European Commission

JRC SCIENCE FOR POLICY REPORT

Particle Number PEMS Inter-Laboratory Comparison Exercise

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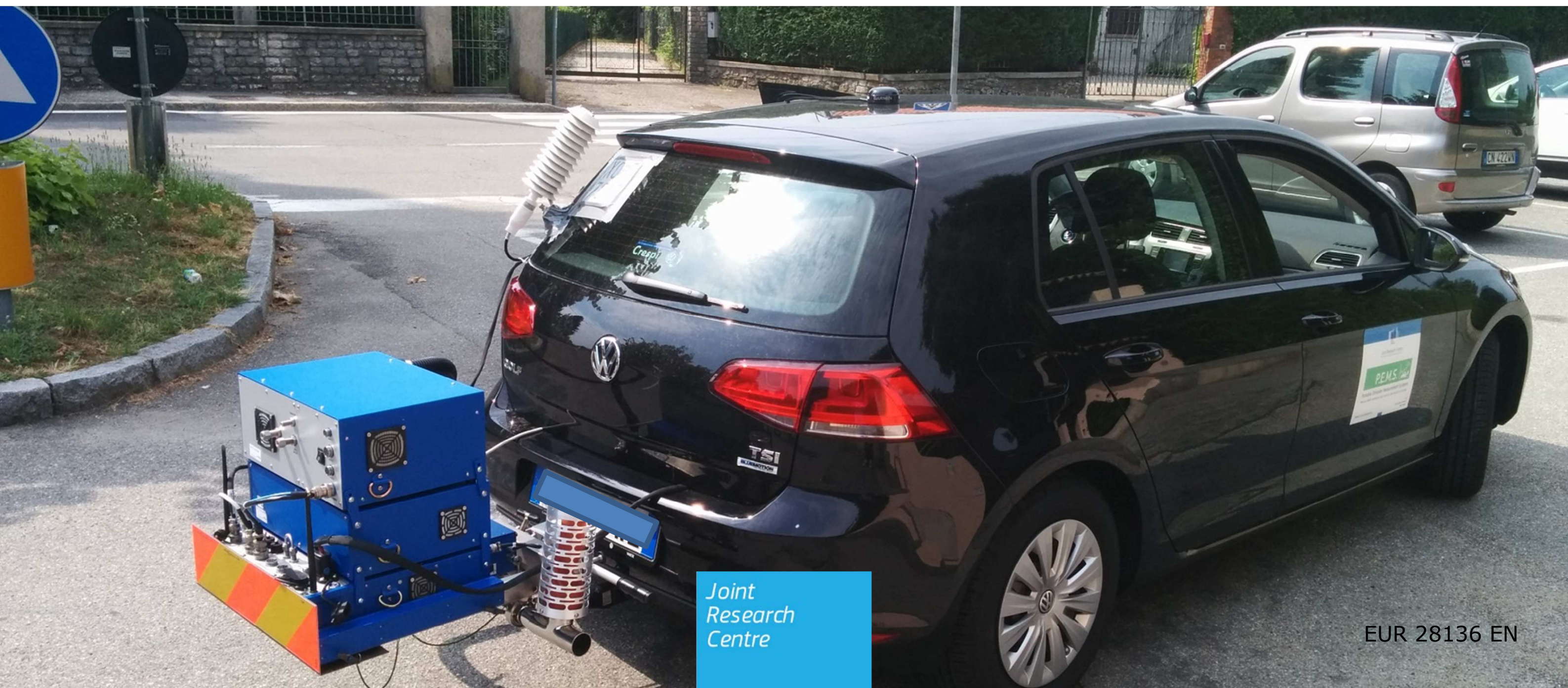
2016



Joint Research Centre

EUR 28136 EN

JRC Science Hub
https://ec.europa.eu/jrc

JRC103206

EUR 28136 EN

Print	ISBN 978-92-79-62297-7	ISSN 1018-5593	doi: 10.2790/229190
PDF	ISBN 978-92-79-62296-0	ISSN 1831-9424	doi: 10.2790/562

Luxembourg: Publications Office of the European Union, 2016

How to cite this report: Francesco Riccobono, Barouch Giechaskiel, Pablo Mendoza Villafuerte, Particle Number PEMS Inter-Laboratory Comparison Exercise, EUR 28136 EN, doi: 10.2790/562.

Particle Number PEMS Inter-Laboratory Comparison Exercise
This report summarizes the results of the Inter-Laboratory Comparison Exercise for the PN-PEMS equipment that took place between September 2015 and January 2016. The accuracy and precision of PN measurement with two different PN-PEMS was assessed with one selected Golden Vehicle in seven different laboratories across Europe, providing indications for drafting the third package of the RDE regulation. The differences of the PN-PEMS to the reference system at the CVS were between -40% and +40%; similar to those between the reference system at the tailpipe and the CVS. The accuracy and precision of the PN-PEMS, as estimated by comparing them with the reference system at the tailpipe were 10.4% ± 11.9% for the diffusion charger based PN-PEMS and -8.0% ± 9.5% for the CPC-based PN-PEMS. The larger differences compared to the reference system at the CVS can be explained by particle transformations between the vehicle tailpipe and the CVS and calibration uncertainties of the reference systems at the CVS. On road tests showed that the PN-PEMS were stable and measuring as in the laboratory. For the tested vehicle technology, there were not significant deviations between the PN emissions measured in the laboratory and the PN emissions measured under real driving conditions at ambient temperatures between 3°C and 25°C.

Contents

Acknowledgements

The authors would like to thank the following instruments manufactures for their support in providing the instruments for the experimental activities: Testo, Horiba, AVL. A special thanks to Sensors for providing the Gas PEMS and the support to all the laboratories of the ILCE.

The work has been possible only with the scientific and technical support of all the experts involved in the laboratories that participate to the ILCE.

Authors

Francesco Riccobono, Barouch Giechaskiel, Pablo Mendoza Villafuerte

Abstract

This report summarizes the results of the Inter-Laboratory Comparison Exercise for the PN-PEMS equipment that took place between September 2015 and January 2016. The accuracy and precision of PN measurement with two different PN-PEMS was assessed with one selected Golden Vehicle in seven different laboratories across Europe, providing indications for drafting the third package of the RDE regulation. The differences of the PN-PEMS to the reference system at the CVS were between -40% and +40%; similar to those between the reference system at the tailpipe and the CVS. The accuracy and precision of the PN-PEMS, as estimated by comparing them with the reference system at the tailpipe were 10.4% ± 11.9% for the diffusion charger based PN-PEMS and -8.0% ± 9.5% for the CPC-based PN-PEMS. The larger differences compared to the reference system at the CVS can be explained by particle transformations between the vehicle tailpipe and the CVS and calibration uncertainties of the reference systems at the CVS. On road tests showed that the PN-PEMS were stable and measuring as in the laboratory. For the tested vehicle technology, there were not significant deviations between the PN emissions measured in the laboratory and the PN emissions measured under real driving conditions at ambient temperatures between 3°C and 25°C.

1 Introduction

The European Commission is committed to improve the air quality by the implementation of emission regulations (EC 2007, EC 2008). The Commission also works on the improvement of testing procedures for pollutant emissions and fuel consumption. This helps to assess the performance of vehicles under real-life conditions. Two new testing procedures are currently being developed: Real Driving Emissions (RDE) for measuring regulated pollutants and the Worldwide Harmonized Light-duty Vehicles Testing Procedure (WLTP) for measuring CO_2 emissions. The RDE procedure has been split into four packages. The 1st and the 2nd RDE packages were voted positively by the Member States in the Technical Committee of Motor Vehicles (TCMV) resulting in Commission Regulation (EU) 2016/427 of 10 March 2016 and Commission Regulation (EU) 2016/646 of 20 April 2016 which amend Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6) (EC 2016a, EC 2016b). From 1 September 2017 the new RDE tests will determine whether a new car model is allowed to be put on the market. From 1 September 2019 a conformity factor is set for NO_x at 2.1 for all new vehicles.
The 3rd RDE package will define a procedure for the measurement of the Particle Number with PEMS (PN-PEMS), of emissions of hybrid electric vehicles and include the effect of vehicle cold starts into the RDE testing.

In this framework, in August 2012, RDE Particle Number (PN) activities started with the a call for expression of interest: Participation in the development of a test protocol to measure Particle Number (PN) emissions on-board of light-duty vehicles for type approval using Portable Emissions Measurement Systems (PEMS). On behalf of the European Commission, DG ENTR (now DG GROW) and the JRC requested industry stakeholders, in particular manufacturers of instrumentation equipment, to communicate information about portable instrumentation that could be used for PN emission measurements on board of light-duty vehicles during a type approval test under real driving conditions.

Many manufacturers provided instruments for the participation to the laboratory testing organized at the JRC to assess the performance of the PN-PEMS (Giechaskiel et al. 2014, Giechaskiel et al. 2015, Riccobono et al. 2015). Among the commercially available PN-PEMS the JRC selected two systems (based on different working principles) for the assessment of their performance through an Inter-Laboratory Comparison Exercise (ILCE). The ILCE aims to assess the accuracy and precision of the PN measurement with two different PN-PEMS on a selected “Golden Vehicle” in different laboratories across Europe directly involving other stakeholders, such as industry and technical services.

This report summarizes the results of the PN-PEMS Inter-Laboratory Comparison Exercise that took place between September 2015 and January 2016.

2 Methods

2.1 The Golden Vehicle

The "Golden Vehicle" (GV) selected for the PN-PEMS ILCE is a Volkswagen Golf, a C-segment vehicle highly representative of the European fleet (the most sold C-segment vehicle in Europe), widely used in European cities. It has a 1.2 liter Gasoline Direct Injection (GDI) engine with 63 kW, full technical specifications of the Golden Vehicle are given in

Table 1.

Table 1 Technical specifications of the Golden Vehicle

Brand	Volkswagen
Model	Golf
Generation	VII
Power	85 hp @4800 rpm
Engine displacement	1197 cm^3
Torque	160 Nm @1400-3500 rpm
Fuel system	Direct injection
Turbine	Turbocharging
Number of cylinders	4, in line
Fuel type	Gasoline
Wheel drive	Front wheel drive
Number of gears (manual)	5
Kerb weight	1205 kg
Max weight	1720 kg

2.2 Instruments

The following instruments were shipped to the participating laboratories together with the Golden Vehicle

- PN-PEMS 1: NanoMet3 (NM3), Testo.
  The NanoMet3 is a PN-PEMS based on Diffusion Charging sensor (DC). It is equipped with a Diffusion Size Classifier - DiSC sensor (Fierz et al., 2011) which charges the aerosol in a unipolar diffusion charger. The charged aerosol passes through a diffusion stage where particles are deposited by diffusion and detected as an electrical current. The remaining particles end up in a second stage, the filter stage where the current is also measured. The ratio of the two currents is a measure of the average particle size and is determined during the instrument calibration. Because the charge per particle is a function of particle diameter, once this relation is known, the particle number can be computed from the total current and flow rate. The raw gas is first diluted by a rotating disk diluter in the proximity of the tailpipe (dilution factor ranges from 10 to 300 automatically adjusted by the system according to actual particle concentration) and then passes through an evaporation tube (kept at 300°C) that removes the volatile particles. The system provides also the Lung Deposition Surface Area (LDSA). It is worth to note that the PN concentrations (p/cm^3) presented in this report as NM3 are calculated from the LDSA value multiplied by a constant converting factor based on 70 nm calibration provided by the manufacturer.

- PN-PEMS 2: Modified Nanoparticle Emission Tester (Mod-NPET) Horiba.
  The modified NPET (Mod-NPET) is a PN-PEMS based on the Condensation Particle Counter (CPC) system. It consists of two cold dilutors, a catalytic stripper in between and a CPC. The first dilution, with dried and filtered dilution air, is carried out directly at the sampling point preventing the condensation of water or volatile components. Subsequently, the volatile components are oxidized in the catalytic stripper at a temperature of 350°C. After passing the second dilutor, the particles are detected and counted in the isopropanol CPC with 23nm 50% cut-point (model 3007, TSI inc.). The sampling line between the first dilution and the catalytic stripper was heated at 47°C. The unit was calibrated by the manufacturer

- Gas-PEMS: Semtech LDV, Sensors.
  The LDV system by Sensors is a Gas-PEMS compliant with the RDE-LDV requirements, it houses the analytical devices for the gaseous measurements of CO, CO_2, NO, and NO_2, the Sample Control System (SCS) and the Exhaust Flow Meter (EFM). The Semtech LDV employs Sensor's vehicle communications interface (VCI) to query the Engine Control Module (ECM) to log data such as vehicle speed, engine speed and coolant temperature. In addition, the LDV logged the GPS coordinates, altitude as well as ambient temperature, pressure and relative humidity. The EFM installed on the Golden Vehicle has a diameter of 1.5 inch.

- PMP Tailpipe: Advanced APC 489, AVL.
  The Advanced APC 489 is a particle counter compliant with the Particulate Measurement Programme requirements. It consists of a rotating disk diluter heated at 150°C, an evaporation tube at 350°C and a secondary dilution stage followed by a TSI 3790 CPC with 50% efficiency at 23 nm. A Particle Concentration Reduction Factor (PCRF) of 2000 was used during the this ILCE.

For the whole duration of the ILCE all PEMS remained installed on the vehicle. The Gas-PEMS was installed on the tow hitch while the PN-PEMS were inside the vehicle Figure 1. The PMP Tailpipe was installed at vehicle's exhaust only during the dynamometer tests. A scheme of the setup for the tests performed on the chassis dynamometer and for on-road tests is shown in Figure 2.

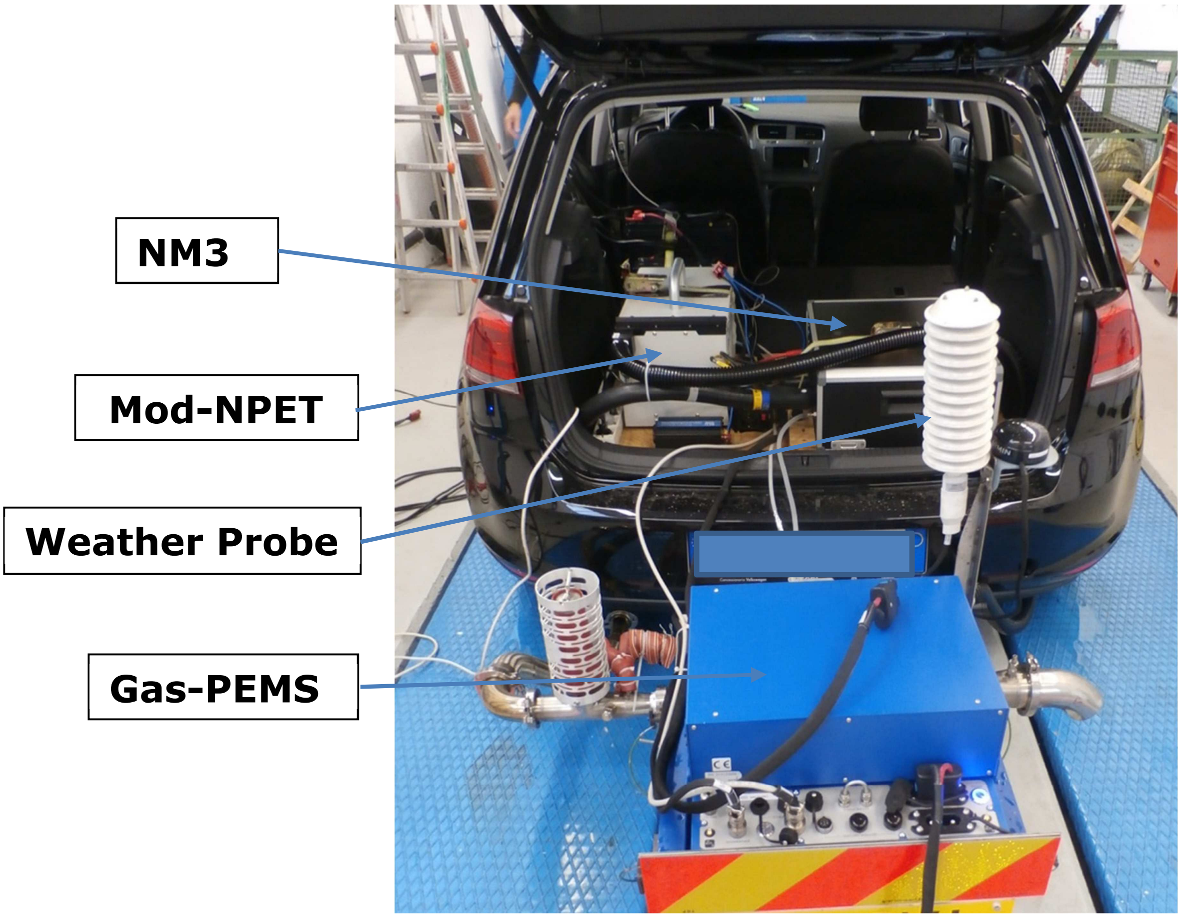


Figure 1 Setup of the PEMS on the Golden Vehicle

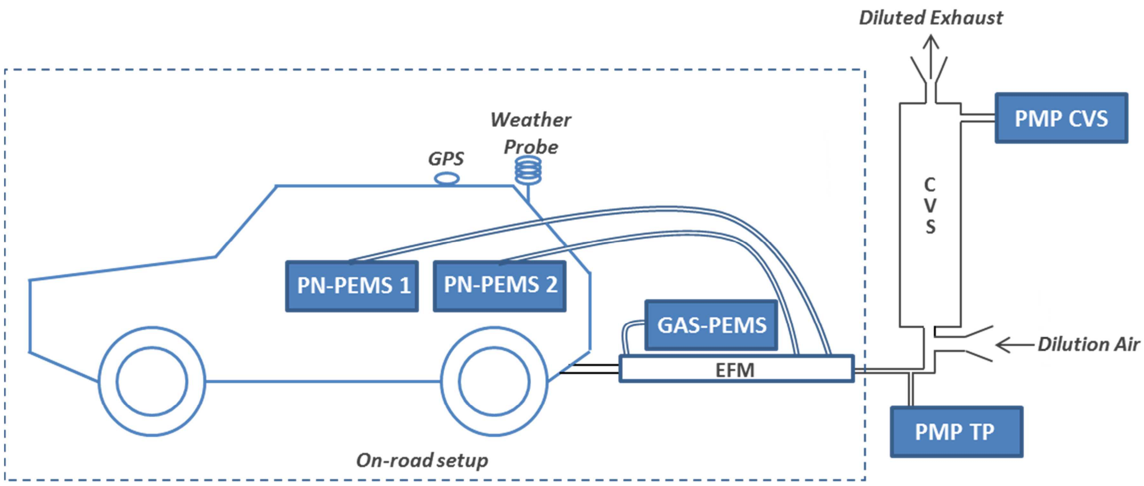


Figure 2 Schematic setup of tests performed on the chassis dynamometer. The dashed rectangle shows the setup for on-road tests.

2.3 Laboratories

Seven laboratories participated to the PN-PEMS ILCE. The list of laboratories, the period of tests and the specification of the PMP systems used at CVS are reported in Table 2.

Table 2 List of participating laboratories, period of tests and settings of PMP system and CVS

Laboratory	Period of tests	PMP system Manufacturer and Model	PMP PCRF (-)	CVS flow (m3/min)	Distance tailpipe-CVS (m)
Lab 1 JRC (Italy)	9-16 September 2015	AVL, APC 489	1000	8.8	7.0
Lab 2 Volkswagen (Germany)	22-29 September 2015	MAHA, SPC 8000	550	6.2	3
Lab 3 BOSMAL Automotive R&D Institute (Poland)	6-13 October 2015	Horiba, MEXA2000-SPCS	750	8.6	5.6
Lab 4 Honda Europe (Germany)	20-23 October 2015	Horiba, MEXA2000-SPCS	1500	8.1	7.0
Lab 5 Audi (Germany)	3-6 November 2015	AVL, APC 489	2000	8.8	5.5
Lab 6 Volvo (Sweden)	17-23 November 2015	Horiba, MEXA2000-SPCS	300	8.0	2
Lab 7 TÜV Nord (Germany)	1-8 December 2015	MAHA, SPC 8000	620	8.2	2.5

JRC concluded the ILCE with the repetition of the tests between 15th and 21st December 2015. Additional dynamometer tests at extreme ambient temperatures (-7°C and 30°C) were performed between 7th and 12th January 2016.

All laboratories corrected the CVS flow for the flow extracted at tailpipe by the PN-PEMS, the Gas-PEMS and the PMP TP for a total flow of 13 l/min as communicated in the laboratory guide distributed to the participating laboratories (Annex 1).

