Wh from the high voltage battery (the negative sign in Table IV indicates the battery discharge). Hence in charge depleting hybrid mode the CO_2 saved is 0.945 CO_2g/Wh.

20160913	CS_GTE
20160915	CS_Batt. Charge
20160916	CS_Batt. Hold
20160927	CS_Hybrid Auto
20160928	CD_Hybrid Auto
20160929	CD_GTE

Note: Different duration of tests due to traffic conditions, unexpected stops, average speed.

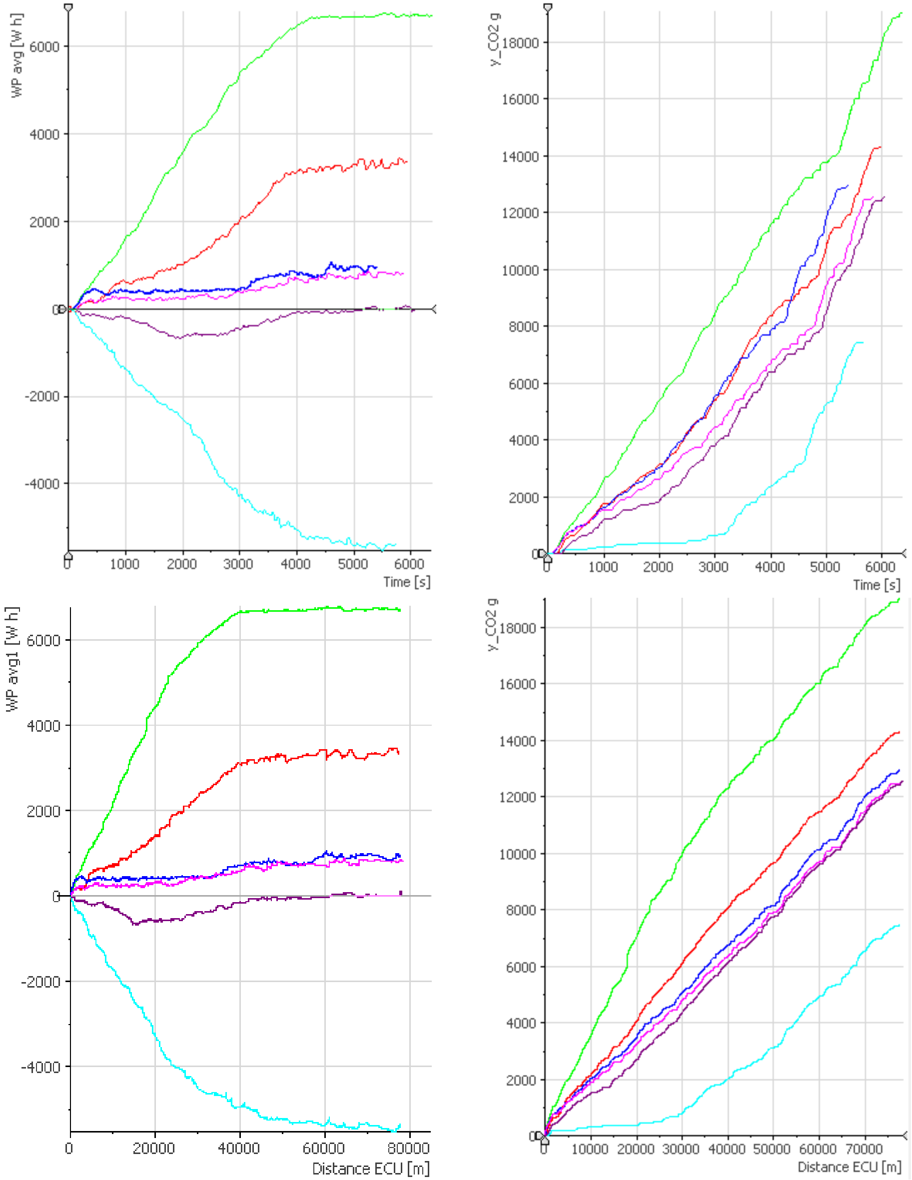
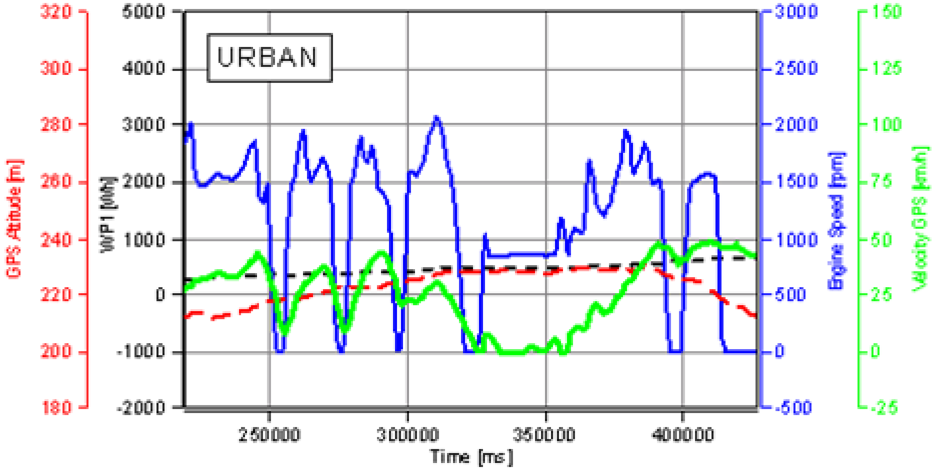
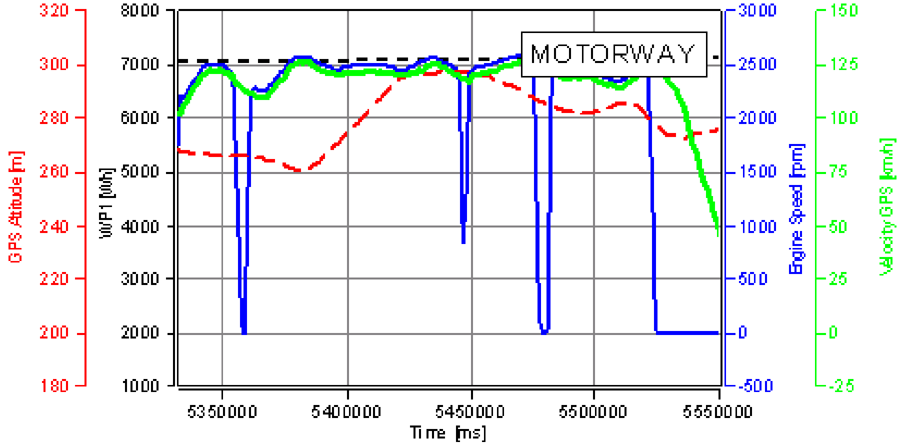