2.4 Test Procedure

Each laboratory was requested to perform a minimum of two NEDC cold tests and five WLTC warm tests on the chassis dynamometer and at least three RDE tests on road (due to a failure of the EFM, only four WLTC warm tests were analysed at Honda Europe). In the laboratory guide distributed to the laboratories the following test matrix was proposed (Table 3).

Table 3 Test matrix

<table>
<tr><th>Day 0</th><th>Day 1</th><th>Day 2</th><th>Day 3</th><th>Day 4</th><th>Day 5</th></tr>
<tr><td rowspan="5">Preparation of the GV in the dynamometer test cell
+
WLTC
+
Coast Down
+
WLTC warm (optional)
+
NEDC preconditioning (NEDC+EUDC)</td><td>NEDC cold</td><td>NEDC cold</td><td rowspan="2">Road test 1</td><td rowspan="2">Road test 3</td><td rowspan="5">Preparation of the GV for shipping</td></tr>
<tr><td>WLTC warm</td><td>WLTC warm</td></tr>
<tr><td>WLTC warm</td><td>WLTC warm</td><td rowspan="3">Road test 2</td><td rowspan="3">Road test 4

(optional)</td></tr>
<tr><td>WLTC warm</td><td>WLTC warm (optional)</td></tr>
<tr><td>NEDC preconditioning (NEDC+EUDC)</td><td>WLTC warm (optional)</td></tr>
</table>

After the preparation of the vehicle in the test cell all the PEMS were switched on, warmed up and stabilized according to the specifications of the PEMS manufacturer until pressures, temperatures and flows had reached their operating set points. Zero and span calibration of the gas analysers were performed using calibration gases chosen to match the range of the expected pollutant concentrations.

The chassis dynamometer controller was then adjusted to simulate the inertia of the Golden Vehicle. The inertia was set to 2750 lbs (1247 kg) with the following road load coefficients: F1 = 74 N, F2 = 0.48 N/(km/h), F3 = 0.0304 $N/(km/h)^2$ (as provided by the vehicle manufacturer). A WLTC was performed before the launch of the coast down procedure. The gear shift strategy for the WLTP was provided by the vehicle manufacturer.

Each laboratory ordered two tanks of 50 liters of reference fuel from the same batch. The compliance certificate of the reference fuel is reported in Annex 2.

Prior to the start of each test, both on dyno and on road, the Start/Stop system and the Electronic Stability Control (ESP) were deactivated.

2.5 Reported emissions and data analysis

In the following sections gaseous (CO, CO_2, NO_x) and PN emission results will be reported for both dynamometer bench analysers and PEMS. The dynamometer bench results derive from the analysis performed by each participating laboratory while the PEMS results derive from data analysis combining Gas-PEMS (containing the exhaust mass flow rate measurement) and PN-PEMS data.

The PN emissions have been calculated according to the current draft of the amendment of the Commission regulation (EU) 2016/427.

The following equation was applied:

$$PN, i = c_{PN,i} q_{mew,i} / \rho_e$$

where:

PN,i is the particle number flux [particles/s]

$c_{PN,i}$ is the measured particle number concentration [particles/m^3] normalized at 0°C

$q_{mew,i}$ is the measured exhaust mass flow rate [kg/s]

ρ_e is the density of the exhaust gas [kg/m^3] at 0°C

The alignment of the particle number concentration and the exhaust mass flow rate signals was performed by applying an algorithm that maximized the correlation coefficients between the two signals both provided at 1 Hz sample frequency.

All dynamometer test results are calculated as integrated second by second data while the on road (RDE) tests are reported both as integrated second by second data and as moving average windows results using the EMROAD data post-processing tool in compliance with Commission regulation (EU) 2016/427.

2.5.1 Exhaust flow measurement

As reported in section 2.5 the PEMS results are obtained from combining the second by second PN concentration and the second by second exhaust mass flow rate provided by the EFM. The comparison of PN results from PN-PEMS and CVS includes the error deriving from the exhaust mass flow measurement.

Figure 3 to Figure 6 show the comparison of the real time signals of the exhaust mass flow measurement provided by the EFM and the exhaust mass flow provided by the CVS for a WLTC and a NEDC cycle. Large discrepancies between the CVS and the EFM signals are visible especially at idle, where indeed the PN emissions are low, thus only marginally influencing the PN emissions integrated over a whole test.

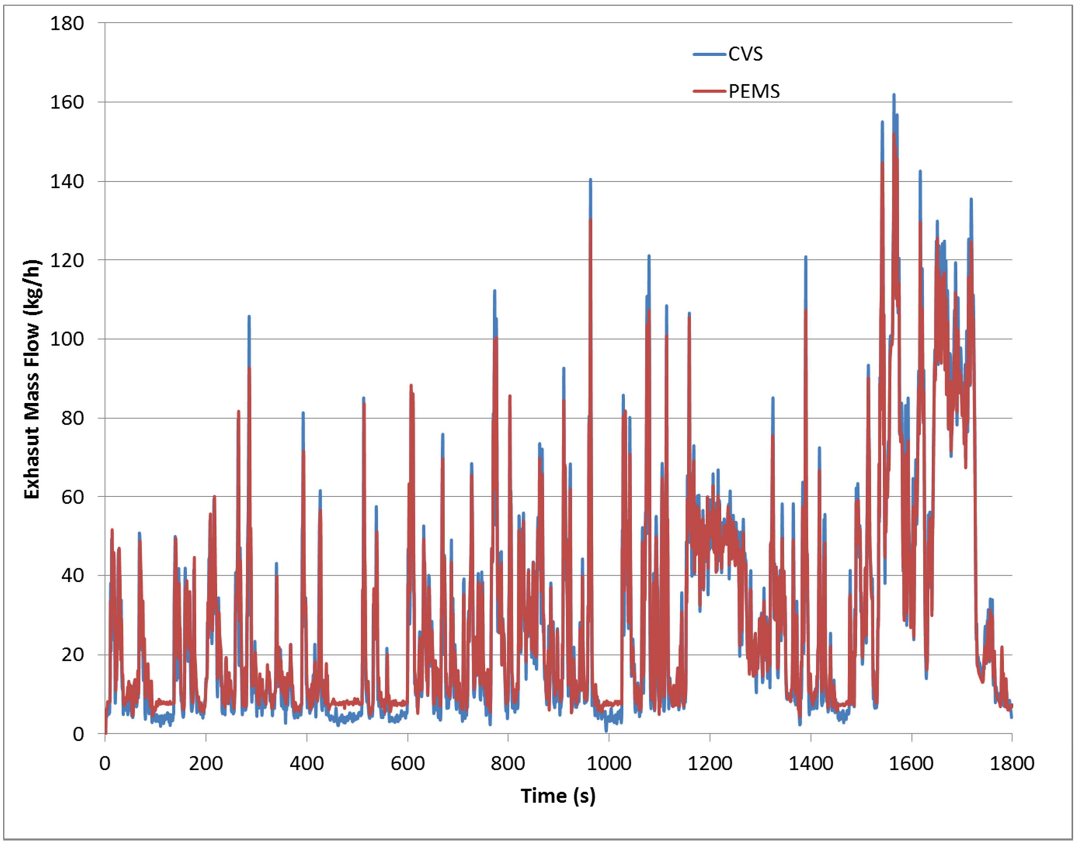


Figure 3 Real time signals of the exhaust mass flow measurement provided by the EFM and the exhaust mass flow provided by the CVS at laboratory 1 for a WLTC warm cycle

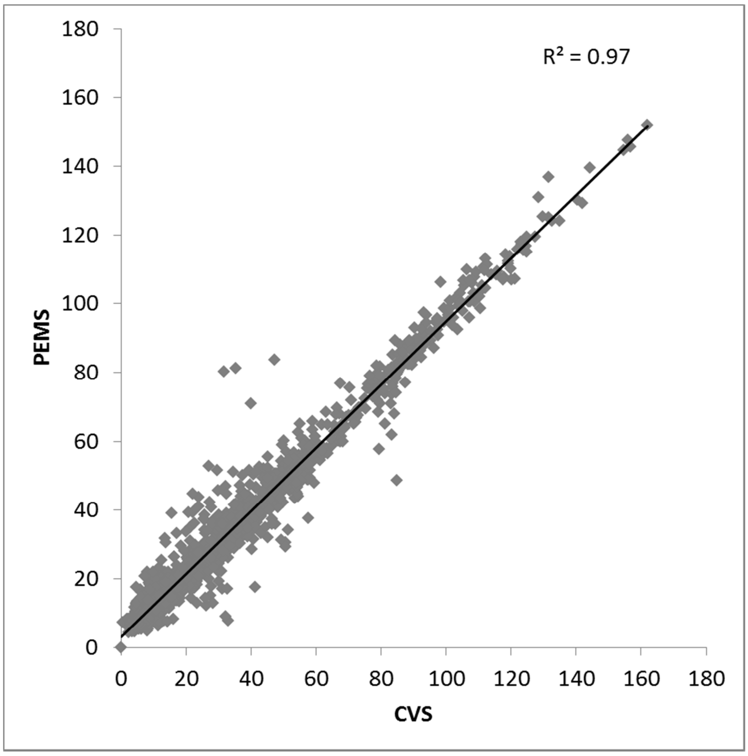


Figure 4 Scatter plot of the data of Figure 3

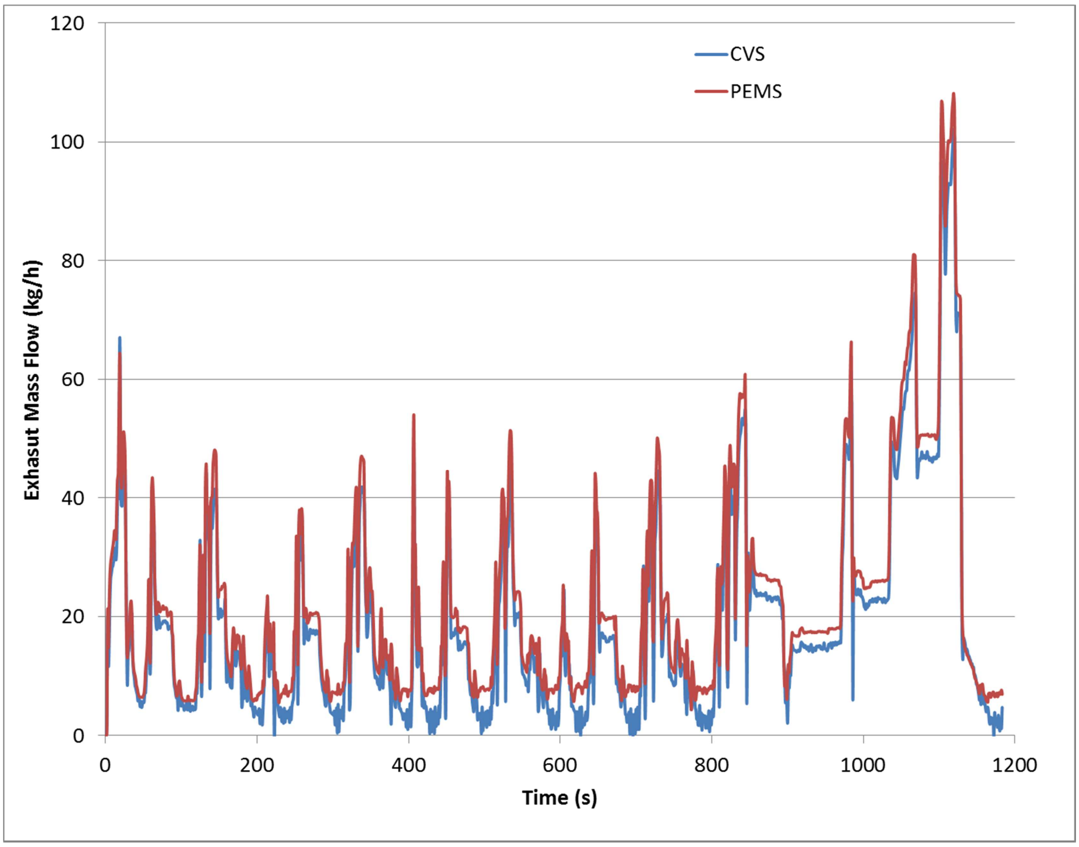


Figure 5 Real time signals of the exhaust mass flow measurement provided by the EFM and the exhaust mass flow provided by the CVS at laboratory 6 for a NEDC cold cycle

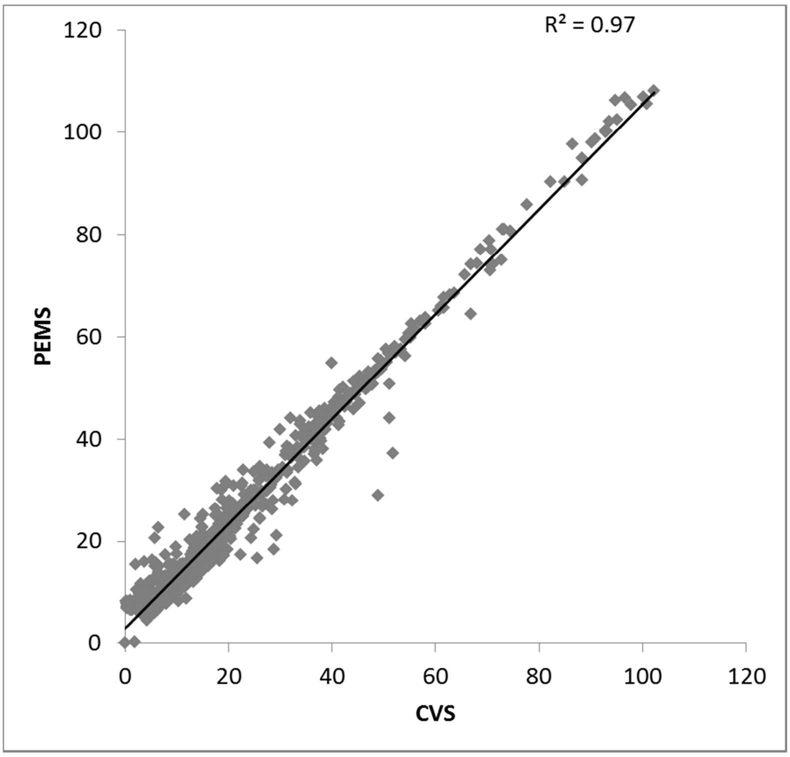


Figure 6 Scatter plot of the data of Figure 5

In order to isolate the error deriving from the exhaust mass flow measurement we have compared the deviations of the mass flow rate measured by PEMS from the mass flow rate measured by CVS for the subset made by the 23 tests performed at laboratory 1 and 6. Results are shown in the first column of Table 4: the PEMS mass flow rate is on average 8.4% ± 3.9% higher than the mass flow rate measured by CVS.

In addition we have calculated the CO_2 emissions as well as the PN emissions of PMP TP, NM3 and Mod-NPET using both the exhaust mass flow of PEMS and CVS. The deviations are reported in Table 4: The CO_2 emissions results 7.9% ± 3.7% higher when using the exhaust flow rate measured by the PEMS, while all the PN devices (PMP TP, NM3 and Mod-NPET) showed deviations in the order of 2%. The reason for the small effect on the PN devices is due to the fact that most of the deviation between exhaust mass flow PEMS and CVS is occurring at idle, where particle emissions are low.

Table 4 Deviations of mass flow rate measured by PEMS and by CVS

	Deviation Mass Flow PEMS / Mass Flow CVS	**Deviation CO_2 Exhaust Flow PEMS / PMP TP Exhaust Flow CVS**	**Deviation PMP TP Exhaust Flow PEMS / PMP TP Exhaust Flow CVS**	**Deviation NM3 Exhaust Flow PEMS / NM3 Exhaust Flow CVS**	**Deviation Mod-NPET Exhaust Flow PEMS / Mod-NPET Exhaust Flow CVS**
Ave	8.4%	7.9%	2.2%	1.9%	2.2%
StDev	3.9%	3.7%	2.1%	2.0%	2.3%
Min	3.6%	3.2%	-0.2%	0.0%	-0.7%
Max	18.4%	17.7%	7.0%	5.8%	7.4%

3 Results and Discussion

3.1 Laboratory tests

The following paragraphs report the dynamometer tests results divided as engine warm start WLTC and cold start NEDC tests.

3.1.1 WLTC tests

Each laboratory performed at least five WLTC warm tests (only four WLTC tests were analysed for Lab 4 due to a failure of the EFM). All tests were performed at 23°C and 50% relative humidity.

The WLTC tests have been performed after the preconditioning of the after-treatment system, the temperature of the engine coolant was monitored until reached 95°C (this was also the time when the tailpipe NO_x concentration dropped by more than 90% compared to the cold start values). Figure 7 shows the evolution of the engine coolant temperature during a cold NEDC cycle indicating a plateau temperature of 95°C used as a starting temperature for the WLTC warm tests. The coolant temperature of 95°C was reached by driving at 100 km/h before the beginning of the warm WLTC test.

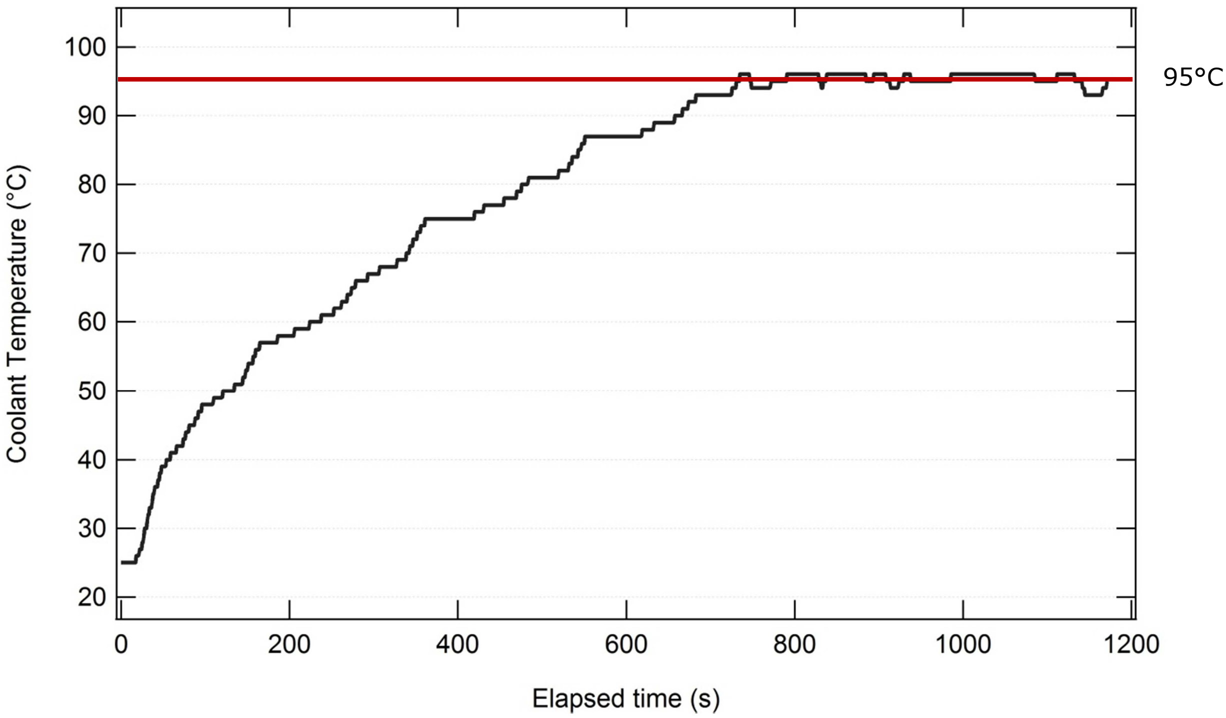


Figure 7 Evolution of the coolant temperature during a cold NEDC test.

3.1.1.1 Gaseous emissions

The stability of the gaseous emissions of the Golden Vehicle is represented by the bag and PEMS CO_2 distance specific emissions reported in Figure 8 and the bag and PEMS NO_x distance specific emissions reported in Figure 9. The average bag CO_2 emission is 112.0 g/km ± 2.8 g/km (min 107.2 g/km, max 123.2 g/km). For comparison Figure 8 also shows the CO_2 values measured by the Gas-PEMS. The average CO_2 measured by the Gas-PEMS is 120.2 g/km ± 3.1 g/km (min 113.9 g/km, max 124.5 g/km).

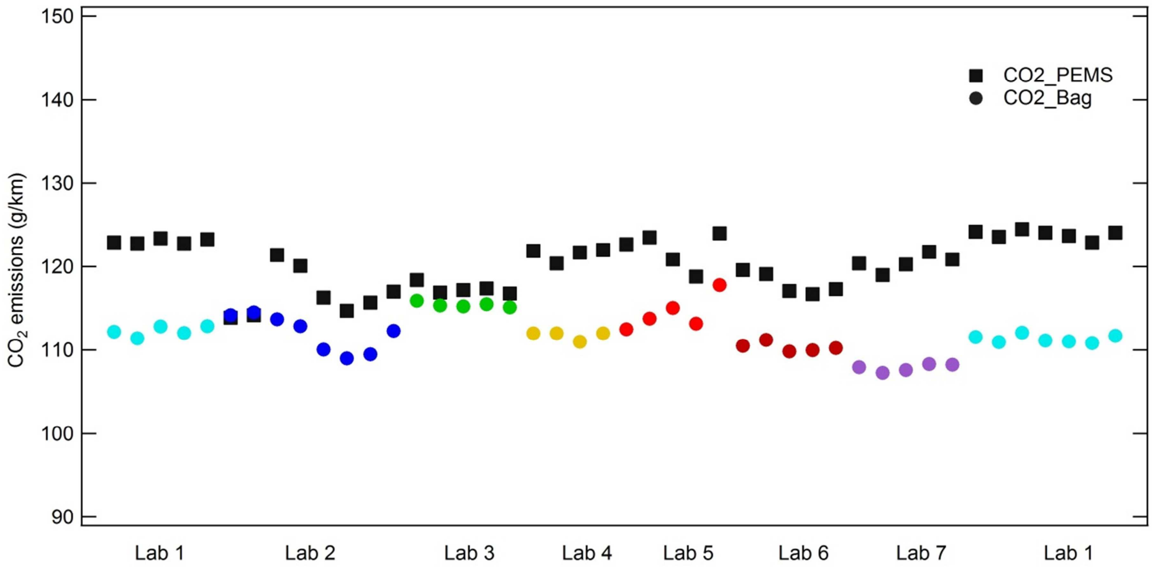


Figure 8 Distance specific bag CO_2 emissions over the 44 WLTC tests in the 7 laboratories (color coded circles) and CO_2 emissions measured with the Gas-PEMS (black squares).

The bag CO_2 distance specific emissions measured over the WLTC tests show a good reproducibility among the laboratories with a relative standard deviation (RSD) of 2.5% (PEMS CO_2 RSD = 2.6%). The average CO_2 PEMS to bag deviation is 7.5% ± 3.6% (min -0.3%, max 12.4%). After the second test at laboratory 2 the high pressure fuel pump was replaced due to malfunctioning, which affected CO_2 and NO_x emissions. Excluding the first two tests at laboratory 2 the average bag CO_2 emission is 112 g/km ± 2.4 g/km (min 107 g/km, max 118 g/km) with a relative standard deviation of 2.1%, while PEMS CO_2 emissions show an average value of 120 g/km ± 2.8 g/km (min 115 g/km, max 126 g/km) with a relative standard deviation of 2.4%.

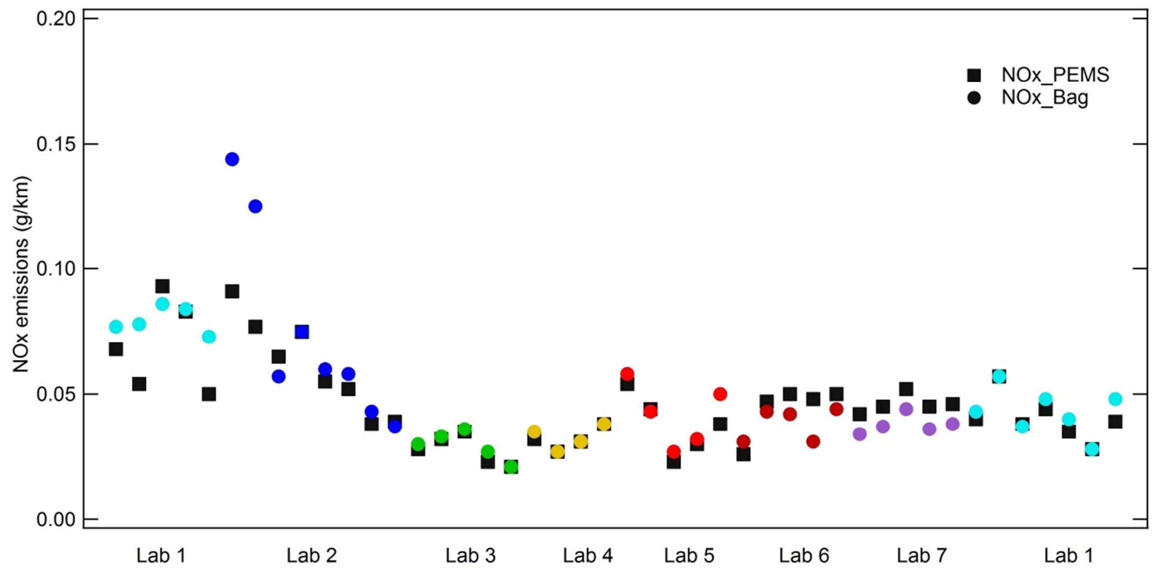


Figure 9 Distance specific bag NO_x emissions over the 44 WLTC tests in the 7 laboratories (color coded circles) and NO_x emissions measured with the Gas-PEMS (black squares).

The average measured bag NO_x emission is 49 mg/km ± 25 mg/km (min 21 mg/km, max 144 mg/km) with a relative standard deviation of 51%, while PEMS NO_x emissions show an average value of 46 mg/km ± 18 mg/km (min 21 mg/km, max 93 mg/km) with a relative standard deviation of 38%. The average NO_x PEMS to bag deviation is 2.0% ± 17.5% (min -38.7%, max 53.3%).

Excluding the first two tests at laboratory 2 the average bag NO_x emission is 45 mg/km ± 17 mg/km (min 21 mg/km, max 86 mg/km) with a relative standard deviation of 37%, while PEMS NO_x emissions show an average value of 44 mg/km ± 16 mg/km (min 21 mg/km, max 93 mg/km) with a relative standard deviation of 36%. The average NO_x PEMS to bag deviation is 1.5% ± 15.3% (min -24.7%, max 53.3%). For all these tests the PEMS NO_x measurements are compliant with RDE regulation (deviations smaller than 15 mg/km).

3.1.1.2 PN emissions

The stability of the PN emissions is reported in Figure 10 showing the PN measured by the PMP Tailpipe system (PMP TP) and the different PMP systems of the laboratories measuring at the Constant Volume Sampler (PMPs CVS).

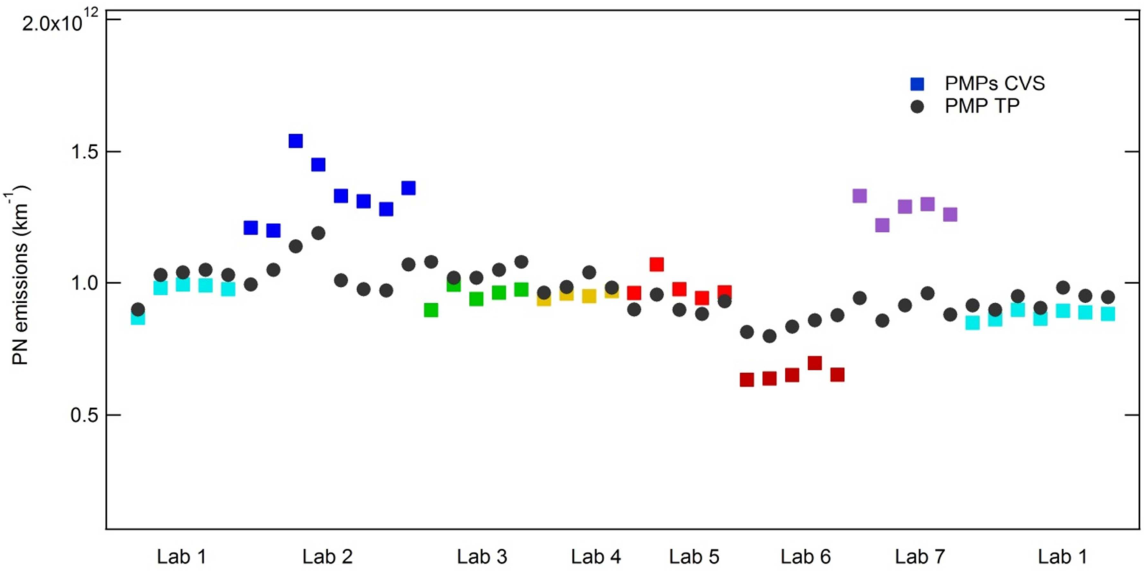


Figure 10 PN distance specific emissions measured with the PMP Tailpipe system (PMP TP, black circles) and the PN emissions measured with the PMP systems of the laboratories measuring at the Constant Volume Sampler (PMPs CVS, color coded squares).

The average distance specific PN emissions measured with the PMP Tailpipe are 9.7e11 km^{-1} ± 0.8e11 km^{-1} (min 8.0e11 km^{-1}, max 1.19e12 km^{-1}) with a relative standard deviation of 8.6%. While the average PN emissions measured with the PMPs at CVS are 10.2e11 km^{-1} ± 2.2e11 km^{-1} (min 6.3e11 km^{-1}, max 1.54e12 km^{-1}) with a relative standard deviation of 21.8%. Two PMP CVS measurements at laboratory 2 were affected by single artefact events in the PN concentration signal (p/s) during engine idle showing concentrations >1e10 p/s. The section of the PN signals affected by the artefact events (about 40 second long) were replaced by the average PN concentration measured at idle at laboratory 2 (3e7 p/s) (results shown are corrected for the artefacts).

Figure 11 shows the deviations of the PMP TP system from the PMP CVS systems for WLTC tests. Black marks shows average and standard deviation of each laboratory. Grey lines show average and standard deviation of all laboratories. Deviations are calculated starting from the distance specific results shown in Figure 10 as (PMP_TP/PMP_CVS-

1)*100. The average deviation (over all the laboratories) of the PMP TP from the PMP CVS is 1.6% with a sigma of 17.5%. In Figure 12 we also show the deviations of the PMP CVS systems from the PMP TP systems for WLTC tests. The average deviation (over all the laboratories) of the PMP CVS from the PMP TP is 5.0% with a sigma of 19.9%.

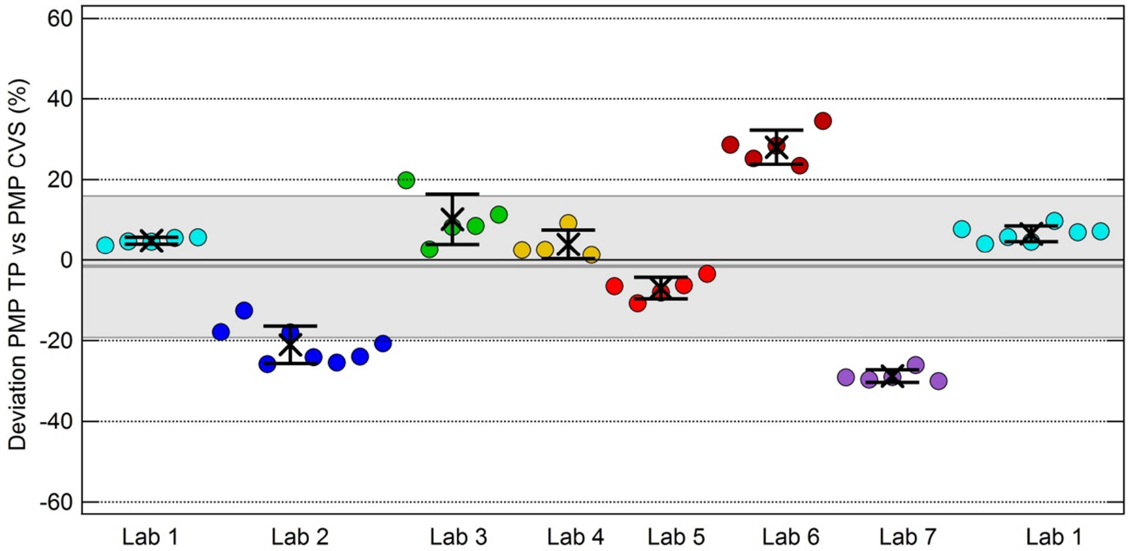


Figure 11 Deviations of the PMP TP system from the PMP CVS systems for WLTC tests. Black marks shows average and standard deviation of each laboratory. Grey lines shows average and standard deviation of all laboratories.

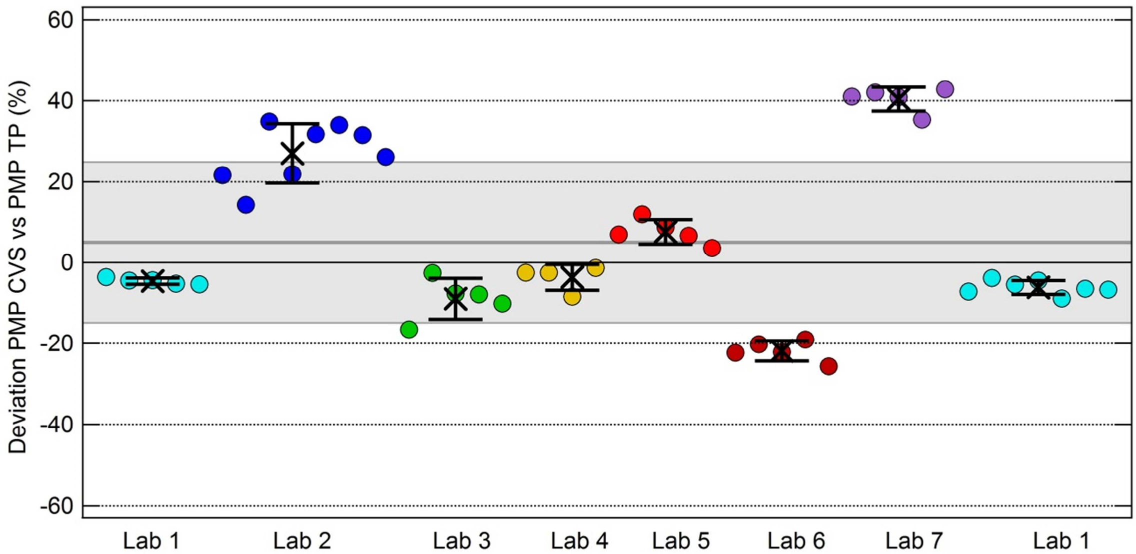


Figure 12 Deviations of the PMP CVS systems from the PMP TP system for WLTC tests. Black marks shows average and standard deviation of each laboratory. Grey lines shows average and standard deviation of all laboratories.

It is important to note that even if the measurement at the CVS is the only PN measurement procedure currently compliant with the regulation, the PN measured with the PMP at tailpipe (always the same reference PMP system unit) better shows the stability of the PN emissions of the Golden Vehicle compared to the measurement of PN at CVS at each laboratory that is performed with a different PMP system in each laboratory.

Figure 13 and Figure 14 show the real time PN signals of PMP CVS, PMP Tailpipe, NM3 and Mod-NPET over a WLTC at laboratory 1. The PN-PEMS systems match the PMP TP over 4 orders of magnitude of concentrations as highlighted in the scatter plots of Figure 15 with an R^2 of 0.99 and 0.95 for NM3 and Mod-NPET respectively.

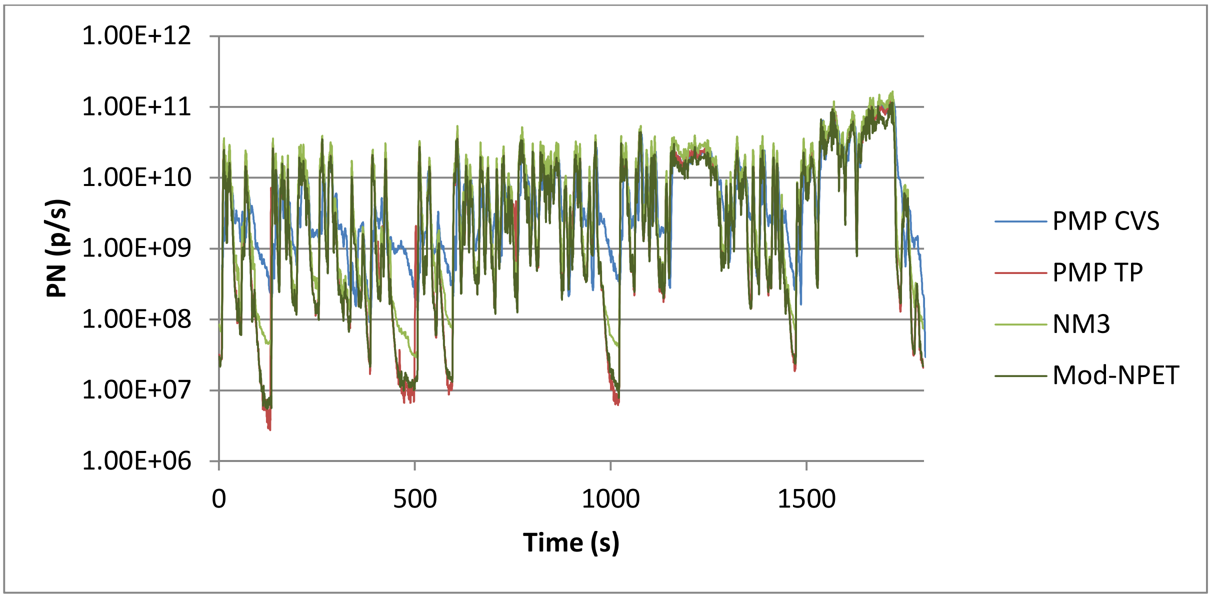


Figure 13 Example of real time PN signals of PMP CVS, PMP Tailpipe, NM3 and Mod-NPET over a WLTC at laboratory 1

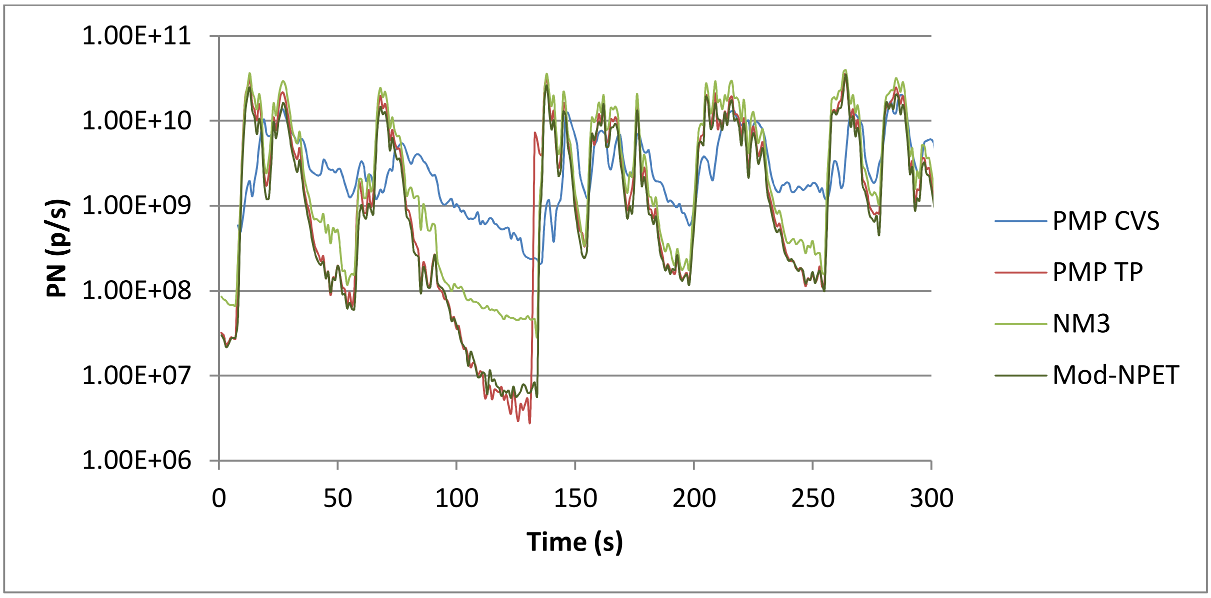


Figure 14 Detail of the first 300 seconds of the test reported in Figure 13

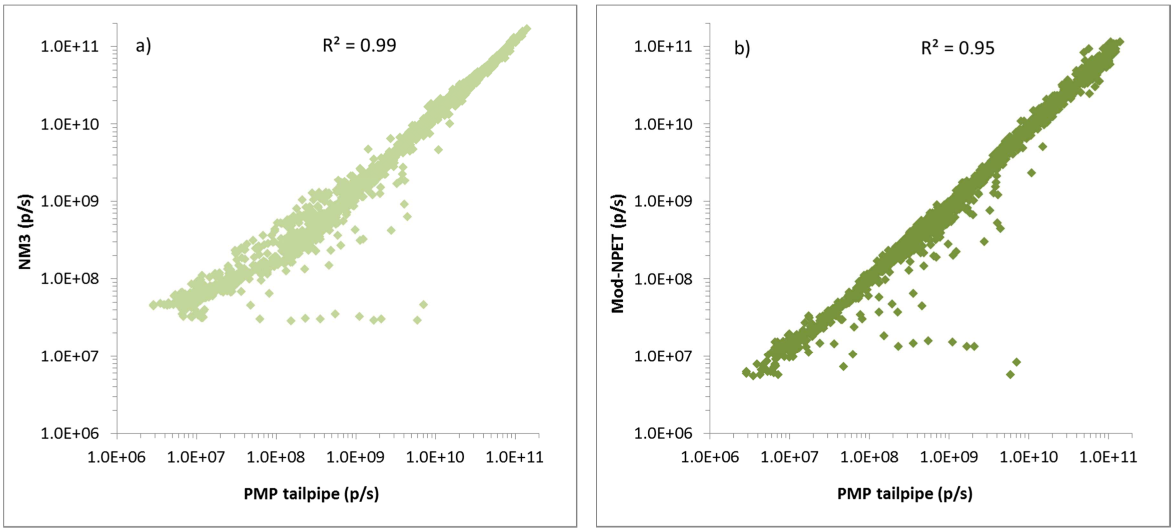


Figure 15 Scatter plots of NM3 vs PMP Tailpipe (a) and of Mod-NPET vs PMP Tailpipe (b) at laboratory 1 during a WLTC test

For comparison Figure 16 and Figure 17 show the real time PN signals of PMP CVS, PMP Tailpipe, NM3 and Mod-NPET over a WLTC at laboratory 6. Also for this laboratory both PN-PEMS systems match the PMP TP over 4 orders of magnitude of concentrations as highlighted in the scatter plots of Figure 18 with an R^2 of 0.99 and 0.97 for NM3 and Mod-PET respectively. The comparison of the first 300 seconds of the PN time series at laboratory 1 and laboratory 6 (Figure 14 and Figure 17) highlights the effect of the length of the transfer tube going from the tailpipe to the CVS on PN concentration, resulting in the smoothing of the PMP CVS signal compared to the other PN systems measuring at tailpipe: The use of a shorter transfer line (2 m at Lab 6 vs 7 m at Lab 1) reduces the smoothing effect of the PMP CVS signal (blue lines).