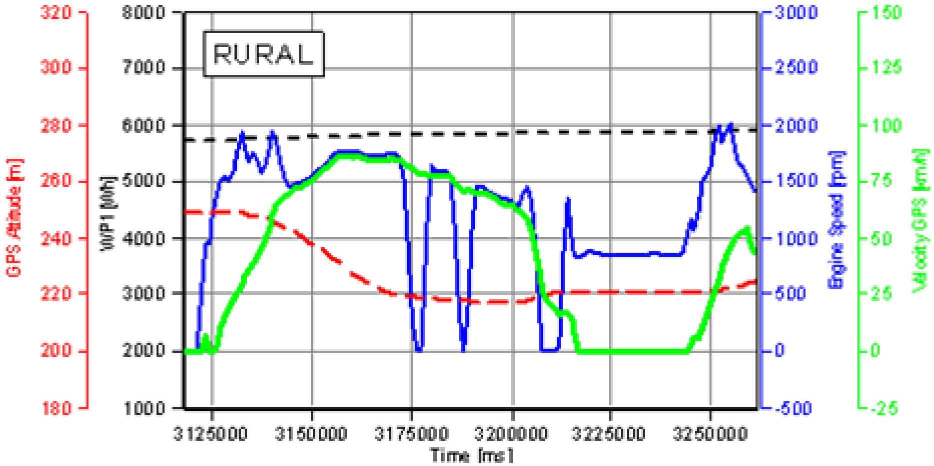
Figure 12: Driving Modes impact on CO2 grams and Wh (over time and over distance)

Esperia: Charge Sustaining – Charging mode

The battery is recharged under any circumstances, by regenerative braking, smart charging (ICE) and even idling while the vehicle is stopped.