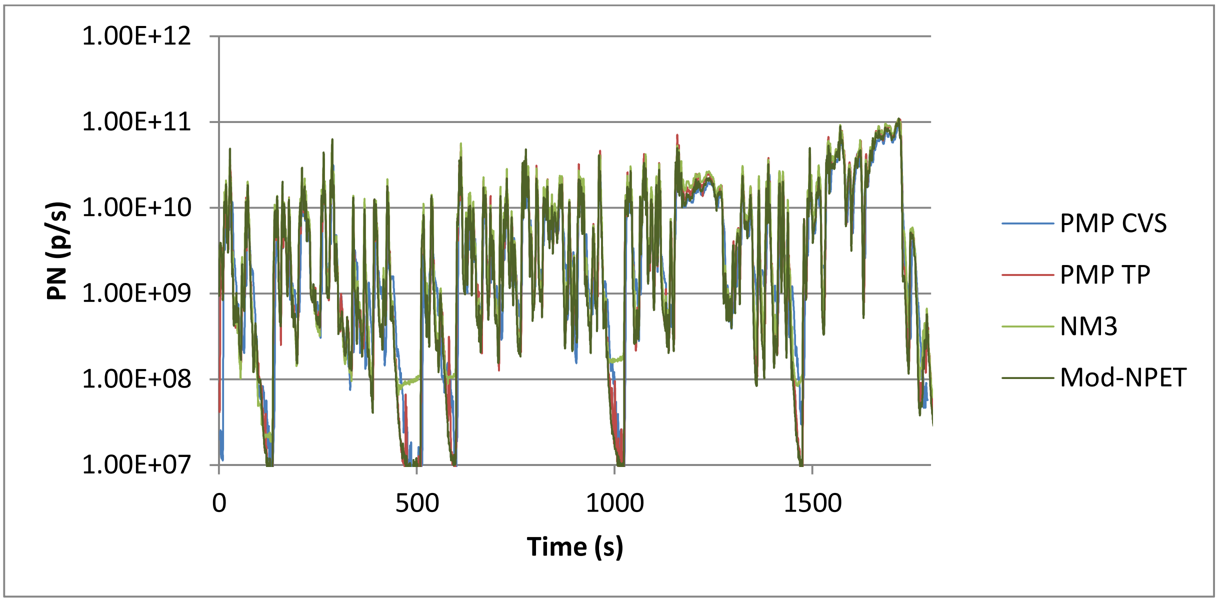


Figure 16 Example of real time PN signals of PMP CVS, PMP Tailpipe, NM3 and Mod-NPET over a WLTC at laboratory 6

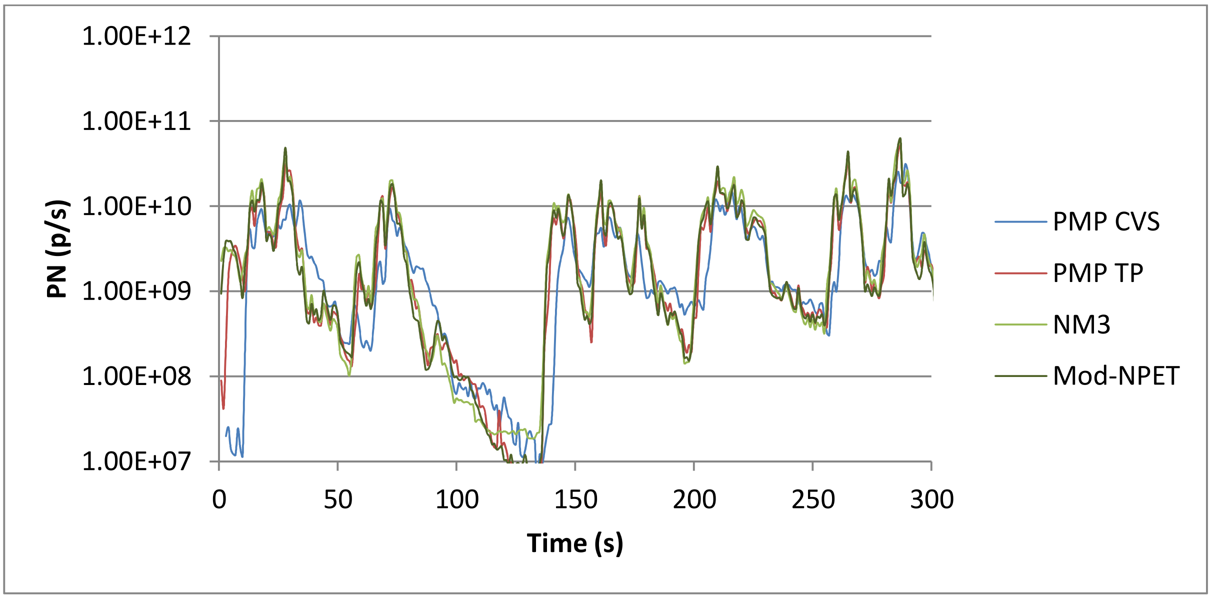


Figure 17 Detail of the first 300 seconds of the test reported in Figure 16

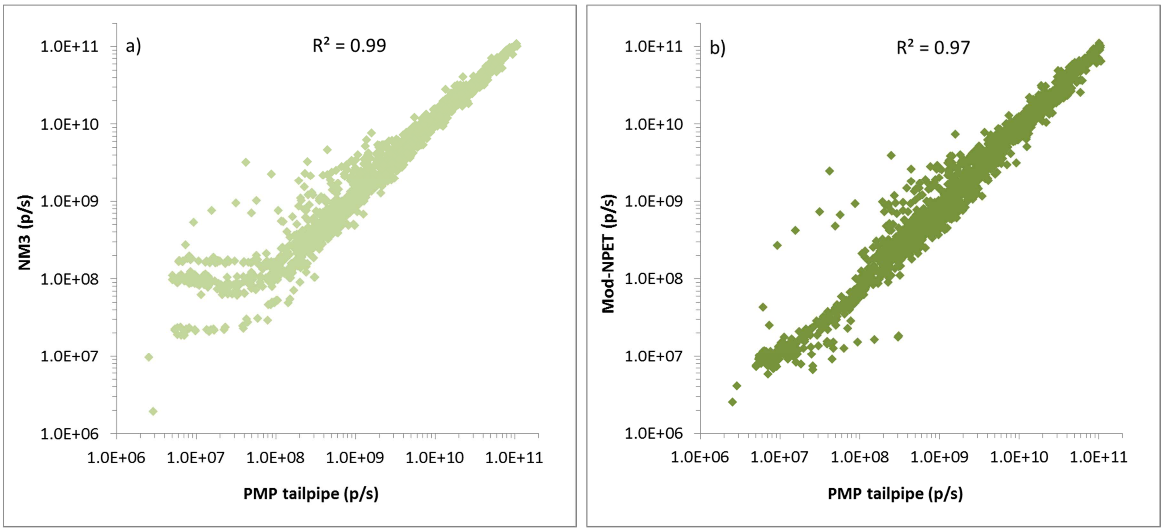


Figure 18 Scatter plots of NM3 vs PMP Tailpipe (a) and of Mod-NPET vs PMP Tailpipe (b) at laboratory 6 during a WLTC test

Figure 19 shows the average PN distance specific emissions measured with the two PN-PEMS and the PMP systems. The average distance specific PN emissions measured with the NM3 are 10.8e11 km^{-1} ± 1.77e11 km^{-1} (min 7.74e11 km^{-1}, max 1.42e12 km^{-1}) with a relative standard deviation of 16.4%. While the average PN emissions measured with the Mod-NPET are 9.10e11 km^{-1} ± 0.80e11 km^{-1} (min 7.25e11 km^{-1}, max 1.03e12 km^{-1}) with a relative standard deviation of 8.8%.

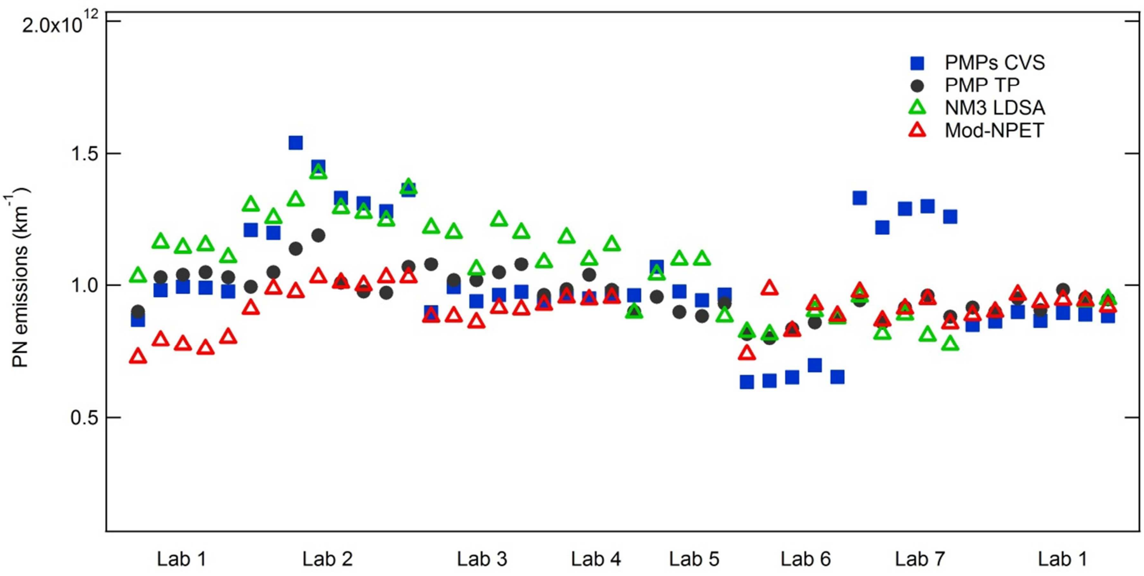


Figure 19 PN distance specific emissions measured with the PN-PEMSs: NM3 (green open triangles) and Mod-NPET (red open triangles). For comparison are reported also the measurement of PMP Tailpipe system (black circles) and the PN emissions measured by the PMPs at CVS (blue squares).

Figure 19 also shows that both NM3 and Mod-NPET showed a high percentage of error free tests: NM3 failed one test at laboratory 6 and 5 tests at laboratory 1, while NPET failed 5 tests at laboratory 5

The reasons for the failure of the systems are:

- NM3: Water in sensor (due to low dilution) fixed upon indication of Testo to select auto dilution mode (5 tests). Unintentional misuse of the SD card (1 test).
- Mod-NPET: Broken water trap and main board connectors due to accidental maloperation, disconnected tubing and heater temperature out of range (5 tests).

Figure 20 and Figure 21 show the deviations of the NM3 system from the PMP Tailpipe and the PMP CVS systems respectively for the WLTC tests. Deviations are calculated starting from the distance specific results shown in Figure 19 as (NM3 / PMP_TP-1)*100. The average deviation (over all the laboratories) of the NM3 from the PMP Tailpipe is 10.4% (accuracy) with a sigma of 11.9% (precision). The average deviation from the PMP CVS systems is 6.3% with a sigma of 20.0%.

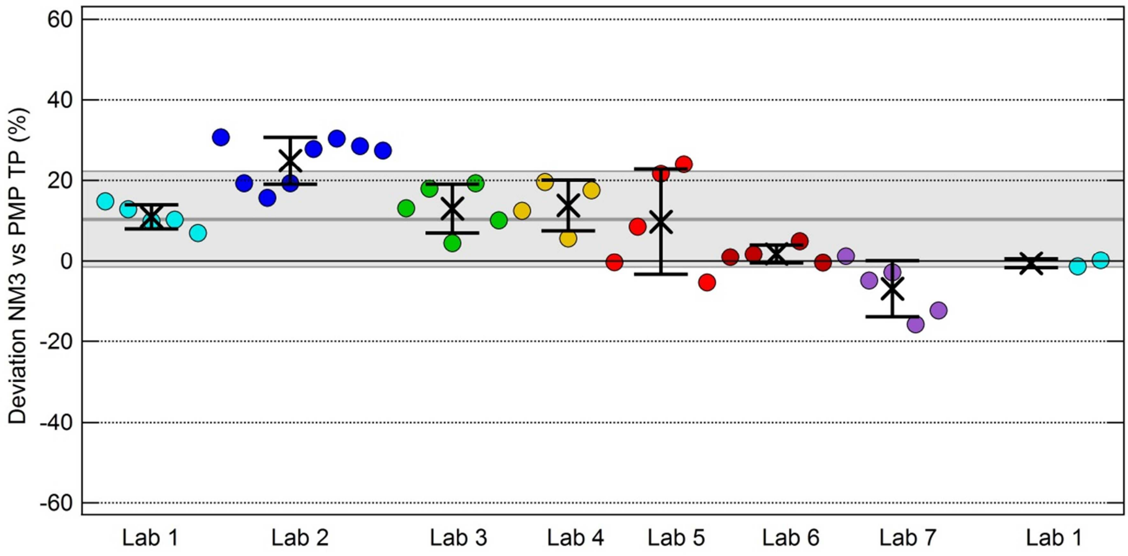


Figure 20 Deviations of the NM3 results from the PMP Tailpipe system. Black marks shows average and standard deviation of each laboratory. Grey lines shows average and standard deviation of all laboratories.

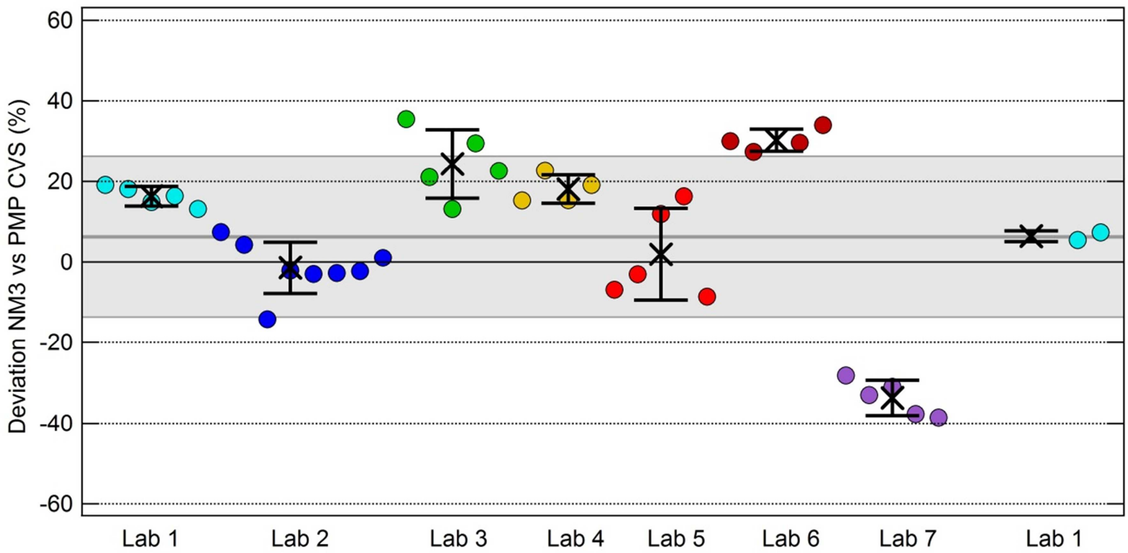


Figure 21 Deviations of the NM3 results from the PMP CVS systems. Black marks shows average and standard deviation of each laboratory. Grey lines shows average and standard deviation of all laboratories.

Figure 22 and Figure 23 show the deviations of the Mod-NPET system from the PMP Tailpipe and the PMP CVS systems respectively for the WLTC tests. The average deviation of the Mod-NPET from the PMP Tailpipe is -8.0% with a sigma of 9.5%. The average deviation from the PMP CVS systems is -12.4% with a sigma of 18.2%.

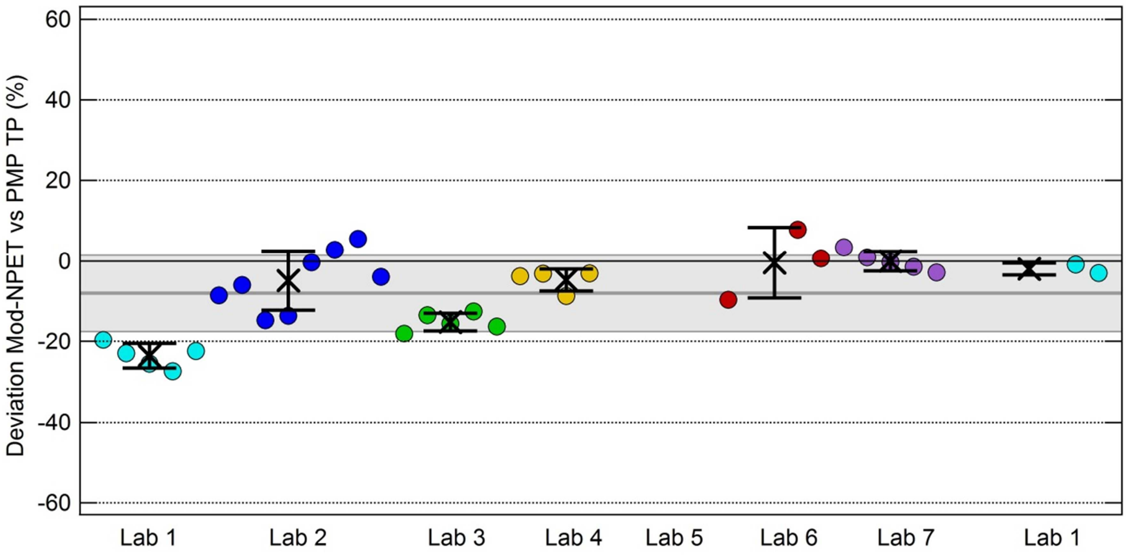


Figure 22 Deviations of the Mod-NPET results from the PMP Tailpipe system. Black marks shows average and standard deviation of each laboratory. Grey lines shows average and standard deviation of all laboratories.