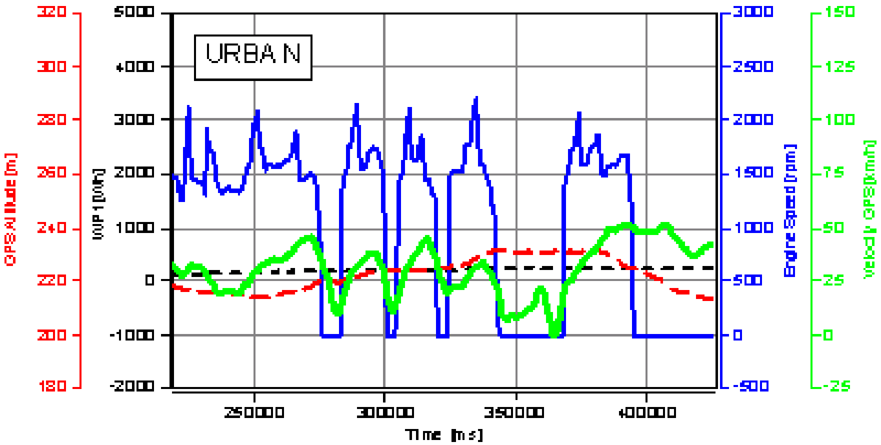


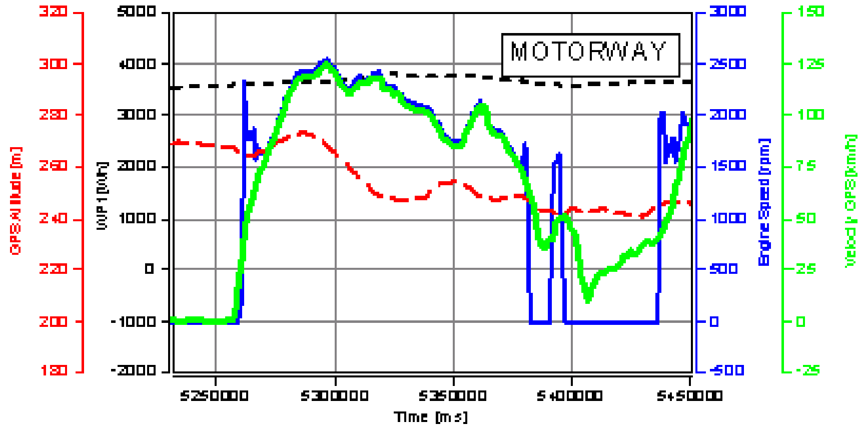
Distance [Km]	Av Speed [Km/h]	CO2 [g/km]	WP [Wh]
77.65	*45.42*	***240.70***	*6531*

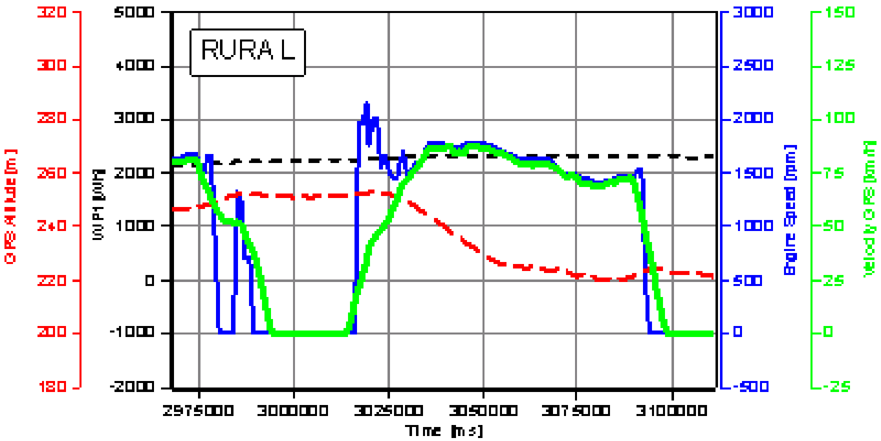
Figure 13: Charging Mode – CS test results for urban, rural and motorway portions. GPS altitude [m] and speed [km/h]; Energy consumption [Wh], Engine speed [rpm].