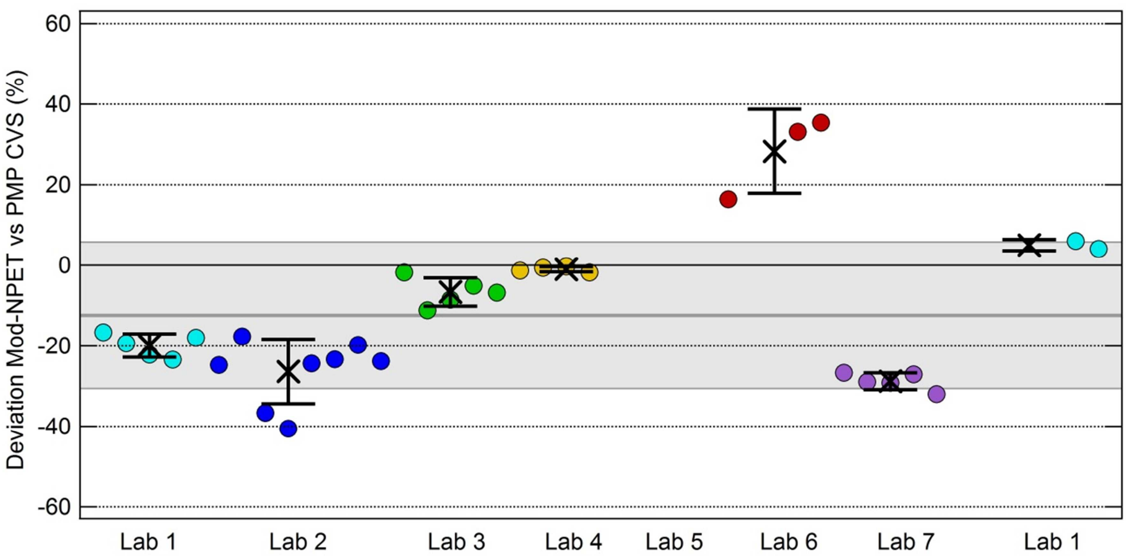


Figure 23 Deviations of the Mod-NPET results from the PMP CVS systems. Black marks shows average and standard deviation of each laboratory. Grey lines shows average and standard deviation of all laboratories.

For both PN-PEMS system the higher standard deviations (meaning lower precision) observed when comparing the results with the PMP CVS systems than when comparing the results with the PMP Tailpipe is reflecting the fact that the PMP system used at tailpipe was the same reference system for all laboratories, while seven different PMP systems (each belonging to the different laboratory) were used at CVS.

The average, standard deviation, minimum and maximum of the deviations of each PN systems to each other at all laboratories are shown in Table 5.

Table 5 Average, standard deviation, minimum and maximum of the deviations between the PN instruments at all laboratories

		Lab 1	Lab 2	Lab 3	Lab 4	Lab 5	Lab 6	Lab 7	Lab 1	All labs
PMP CVS vs PMP TP	Ave	-4.6	27.0	-9.0	-3.7	7.6	-21.9	40.4	-6.1	**5.0**
	StDev	0.7	7.3	5.1	3.2	3.1	2.5	3.0	1.7	**19.9**
	Min	-5.4	14.3	-16.5	-8.4	3.6	-25.7	35.3	-8.9	**-25.7**
	Max	-3.6	34.8	-2.6	-1.3	12.0	-19.0	42.9	-3.9	**42.9**
PMP TP vs PMP CVS	Ave	4.8	-21.0	10.1	3.9	-7.0	28.1	-28.8	6.6	**1.6**
	StDev	0.8	4.7	6.3	3.6	2.7	4.2	1.5	2.0	**17.5**
	Min	3.7	-25.8	2.7	1.3	-10.7	23.5	-30.0	4.6	**-30.0**
	Max	5.7	-12.5	19.8	9.2	-3.4	34.5	-26.1	9.8	**34.5**
NM3 vs PMP TP	Ave	11.0	24.9	13.0	13.8	9.7	1.8	-6.9	-0.5	**10.4**
	StDev	3.0	5.9	6.0	6.2	13.0	2.3	7.0	1.1	**11.9**
	Min	7.0	15.7	4.5	5.7	-5.3	-0.4	-15.7	-1.3	**-15.7**
	Max	14.8	30.8	19.3	19.6	24.0	5.0	1.3	0.2	**30.8**
NM3 vs PMP CVS	Ave	16.3	-1.4	24.4	18.1	2.0	30.3	-33.7	6.5	**6.3**
	StDev	2.4	6.4	8.5	3.5	11.4	2.8	4.4	1.3	**20.0**
	Min	13.2	-14.2	13.2	15.3	-8.6	27.4	-38.6	5.6	**-38.6**
	Max	19.1	7.5	35.5	22.7	16.3	34.0	-28.2	7.4	**35.5**
Mod-NPET vs PMP TP	Ave	-23.6	-4.8	-15.1	-4.7	\	-0.4	0.0	-1.9	**-8.0**
	StDev	3.0	7.3	2.2	2.7	\	8.8	2.4	1.5	**9.5**
	Min	-27.4	-14.6	-18.0	-8.7	\	-9.6	-2.8	-3.0	**-27.4**
	Max	-19.6	5.5	-12.5	-3.0	\	7.8	3.4	-0.9	**7.8**
Mod-NPET vs PMP CVS	Ave	-19.9	-26.4	-6.6	-1.0	\	28.3	-28.8	5.0	**-12.4**
	StDev	2.9	8.0	3.5	0.7	\	10.4	2.1	1.4	**18.2**
	Min	-23.4	-40.6	-11.1	-1.8	\	16.3	-32.0	4.0	**-40.6**
	Max	-16.6	-17.6	-1.8	-0.3	\	35.4	-26.7	6.0	**35.4**

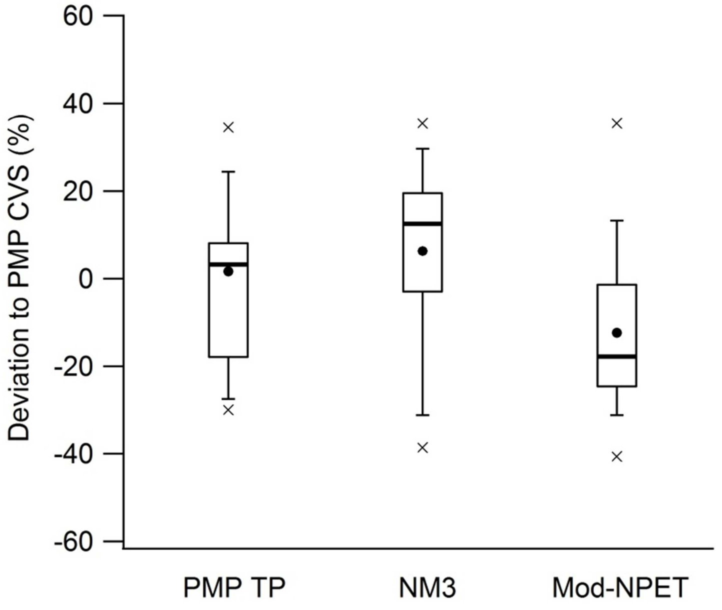


Figure 24 Boxplot of the deviations to the PMP CVS of PMP Tailpipe, NM3 and Mod-NPET for the WLTC tests. Bold line is the median, dot is the mean, boxes are 25th and 75th percentile, whiskers are 10th and 90th percentile and crosses are minimum and maximum.

Figure 24 shows the boxplot of the deviations to the PMP CVS of PMP Tailpipe, NM3 and Mod-NPET, while the PMP Tailpipe shows mean and median closer to the zero compared to the mean and median on the PN-PEMS, the width of the distribution (min, max and 10th, 25th, 75th, 90th percentiles) is similar for both the PMP Tailpipe and the PN-PEMS systems with values ranging between -41% and 35%.

3.1.2 NEDC tests

In addition to the WLTC tests the participating laboratories performed at least two NEDC tests. All tests were started at cold engine conditions following a night period of soaking at 23°C and 50% relative humidity. The day before the tests the vehicle was pre-conditioned running the sequence of NEDC+EUDC tests.

As for the WLTC tests the stability of the gaseous emissions of the Golden Vehicle is represented by the bag and PEMS CO_2 distance specific emissions reported in Figure 25. Excluding the first test of laboratory 2 (only one NEDC test was affected by the fuel pump malfunctioning reported in section 3.1.1.1) the average bag CO_2 emission for the NEDC tests is 124.2 g/km ± 2.9 g/km (min 118.1 g/km, max 130.6 g/km) with a relative standard deviation of 2.3%. The average CO_2 value measured by the Gas-PEMS is 135.9 g/km ± 3.4 g/km (min 129.7 g/km, max 139.7 g/km) with a relative standard deviation of 2.5%. The average CO_2 PEMS to bag deviation is 9.4% ± 2.9% (min 2.9%, max 13.0%).

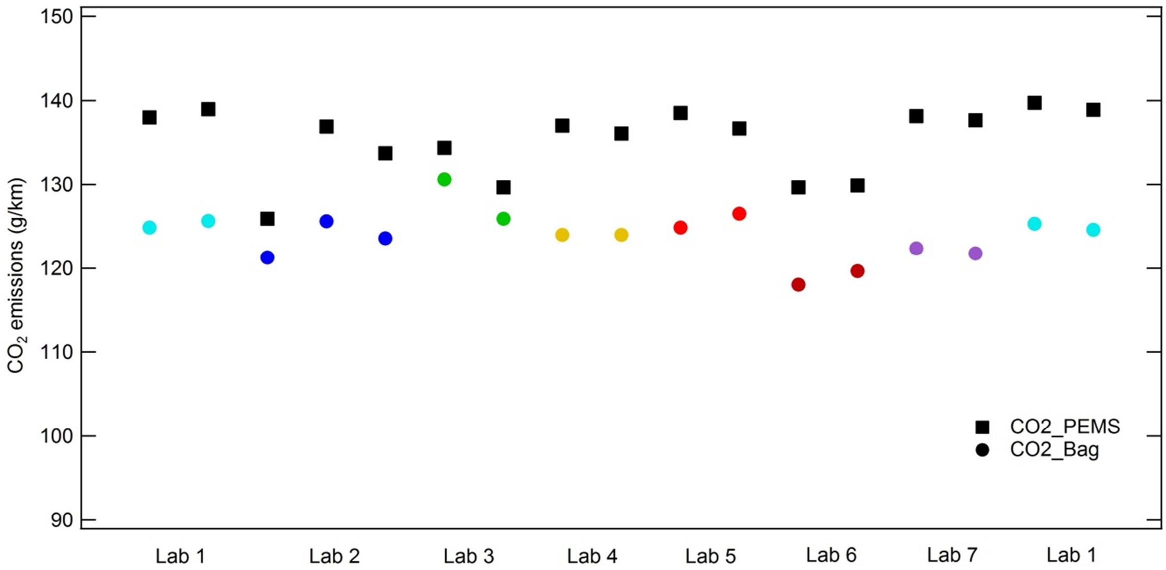


Figure 25 Distance specific bag CO_2 emissions over NEDC tests (laboratory color coded circles) and CO_2 emissions measured with the Gas-PEMS (black squares).

The bag and PEMS NO_x distance specific emissions are reported in Figure 26. Excluding the first test at laboratory 2 the average bag NO_x emission is 12 mg/km ± 2 mg/km (min 6 mg/km, max 15 mg/km) with a relative standard deviation of 20%. The average PEMS NO_x emission value is 13 mg/km ± 3 mg/km (min 7 mg/km, max 17 mg/km) with a relative standard deviation of 24%. The average NO_x PEMS to bag deviation is 17.3% ± 25.0% (min -47.2%, max 44.0%).

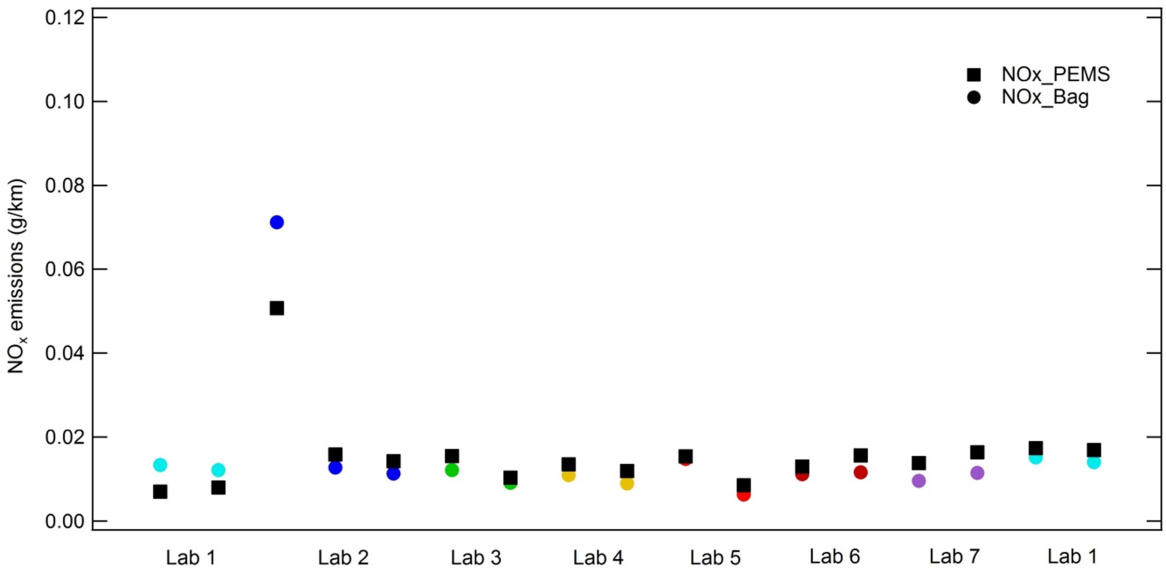


Figure 26 Distance specific bag NO_x emissions over NEDC tests (laboratory color coded circles) and NO_x emissions measured with the Gas-PEMS (black squares).

The PN distance specific emissions measured with the PMP Tailpipe and PMPs CVS are reported in Figure 27. The average distance specific PN emissions measured with the PMP Tailpipe are 10.6e11 km^{-1} ± 1.1e11 km^{-1} (min 9.1e11 km^{-1}, max 1.34e12 km^{-1}) with a relative standard deviation of 10.7%. While the average PN emissions measured with the PMPs at CVS are 10.2e11 km^{-1} ± 2.4e11 km^{-1} (min 5.9e11 km^{-1}, max 1.46e12 km^{-1}) with a relative standard deviation of 23.7%.

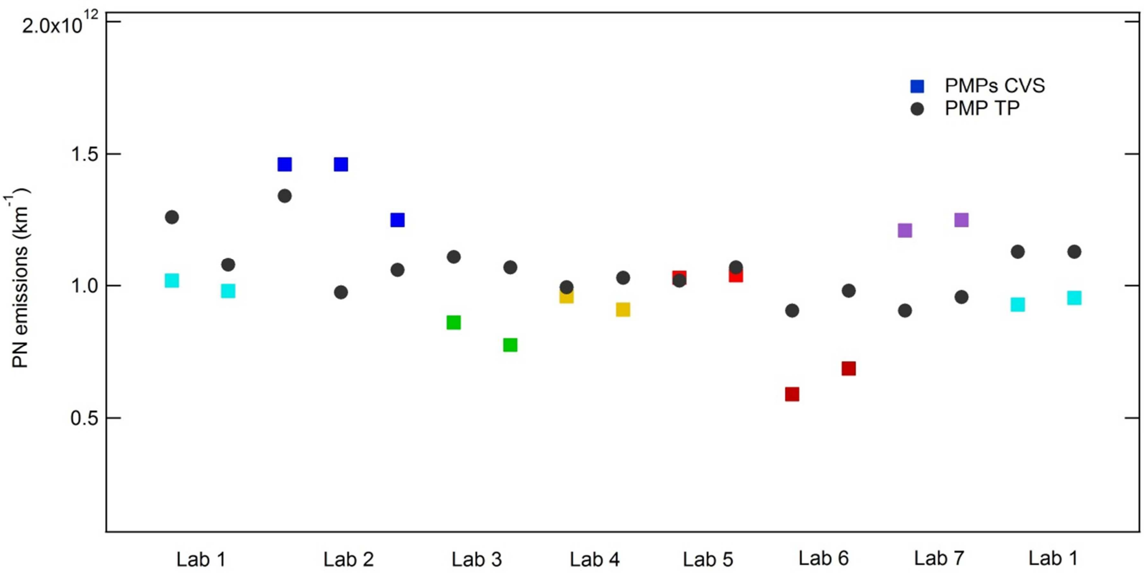


Figure 27 PN distance specific emissions measured with the PMP Tailpipe system (PMP TP, black circles) and the PN emissions measured with the PMP systems of the laboratories measuring at the Constant Volume Sampler (PMPs CVS, color coded squares) for the NEDC tests.

Figure 28 and Figure 29 show the real time PN signals of PMP CVS, PMP Tailpipe, NM3 and Mod-NPET over a NEDC test at laboratory 1. As for the WLTC tests the PN-PEMS systems match the PMP TP over 4 orders of magnitude of concentrations as highlighted in the scatter plots of Figure 30 with an R^2 of 0.98 and 0.97 for NM3 and Mod-NPET respectively.

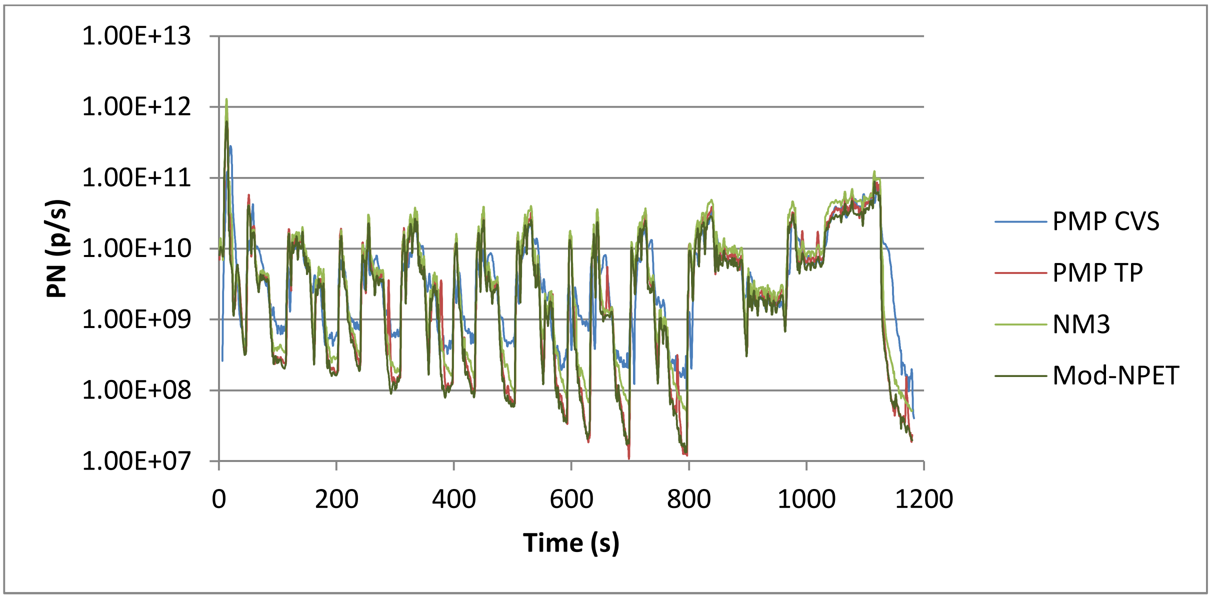


Figure 28 Example of real time PN signals of PMP CVS, PMP Tailpipe, NM3 and Mod-NPET over a NEDC at laboratory 1

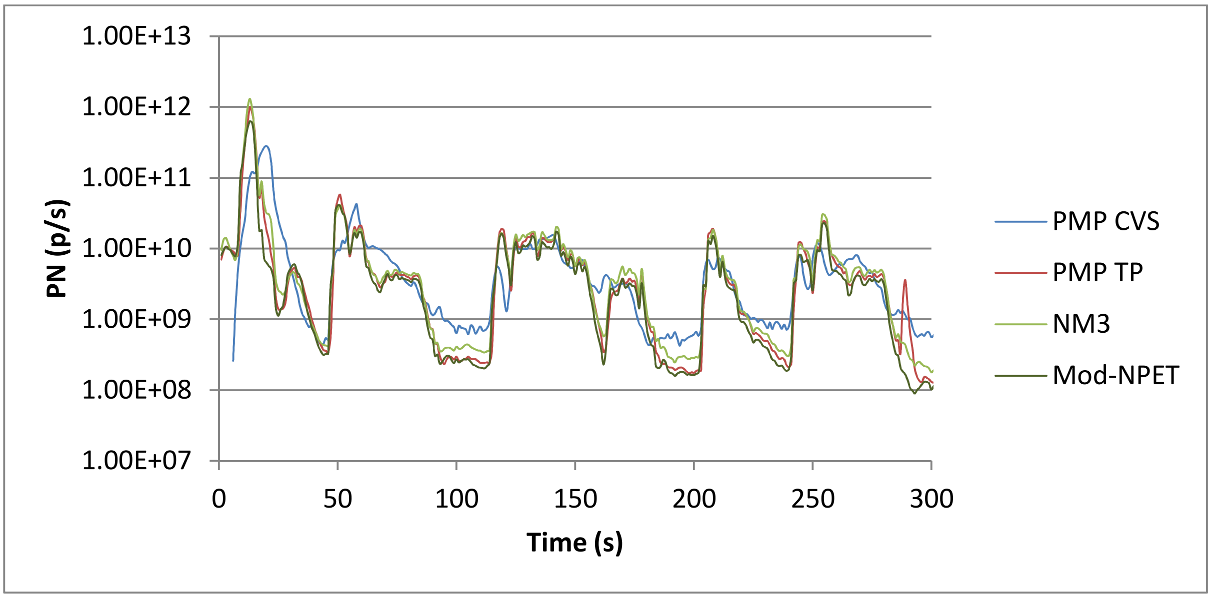


Figure 29 Detail of the first 300 seconds of a NEDC test at laboratory 1

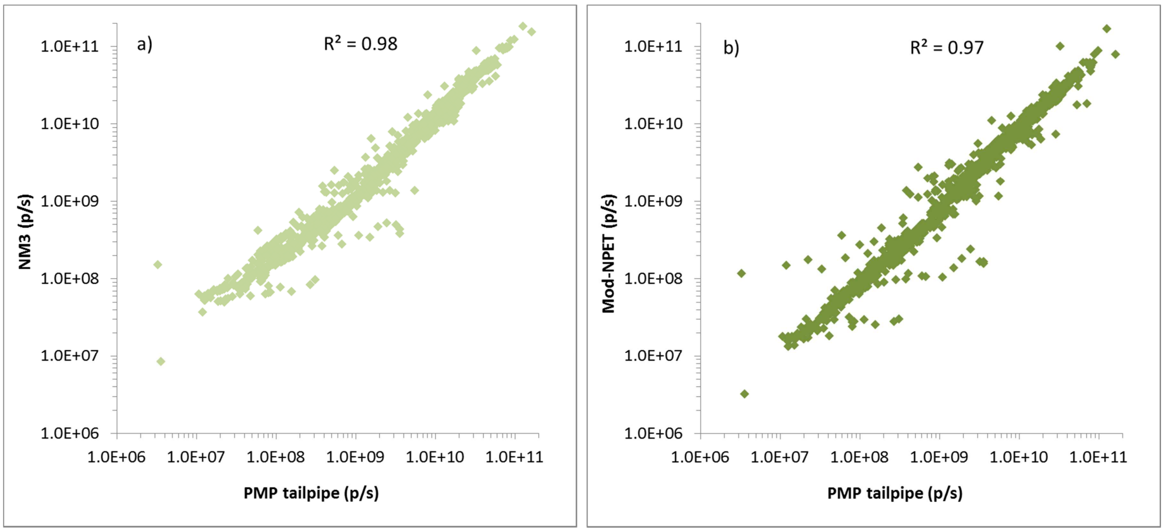


Figure 30 Scatter plots of NM3 vs PMP Tailpipe (a) and of Mod-NPET vs PMP Tailpipe (b) at laboratory 1 during a NEDC test

For comparison Figure 31 and Figure 32 show the real time PN signals of PMP CVS, PMP Tailpipe, NM3 and Mod-NPET over a NEDC test at laboratory 6. Also for this laboratory PN-PEMS systems match the PMP TP over 4 orders of magnitude of concentrations as highlighted in the scatter plots of Figure 33 with an R^2 of 0.97 and 0.98 for NM3 and Mod-PET respectively.

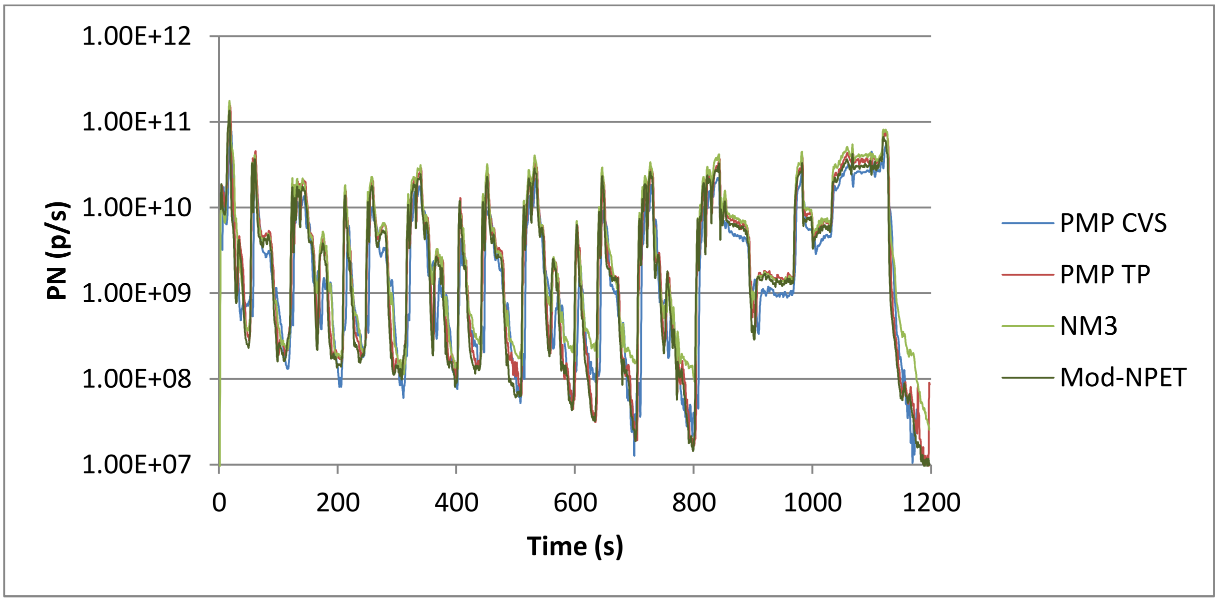


Figure 31 Example of real time PN signals of PMP CVS, PMP Tailpipe, NM3 and Mod-NPET over a NEDC at laboratory 6

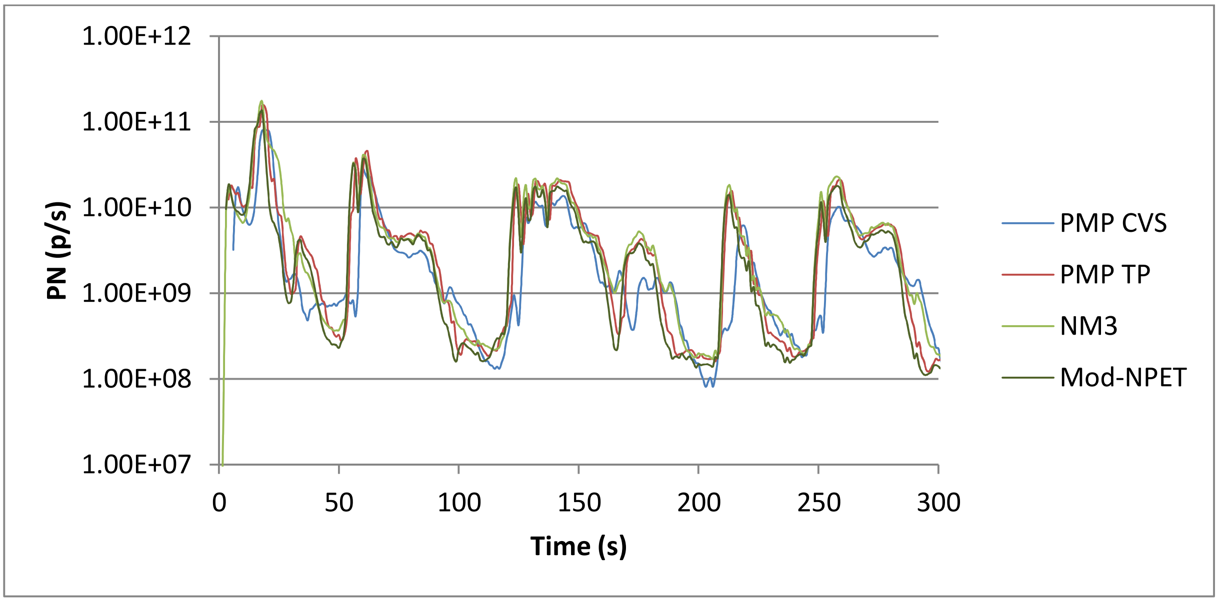


Figure 32 Detail of the first 300 seconds of a NEDC test at laboratory 6

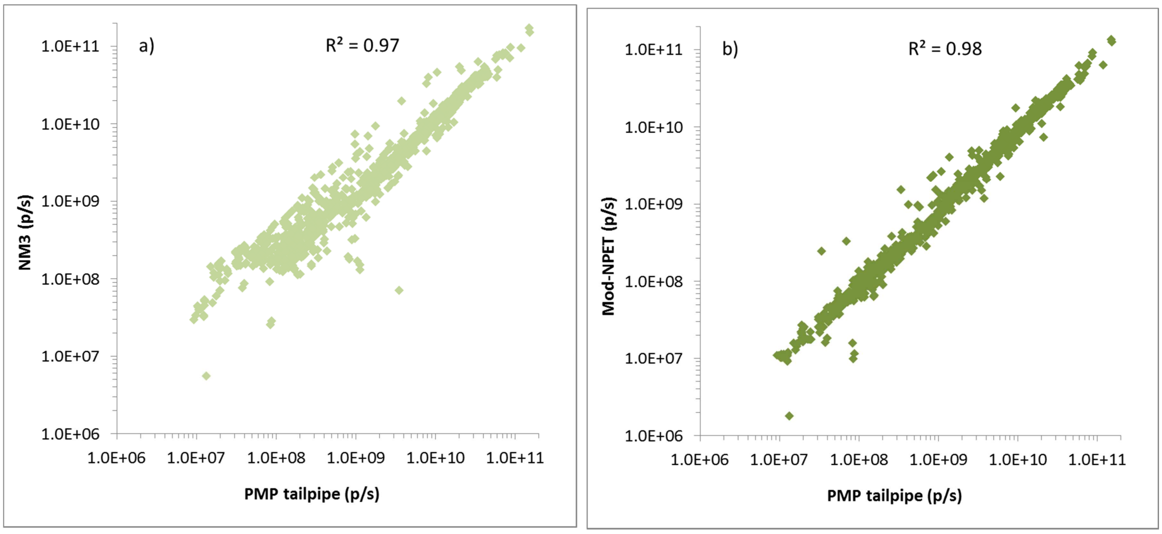


Figure 33 Scatter plots of NM3 vs PMP Tailpipe (a) and of Mod-NPET vs PMP Tailpipe (b) at laboratory 6 during a NEDC test

Figure 34 shows the average PN distance specific emissions measured with the two PN-PEMS and the PMP systems. The average distance specific PN emissions measured with the NM3 are 11.3e11 km^{-1} ± 1.7e11 km^{-1} (min 8.8e11 km^{-1}, max 1.45e12km^{-1}) with a relative standard deviation of 14.8%. While the average PN emissions measured with the Mod-NPET are 9.8e11 km^{-1} ± 1.1e11 km^{-1} (min 7.6e11 km^{-1}, max 1.23e12 km^{-1}) with a relative standard deviation of 11.3%.

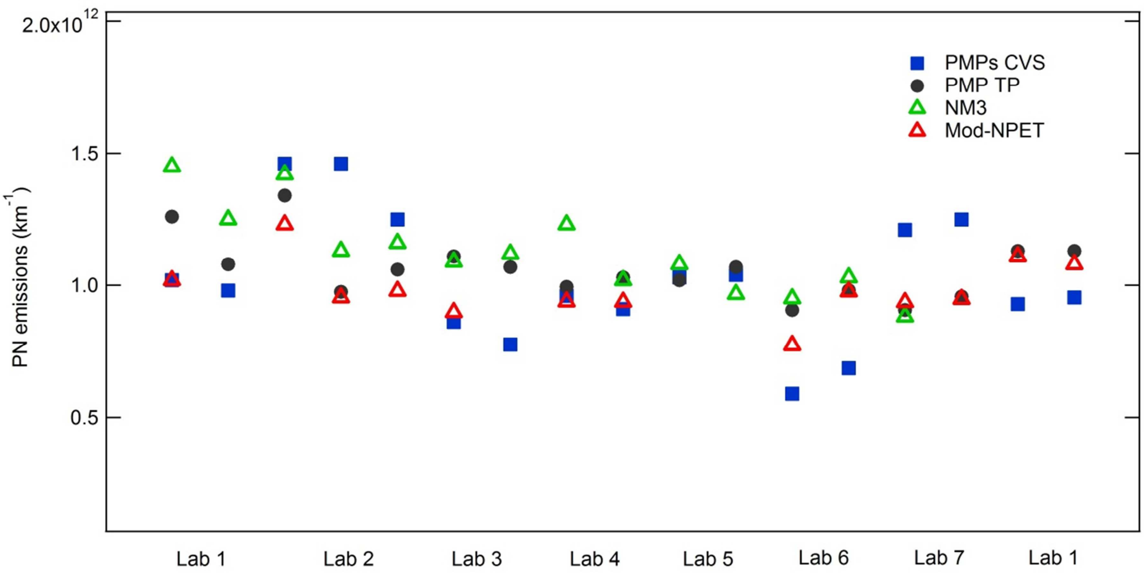


Figure 34 PN distance specific emissions measured with the PN-PEMSs (NM3 green open triangles and Mod-NPET, red open triangles). For comparison are reported also the measurement of PMP Tailpipe system (black circles) and the PN emissions measured with the PMPs at CVS (blue squares)

As for the WLTC tests the boxplot of the deviations to the PMP CVS of PMP Tailpipe, NM3 and Mod-NPET for the NEDC tests shows that the PN-PEMS and PMP TP span over the same range of vales ranging from -38% to +54%.

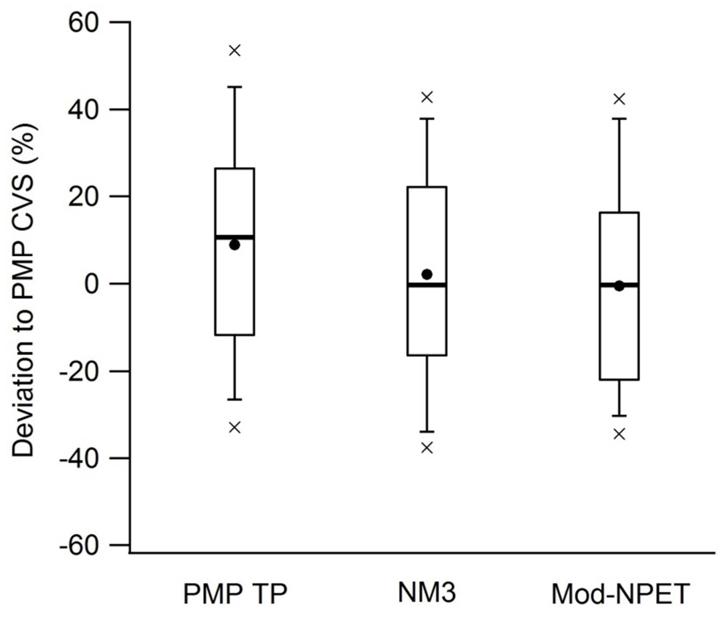


Figure 35 Boxplot of the deviations to the PMP CVS of PMP Tailpipe, NM3 and Mod-NPET for the NEDC tests. Bold line is the median, dot is the mean, boxes are 25th and 75th percentile, whiskers are 10th and 90th percentile and crosses are minimum and maximum.

3.1.3 Cold start NEDC and WLTC

Cold start emissions are currently recorded in RDE but excluded from calculations due to the following reasons:

- Absence of vehicle conditioning
- Low repeatability and reproducibility of test conditions that may lead to high variability of warm-up durations and cold start emissions
- Cold start contributes little to the overall emissions of comparatively long (up to 2h) RDE tests

The issue of cold start contains inherently two issues: (i) Engine start (i.e. inclusion of first minutes of test into the evaluation) and (ii) Start of the vehicle in cold atmospheric conditions.

The effect of engine start temperature on PN emission measurements at tailpipe and CVS can be estimated assessing the deviations of PMP Tailpipe from PMP CVS during the first part of the cycle and the second part of the cycle for NEDC (cold start tests) and WLTC (warm start tests).

We applied the following analysis to a subset of 6 NEDC cold start tests and 17 warm start tests (tests performed at laboratory 1 and 6):

1) for NEDC we separated the PN emissions of the first part of the Urban Driving Cycle (UDC, 0-300 seconds) from the second part of the UDC (301-780 seconds)

2) for WLTC we separated the PN emissions of the first part of the first WLTC phase (0-300 seconds) from the second part (301-590 seconds).

We report the deviations between PMP Tailpipe and the PMP CVS in Table 6. Results show that for laboratory 6 the deviations between the PMP systems between the two parts of the test are stable, independently of cold or warm start conditions, indicating PN measurement at tailpipe is not affected by cold start engine conditions. However, for laboratory 1 a 10% difference between the cold part and hot part is seen. Laboratory 1 had longer transfer line compared to laboratory 6 between the vehicle and the CVS (7 m vs 2 m). This difference in the length of the transfer line could be responsible for the observed deviations due to particle transformations occurring in the transfer line with longer residence time (Table 6).

Table 6 Average, standard deviation, minimum and maximum of the deviations of the PMP Tailpipe, NM3 and Mod-NPET to the PMP CVS for cold start and second part of the NEDC cold and WLTC warm tests performed at laboratory 1, 2 and 6

	Test	Cold start (0 - 300 s)	Second part (300 - 780 s NEDC, or 300 - 590 WLTC)
Lab 1	NEDC cold	33% ± 15%	21% ± 4%
	WLTC warm	32% ± 5%	34% ± 15%
Lab 6	NEDC cold	57% ± 12%	61% ± 6%
	WLTC warm	53% ± 9%	50% ± 16%

3.2 Road tests

A total of 31 RDE road tests were performed at the 7 different locations of the participating laboratories. The average ambient temperature during the RDE tests ranged between 3°C and 25°C with a an average value of 13.2°C ± 5.1°C. The average ambient pressure ranged between 988 hPa to 1081 hPa with an average value of 1020 hPa ± 15 hPa. The trip characteristics of the 31 RDE tests are reported in Annex 3 according to definitions of RDE regulation.

Gaseous emissions recorded during the RDE tests resulted in the following ranges (integrated second by second):

- CO_2 emissions range 124 g/km to 172 g/km (Ave. 142 g/km ± 14 g/km)
- CO emissions range 29 mg/km to 82 mg/km (Ave. 54 mg/km ± 14 mg/km)
- NO_x emissions range 50 mg/km to 138 mg/km (Ave. 78 mg/km ± 22 mg/km)

Figure 36 and Figure 37 show the real time series of particle fluxes measured with the two PN-PEMS during a RDE road test. In Figure 38 we report the scatter plot of the time series of Figure 36 highlighting the correlation between the two PN-PEMS signals.