Esperia: Charge Sustaining – Sport mode

The battery is recharged by regenerative braking and smart charging (ICE)





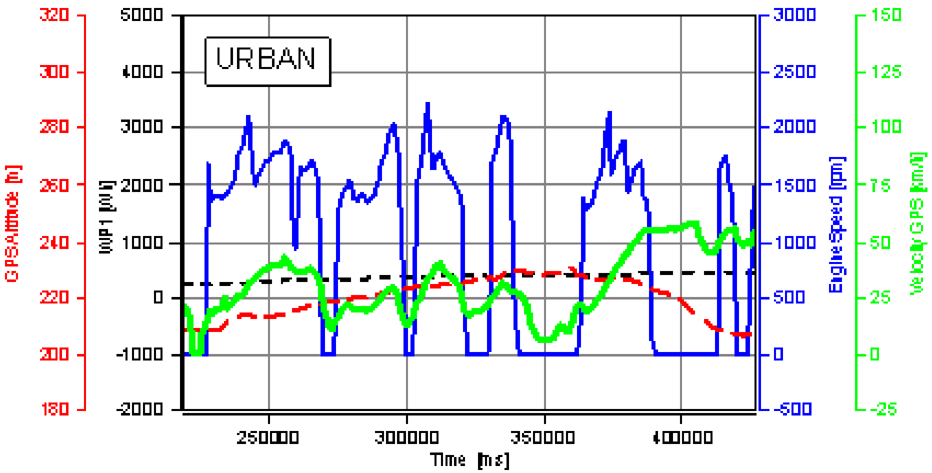


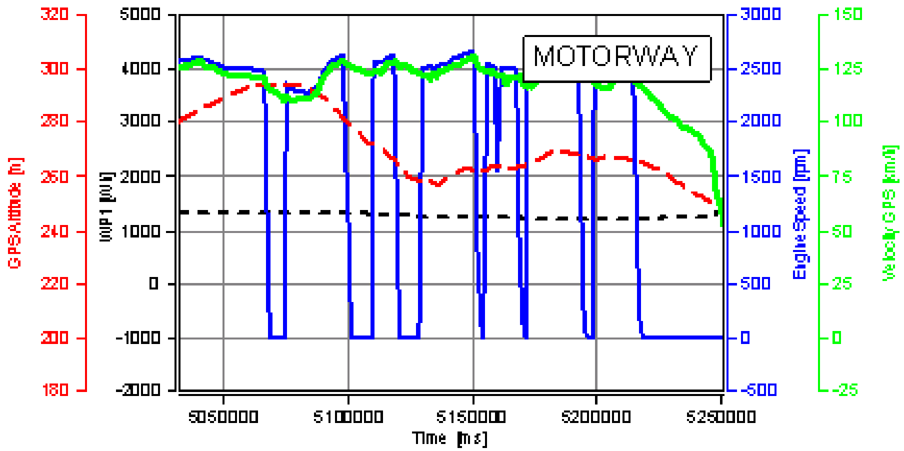
Distance [Km]	Av Speed [Km/h]	CO2 [g/km]	WP [Wh]
77.84	46.97	184.19	3354

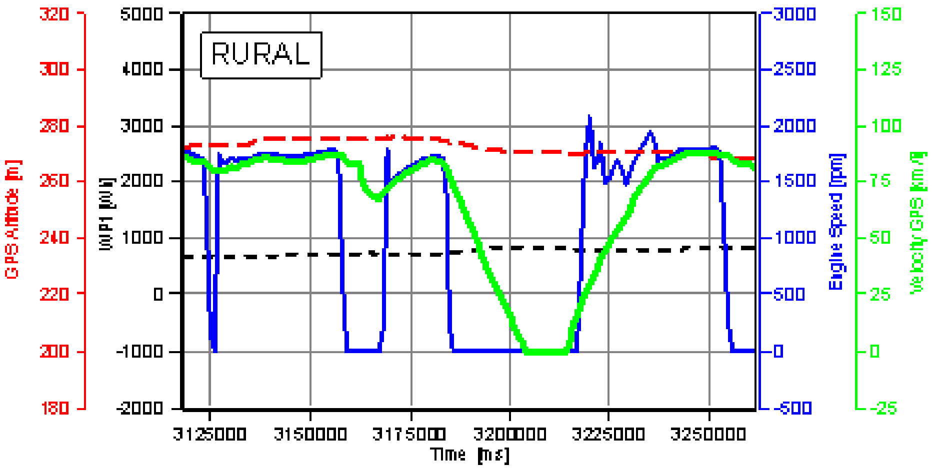
Figure 14: Sport Mode - CS test results for urban, rural and motorway portions. GPS altitude [m] and speed [km/h]; Energy consumption [Wh], Engine speed [rpm].