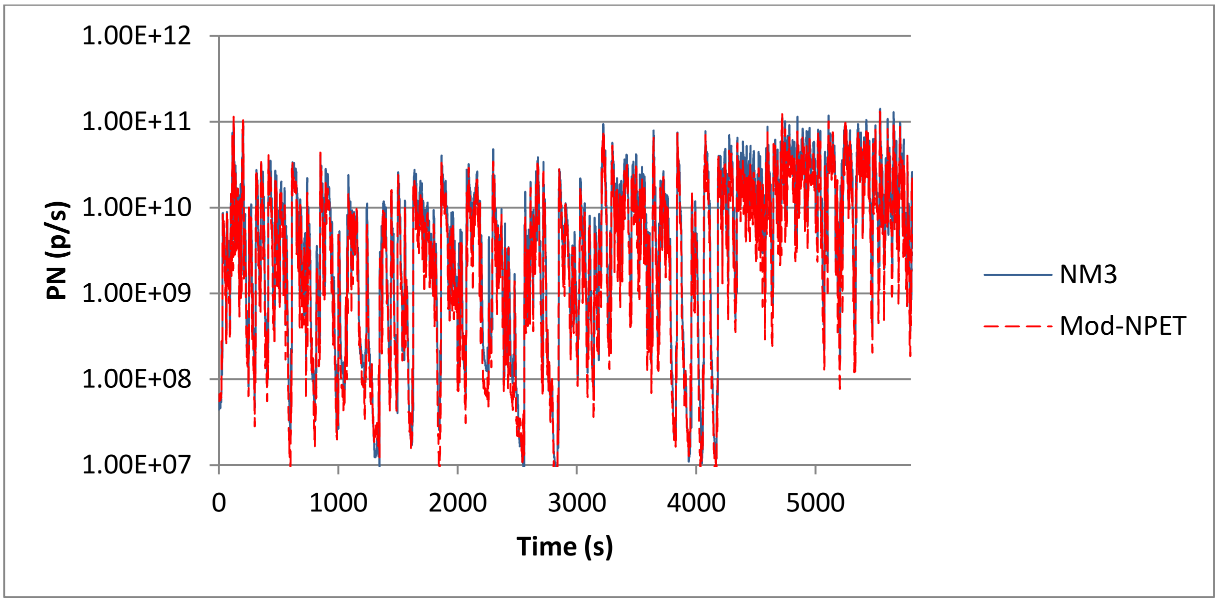


Figure 36 Example of real time PN signals on NM3 and Mod-NPET during a RDE road test

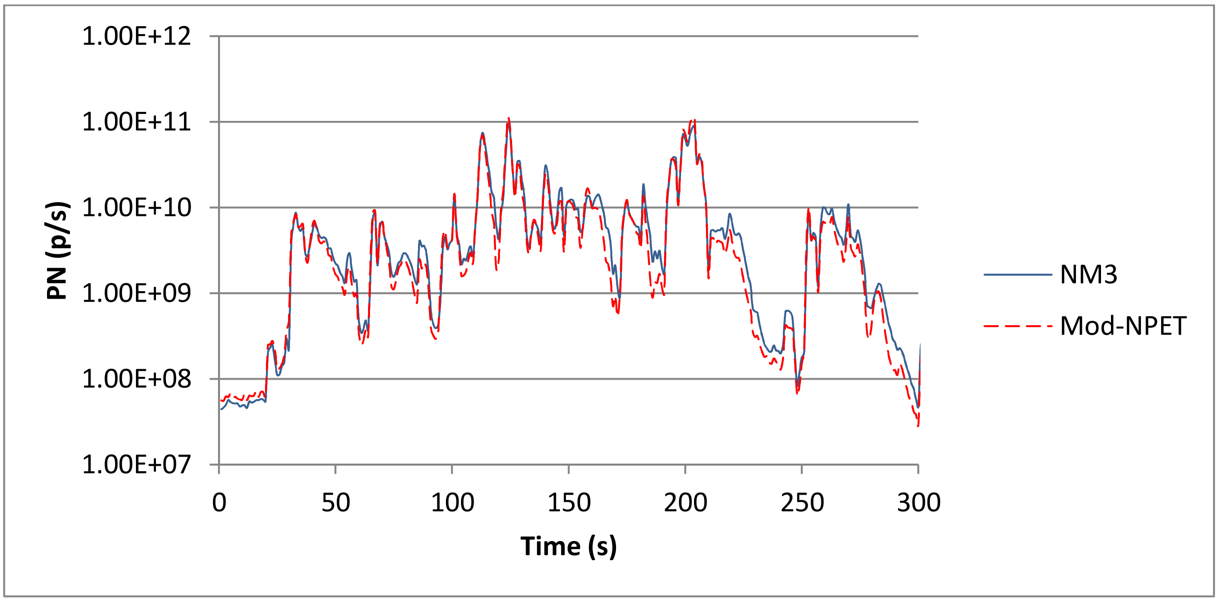


Figure 37 Detail of the first 300 seconds of a RDE road test

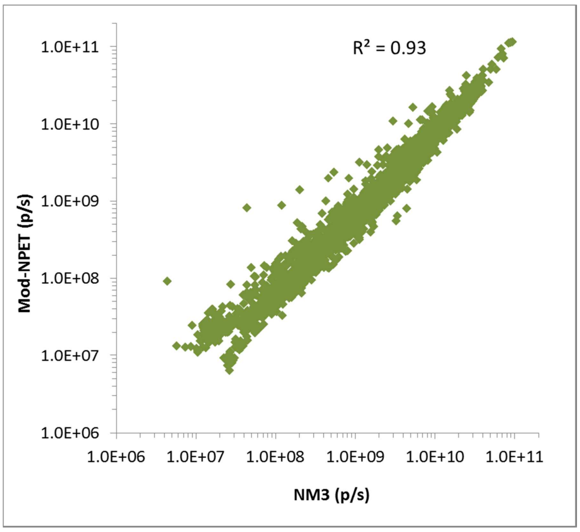


Figure 38 Scatter plots of Mod-NPET vs NM3 during a RDE road test

We analysed the RDE tests with the post-processing tool EMROAD: in Figure 39 we report the EMROAD Moving Average Window (MAW) results for NM3 and Mod-NPET (open circles and squares) and the second by second integrated distance specific PN emissions (circles and squares).

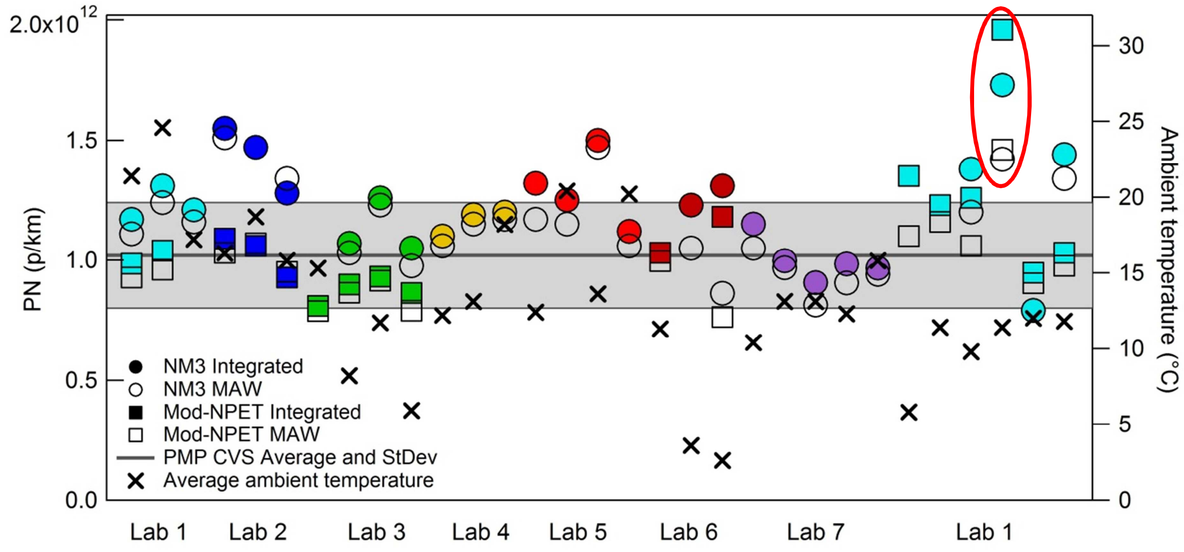


Figure 39 Integrated distance specific PN-PEMS emissions color coded by location (laboratory) for NanoMet3 (circles) and Mod-NPET (squares). Open symbols refers to MAW results. Black line shows the average PN emissions over the WLTC tests with relative standard deviation (gray bands). Black crosses show the average ambient temperature for each test (rhs axis). Highlighted in a red circle the test performed at aggressive driving conditions.

The integrated distance specific NM3 PN emissions ranged between 7.90e11 km^{-1} and 1.73e12 km^{-1} with an average value of 1.22e12 ± 0.21e12 km^{-1}, while Mod-NPET ranged between 8.09e11 km^{-1} and 1.96e12 km^{-1} with an average value of 1.09e12 ± 0.27e12 km^{-1}. The highest emissions occurred during the third last test at laboratory 1 due to aggressive driving conditions. Figure 40 and Figure 41 show the CO_2 emissions curves of a test under "normal" driving conditions and the tests performed under "aggressive" driving conditions, highlighting the difference between the two types of driving dynamics.

Distance specific PN emissions on road result slightly higher than PN emissions in the laboratory: Deviations between the integrated road tests and the laboratory tests are 10% for NM3 and 16% for Mod-NPET. If we compare RDE MAW PN emissions with laboratory emissions, deviations are then reduced to 3% for NM3 and 4% for Mod-NPET. In Figure 39 we also report the average ambient temperature measured during the RDE tests. Ambient temperature does not seem to have a direct effect on PN emissions on road.

NM3 showed 4 void tests over 31 total tests (87% error free tests), while Mod-NPET showed 14 void tests (55% error free test). The large number of void tests of the Mod-NPET is due to the absence of the system during the testing in laboratory 4, 5 and 7 due to maintenance of the system (disconnected tubing and heater temperature out of range).

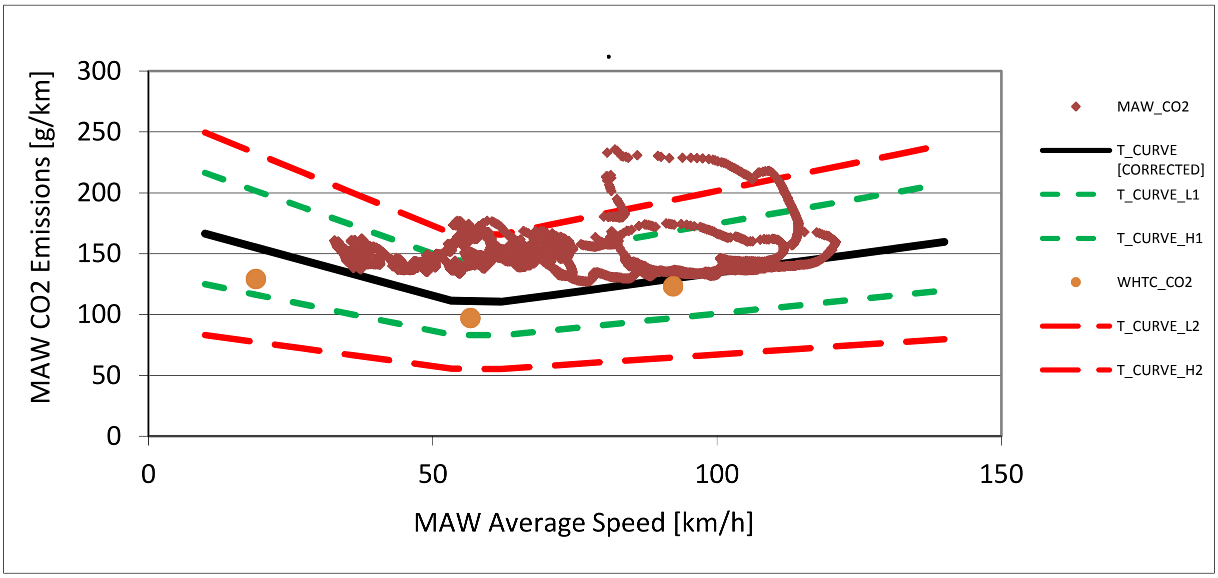


Figure 40 MAW CO_2 emissions vs MAW average speed for a "normal" drive at laboratory 1 ("Esperia" route)

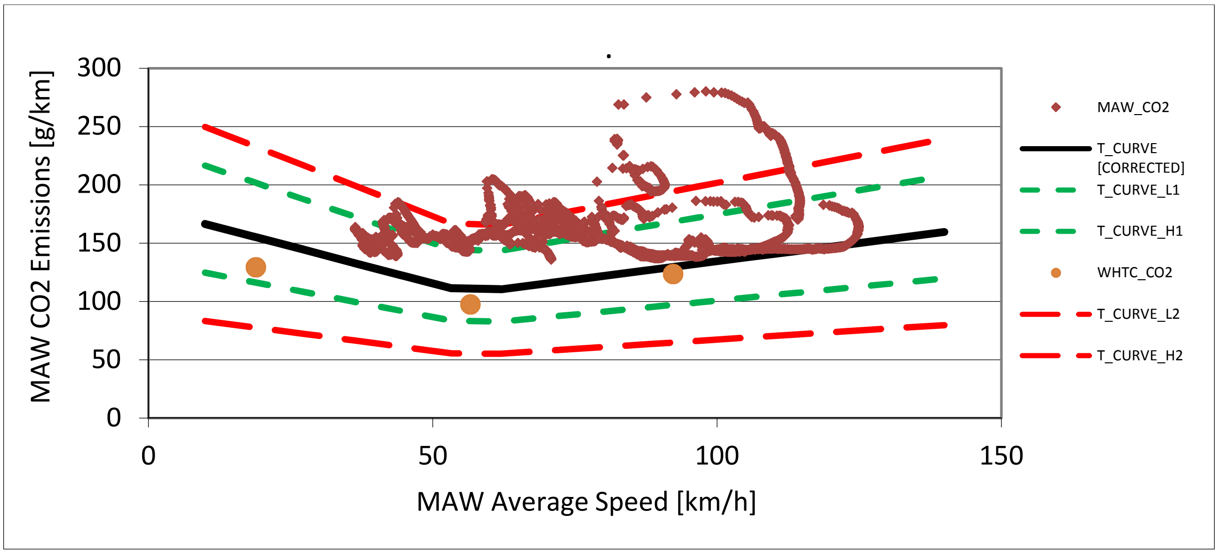


Figure 41 MAW CO_2 emissions vs MAW average speed for an "aggressive" drive at laboratory 1 ("Esperia" route)

In order to compare the performance of PN-PEMS on road and in the laboratory we plot the distributions of the deviations between the NM3 and Mod-NPET (second by second integrated emissions, Figure 42). Laboratory tests show deviations ranging between -17% and +52% (with an average of 20%), while road tests deviations range between -17% and +42% (with an average of 21%). These results indicate that the performance of the PN-PEMS can be considered stable when moving the instruments from laboratory to road tests.

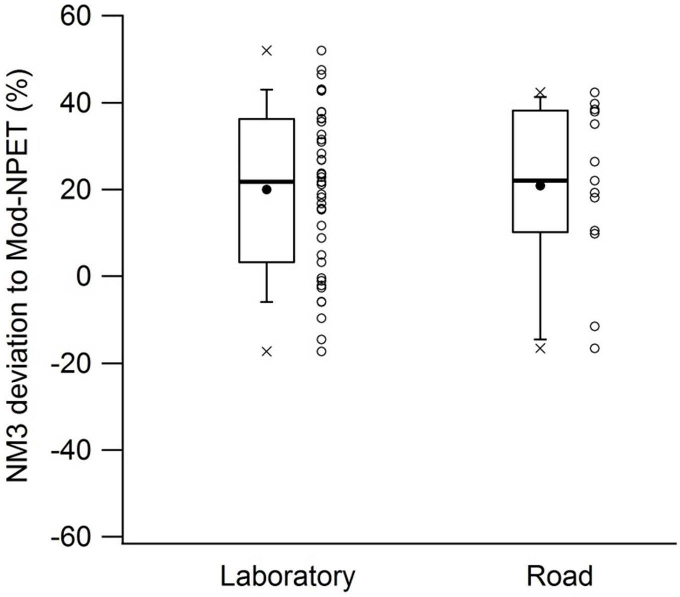


Figure 42 Boxplot of deviations between the PN-PEMS for the laboratory and road tests. Bold line is the median, dot is the mean, boxes are 25th and 75th percentile, whiskers are 10th and 90th percentile and crosses are minimum and maximum. Open dots show the complete datasets.

3.2.1 Cold start RDE tests

For RDE tests the following approaches for the inclusion of cold start are currently under assessment:

- Approach 0 - Cold-start as part of RDE urban evaluation
- Approach 2a - Weighted emissions:

$$PN_{urban}\left[\frac{\#}{km}\right] = w \cdot PN\left[\frac{\#}{km}\right] + (1-w) \cdot RDE_{hot,\,urban}\left[\frac{\#}{km}\right]$$

$$\text{with } w = \frac{d_{cold}[km]}{d_{urban}[km]}$$

Out of the 31 RDE tests only ten tests are satisfying the conditions of (i) starting at cold engine conditions and (ii) having an average cold-start speed ranging between 15 and 40 km/h. NM3 was measuring during nine tests out of those ten RDE tests, while Mod-NPET was measuring during five tests.

Table 7 reports the error free tests of PN-PEMS and ambient temperatures of the ten RDE cold start tests.

Table 7 PN-PEMS error free test and ambient temperatures of the cold RDE tests

Cold RDE test ID	NM3 error free test	Mod-NPET error free test	Ambient temperature (°C)
Lab 1 Road 03	x		17
Lab 4 Road 01	x		12
Lab 4 Road 02	x		13
Lab 6 Road 03	x		4
Lab 6 Road 04	x	x	3
Lab 7 Road 04	x		12
Lab 1 Road 05		x	6
Lab 1 Road 07	x	x	10
Lab 1 Road 08	x	x	12
Lab 1 Road 09	x	x	12

The absolute effect on distance specific PN emissions of the application of the different approaches for the inclusion of cold start for each test are reported in Figure 43 and Figure 44, while average percentage increments relative to the default RDE calculation (exclusion of the cold start) are reported in Table 8.

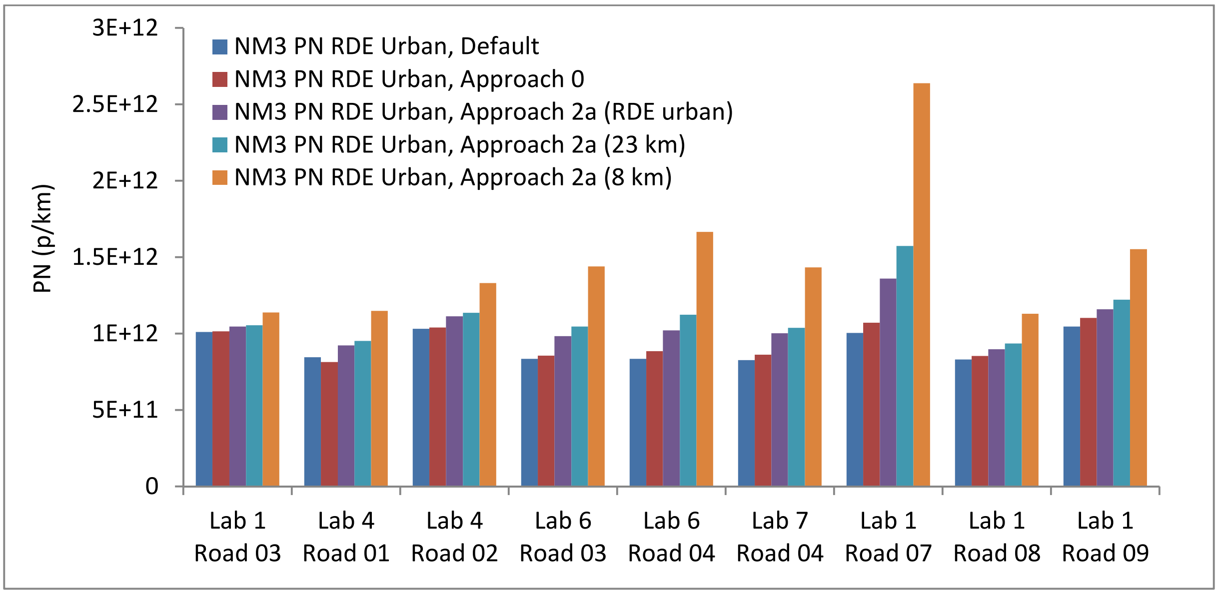


Figure 43 Effect of approaches 0 and 2a compared to the default RDE (excluding cold start) for the NanoMet3

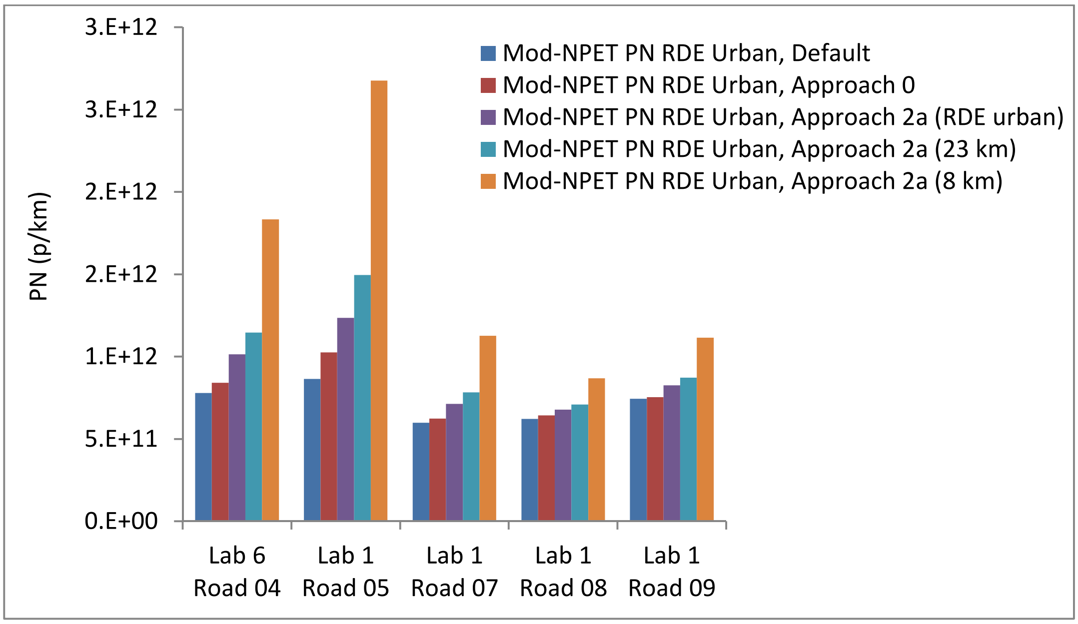


Figure 44 Effect of approaches 0 and 2a compared to the default RDE (excluding cold start) for the Modified NPET

Table 8 Effect of different approaches for the inclusions of the cold start emissions as percentage deviation from the RDE default calculation (exclusion of cold start)

	NM3	**Mod-NPET**
Approach 0 (CS part in default RDE)	3% (±3 %)	7% (±7 %)
Approach 2a (durban=RDEurban)	15% (±10%)	22% (±14%)
Approach 2a (durban=23km)	22% (±16%)	36% (±24%)
Approach 2a (durban=8km)	63% (±46%)	105% (±70%)

4 Effect of ambient temperatures

At the end of the ILCE (7th-12th January 2016) we run additional chassis dynamometer tests at the JRC to evaluate the performance of the PN-PEMS at extreme ambient temperatures (-7°C and 30°C). In order to provide a robust measurement of PN at tailpipe (not affected by extreme ambient temperatures) a second PMP system was installed outside of the test cell (kept at constant 20°C) just before the dilution air of the CVS: We will refer to this system as PMP TP 20C.