Esperia: Charge Sustaining – Hold mode

The battery is recharged by regenerative braking and smart charging (ICE)



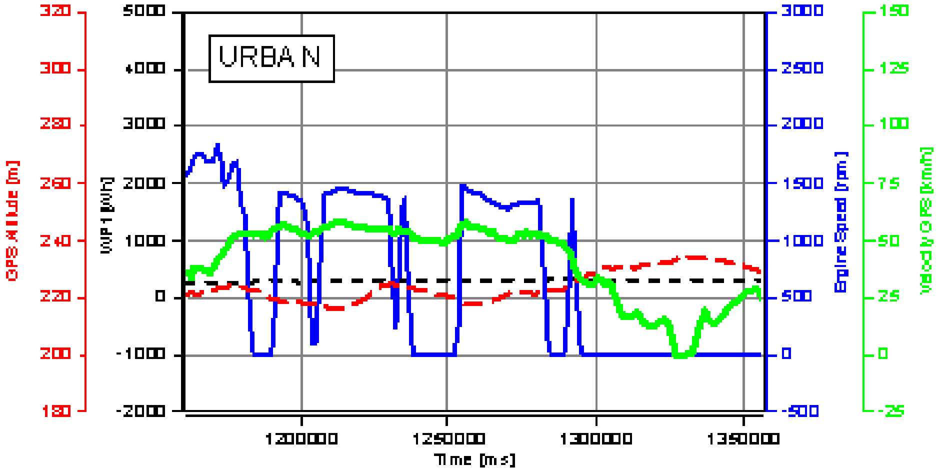


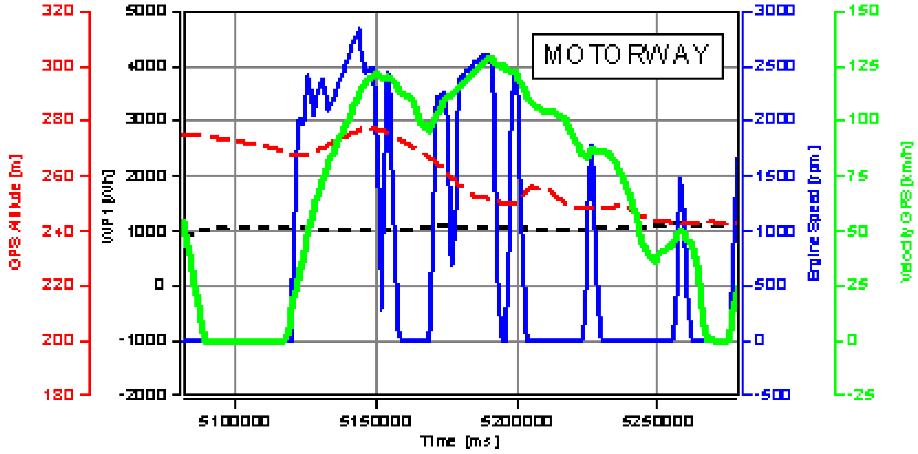


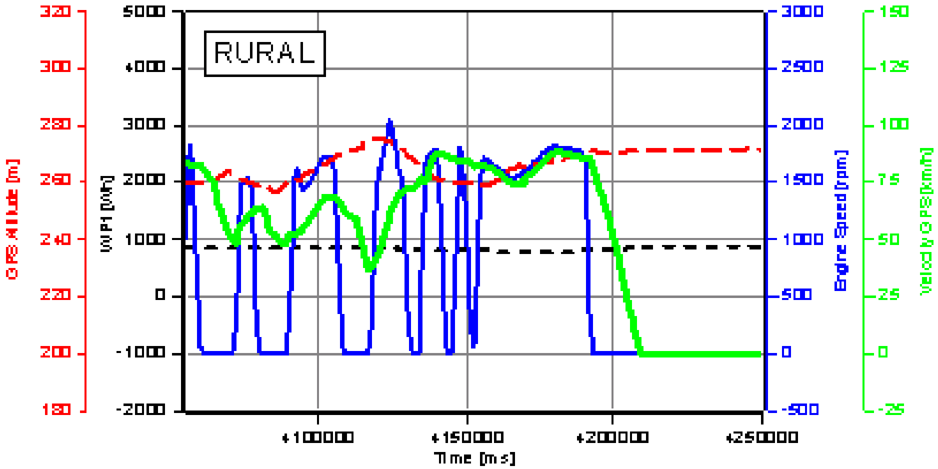
Distance [Km]	Av Speed [Km/h]	CO2 [g/km]	WP [Wh]
77.70	51.82	167.02	938.5

Figure 15: Hold mode - CS test results for urban, rural and motorway portions. GPS altitude [m] and speed [km/h]; Energy consumption [Wh], Engine speed [rpm].

Esperia: Charge Sustaining – Hybrid mode





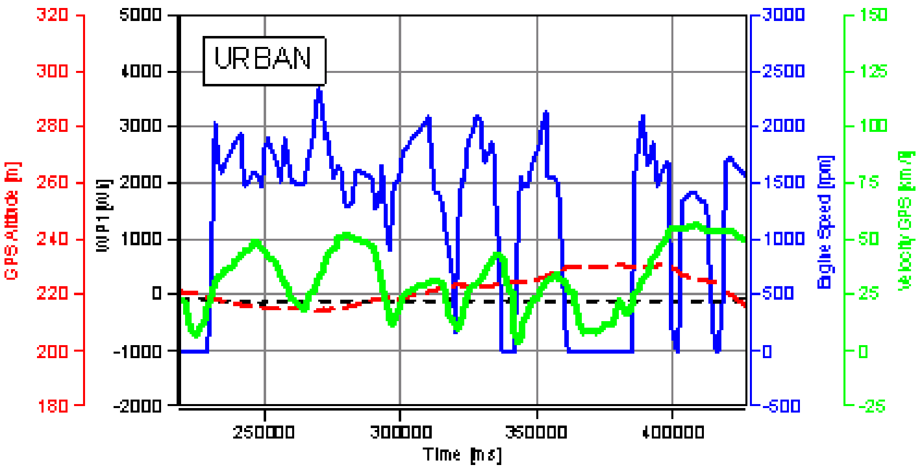


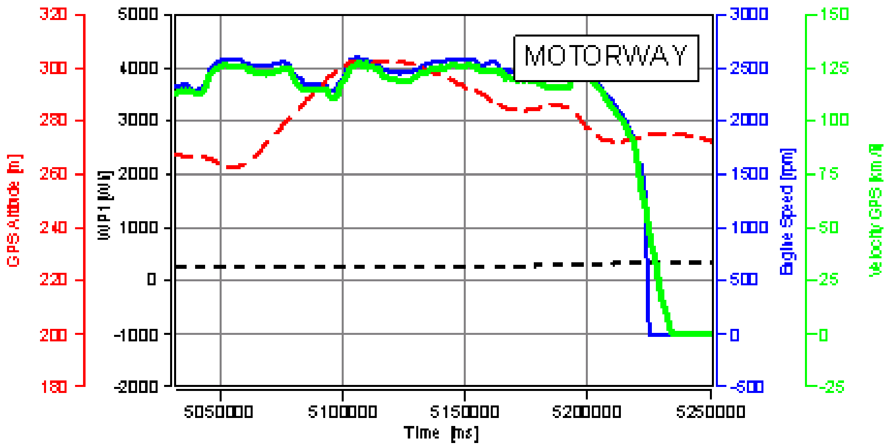
Distance [Km]	Av Speed [Km/h]	CO2 [g/km]	WP [Wh]
78.32	48.38	160.75	813.5

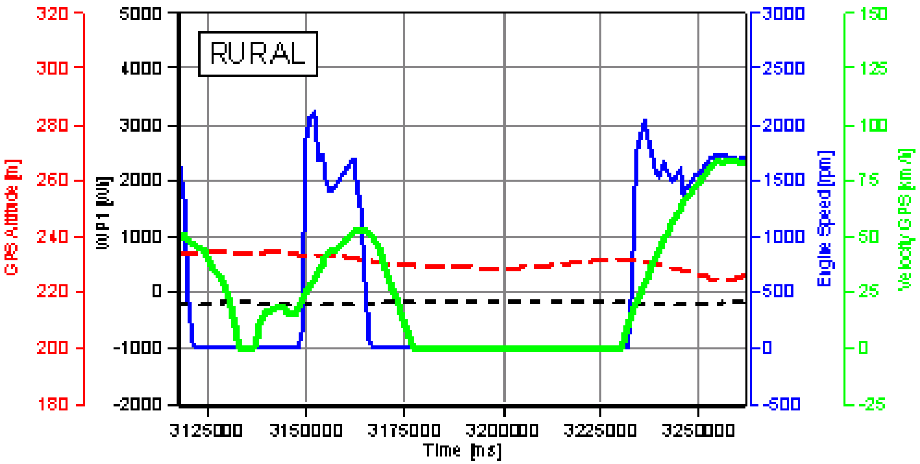
Figure 16: Hybrid mode – CS test results for urban, rural and motorway portions. GPS altitude [m] and speed [km/h]; Energy consumption [Wh], Engine speed [rpm].

Esperia: Charge Depleting – Sport mode

Almost no energy is taken from the battery which is still over the 95% of its capacity at the end of the test.



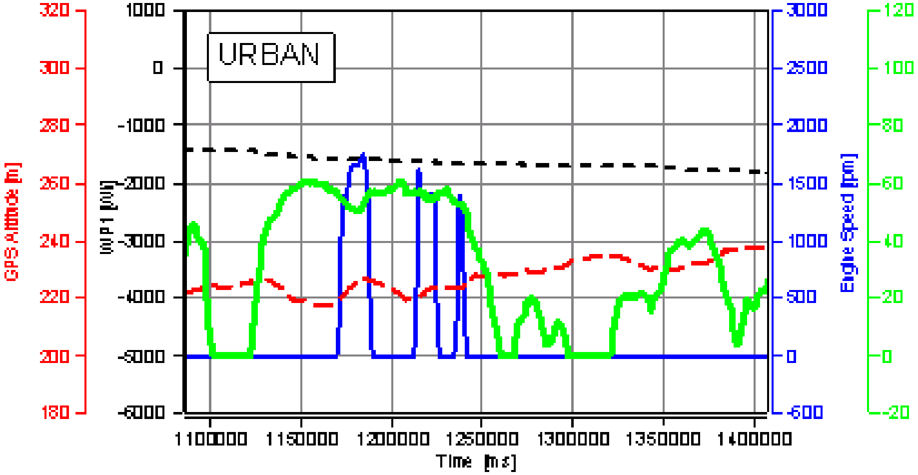


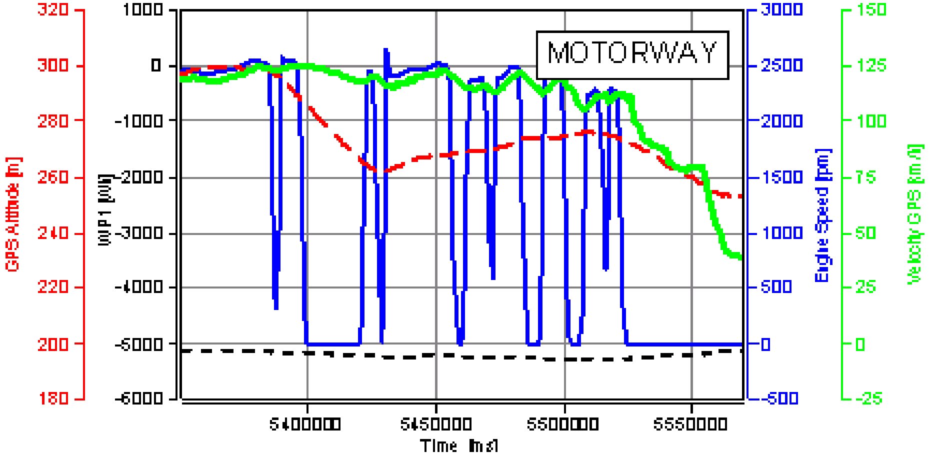


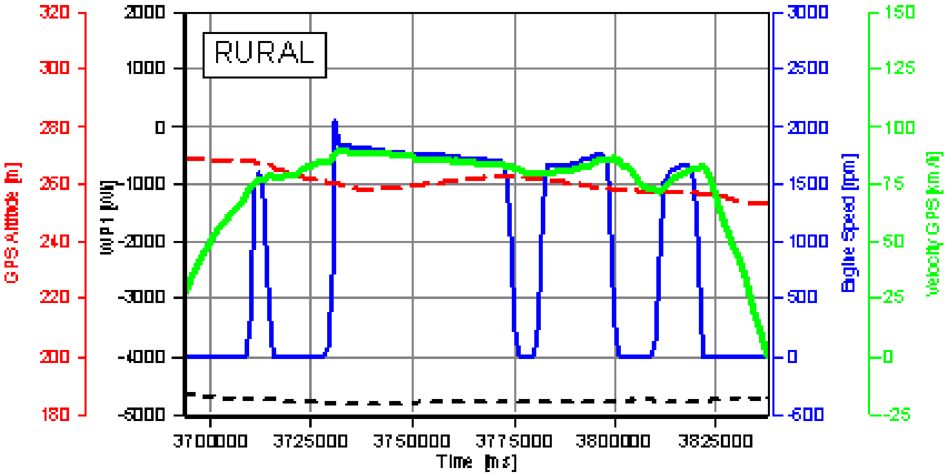
Distance [Km]	Av Speed [Km/h]	CO2 [g/km]	WP [Wh]
78.31	47.32	160.79	-34

Figure 17: Sport mode – CD test results for urban, rural and motorway portions. GPS altitude [m] and speed [km/h]; Energy consumption [Wh], Engine speed [rpm].

Esperia: Charge Depleting – Hybrid mode







Distance [Km]	Av Speed [Km/h]	CO2 [g/km]	WP [Wh]
78.35	49.57	96.31	-5391

Figure 18: Hybrid mode – CD test results for urban, rural and motorway portions. GPS altitude [m] and speed [km/h]; Energy consumption [Wh], Engine speed [rpm].

6 Conclusions

The reported test campaign has highlighted the impact of different driving modes on energy consumption and CO_2 and NOx emissions during RDE tests (all considered tests are compliant with the trip requirements of RDE3, except one), focusing on practical aspects of the measurements such as safety and accuracy.

Results showed that charging and sport mode are the most consuming driving modes in terms of CO_2 emissions, and in the meanwhile they are the most energy saving due to the recharge of the HV battery.

It has to be highlighted that for all hybrid modes when the electric autonomy is 0 km, the ICE remains idling during the stops until the battery reaches a minimum level of autonomy (~3km). Above ~3-4Km of autonomy the Start/Stop system of the ICE works normally and when starting from rest, the first few metres are run in electric and once the vehicle is moving the ICE starts (excluding Charging mode).

Moreover, it is worth underlining that the order of the different portions of the route (urban/rural/motorway) might have a remarkable influence on the results: being the motorway section at the end of the route, the HV battery mainly contributes during the urban and the first half of the rural phase. This situation results in the ICE working mainly in the motorway phase where it is more efficient in terms of CO_2 emissions. Changing the order of the phases in charge depleting mode, the fully charged HV battery could be fully exploited for more demanding parts of the trip. Consequently, the urban phase would start with a different level of SoC of the battery, implying a different usage of the ICE, in conditions where it is less efficient.

In the same way, in charge sustaining mode, starting with a portion of the trip at higher speeds, the ICE could charge more the HV battery. Consequently, the urban phase would start with a certain available range of the battery, allowing electric drive at lower speeds. Hence the effect of different variants of the phases order should be taken into consideration and evaluated in future test campaigns.

The emissions of NOx complied with the NTE limit settled in RDE for all tests done during the campaign with independence of the driving mode and initial battery SoC. The distance-specific NOx emissions of the vehicle were similar on CD and CS.

However, on the CD hybrid test, the one with the most electric driving on the urban part, mass emissions of NOx were one third (340 mg) of the ones emitted on the urban part of the trip on CS battery charge mode (990 mg), the test where the electric motor was not operated. Considering the air quality problems in the cities related to NOx, this emission reduction is a relevant benefit of the CD operation of PHEVs.

References

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[2] "On-road testing with Portable Emissions Measurement Systems (PEMS) - Guidance note for light-duty vehicles", Víctor Valverde Morales, Pierre Bonnel – JRC Technical Reports July 2017

[3] RDE 3 (Real Driving Emissions) Regulation 2017/1154 (7.7.2017)

List of abbreviations and definitions

PEMS	Portable Emissions Measurements System
PHEV	Plug In Hybrid Electric Vehicle
OBD	On Board Diagnostic
SoC	State of Charge
HV	High Voltage
ICE	Internal Combustion Engine
GPS	Global Positioning System
ECU	Engine Control Unit
RDE	Real Driving Emissions
CD	Charge Depleting
CS	Charge Sustaining
NOx	Nitrogen oxides
NTE	Not-to-Exceed limit

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