Five tests were performed at -7ºC (1 cold start and 5 warm start) and two tests at 30°C (both warm start), in addition six reference tests were performed at 22°C (3 cold start and 3 warm start). The PN emissions in p/km of all the 13 tests measured by the PMP CVS, PMP TP, PMP TP 20C and the two PN-PEMS are shown in Figure 45, tests are reported in order of increasing ambient temperature. It is worth to note that the 4th and 5th tests performed at -7°C were performed leaving the PN-PEMS instruments the whole night soaking at -7°C, which is an extreme testing condition.

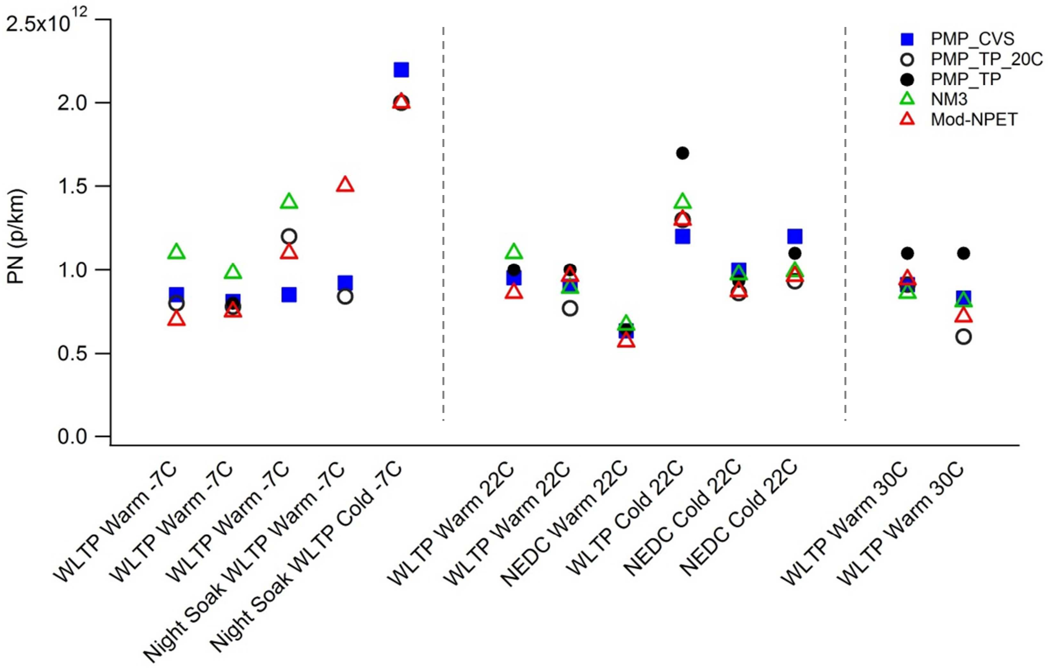


Figure 45 Distance specific PN emissions of the 13 additional tests run at three ambient temperatures (-7°C, 22°C and 30°C)

Figure 46 shows the relative deviations of PMP TP, PMP TP 20C and the PN-PEMS to the PMP CVS system: PN-PEMS deviations from PMP CVS are not affected by ambient temperature ranging between +15% and -15% (for one single laboratory, i.e. JRC). Only for the night soak tests at -7°C the Modified NPET (red open triangles) shows a high deviation of 40% in one test. NM3 did not work at any of the night soak tests: it is worth to note according to manufacturer specifications the temperature working condition range is 5°C to 35°C. The recommendation to safely run tests at extremely cold ambient temperature is to keep the instrument warm with thermo covers or install the instruments just before the start of the test avoiding the night soaking at -7°C.

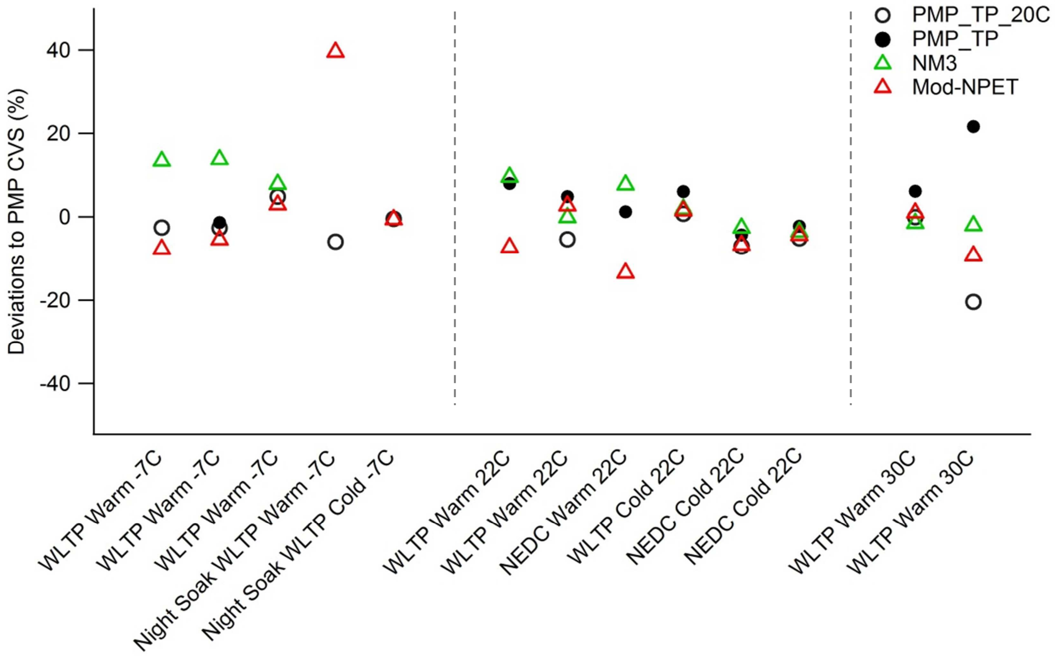


Figure 46 Relative deviations of PMP TP, PMP TP 20C and the PN-PEMS to the PMP CVS system

5 Deviations of PN emissions at tailpipe and CVS

In Section 2.5.1 we discussed the effect of the exhaust flow rate on PN emissions measured at tailpipe and CVS. In addition to this, some of the deviations observed between the PN measurements performed at CVS (PMP CVS) and the PN measurements performed at tailpipe (PMP TP and PN-PEMS) can be attributed to particle losses occurring in the tubing between tailpipe and CVS sampling point and differences in the counting efficiency of the particle counters.

The physical mechanisms responsible for particle losses are: thermophoresis, diffusion and coagulation.

Thermophoresis is a phenomenon occurring in presence of a gradient of temperature: Particles are pushed towards the colder region, the larger the difference of temperature between the exhaust and the wall of the tubes the larger will be the fraction of particle lost. Measurements at CVS are thus affected by thermophoretic losses depending on the temperature of the exhaust flow and temperature of tube walls. When particles exit the tailpipe are pushed towards the tube walls until CVS mixing point where temperature is stabilized to the same temperature of the tubing wall. Figure 47 shows the estimate of the thermophoretic losses for a cold NEDC test: Assuming that particles are not re-entering from walls when the exhaust temperature is lower than the temperature of the wall, the average particle loss over the whole cycle results to be 1%.

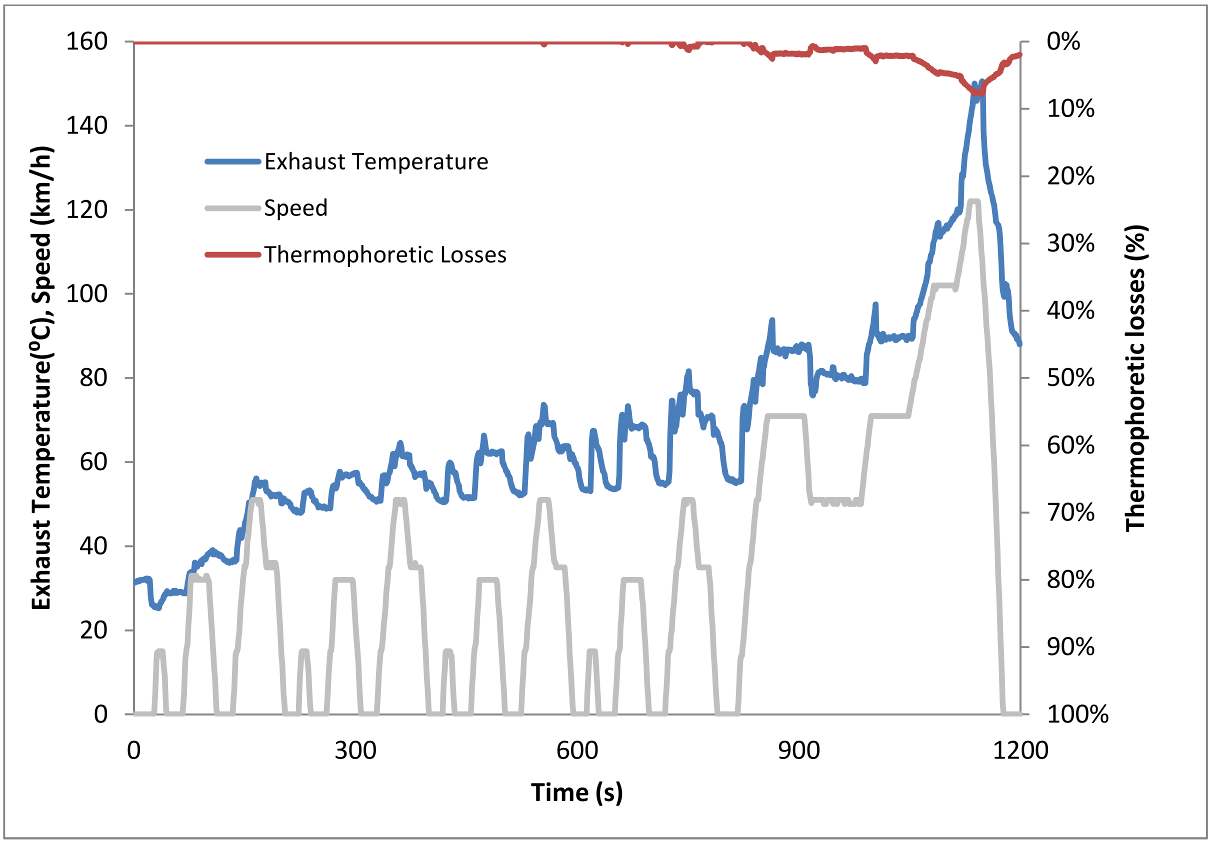


Figure 47 Estimated thermophoretic losses over a NEDC test

Figure 48 shows the estimate of the thermophoretic losses for a warm WLTC test: In this case due to the higher exhaust flow temperature the average particles loss over the whole cycle results to be 4%.

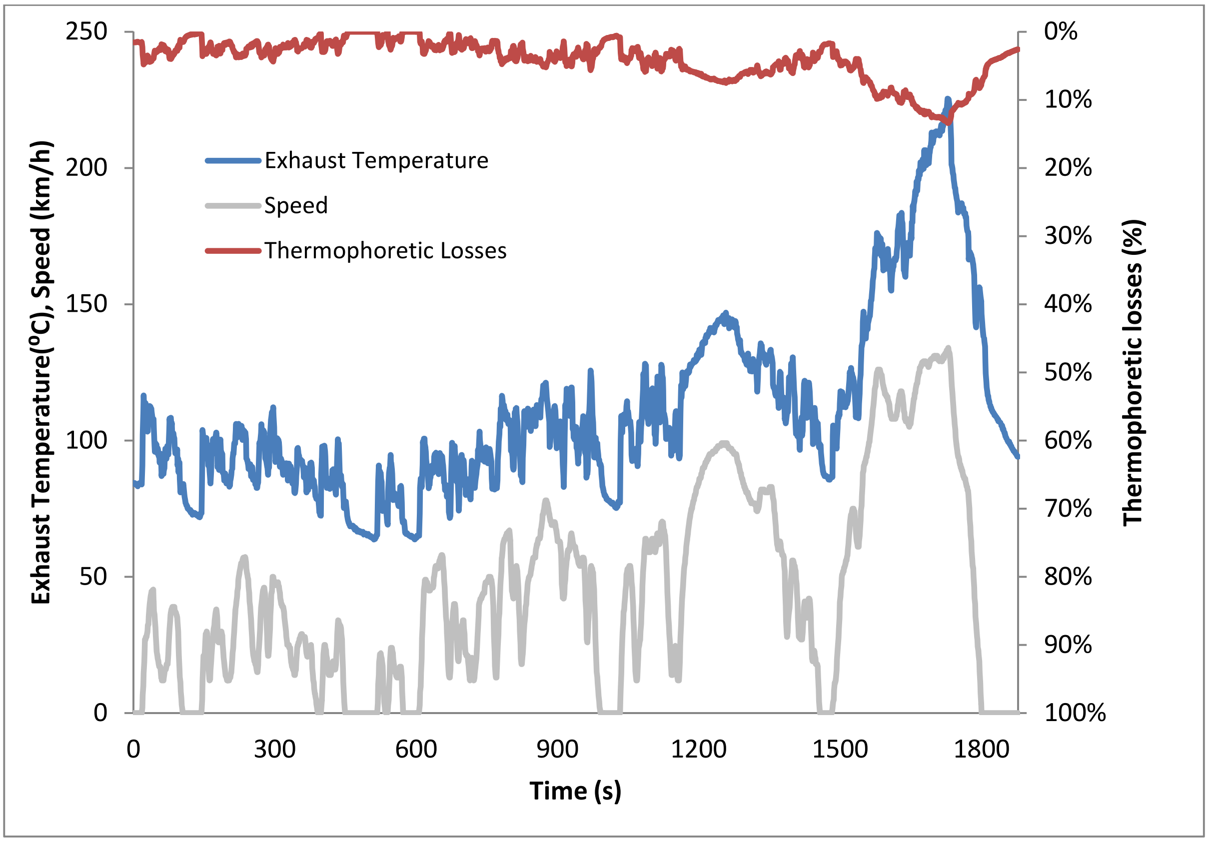


Figure 48 Estimated thermophoretic losses over a WLTC test

Diffusion losses happen due to Brownian motion of small particles that collide with the tube walls, thus being lost before reaching the counter at the CVS. The fraction of particles lost by diffusion is a function of particle size, tube length and flow velocity. Due to the high flow velocity in the CVS we can assume that diffusional losses occur only in the transfer tube from tailpipe to the mixing point of CVS.

We calculated the diffusional losses in the transfer tube as a function of particle size (using the equation 8-56 in Baron and Willeke (2001) valid for turbulent flow) at the lowest flow rate (idle) of 0.1 m^3/min at the JRC which had the longest transfer tube (7 m, thus when the diffusion losses are maximised). The estimated diffusional losses as a function of particle size are shown in Figure 49. For the range of interest of particles diameters (>20 nm) diffusional losses result always smaller than 1%.

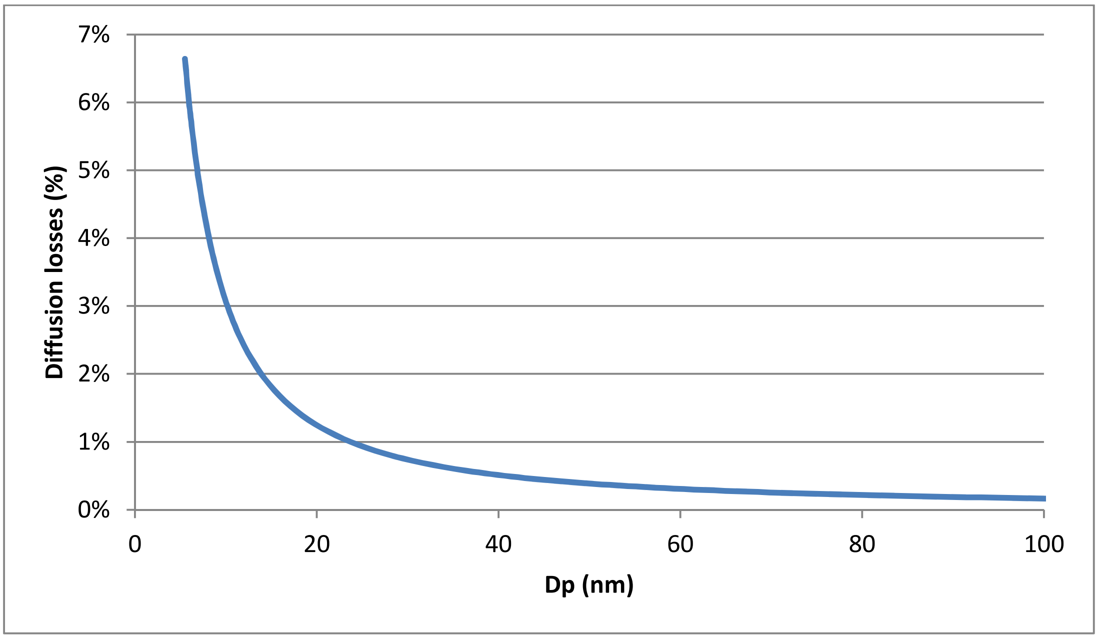


Figure 49 Estimated diffusional losses as a function of particle diameter (Dp) during idle at the JRC

Coagulation losses occur when one particle collides with another particle resulting in the loss of one particle (in number). Coagulation is a function of particle size, particle concentration and residence time (Giechaskiel et al., 2012). We estimated the effect of coagulation for an average particle diameter of 50 nm (coagulation coefficient = 9.9e-10 cm^3/s) and an average particle concentration of 1e6 p/cm^3 in the worst case scenario corresponding to the largest residence time of 33 seconds (JRC at idle conditions) resulting in 3% particle losses. At cold start, PN concentration can reach 1e7 p/cm^3 in this short period and in the worst case of low flow rate (idle) coagulation losses can reach 20%.

In addition to particle losses, also the differences between the counting efficiencies of CPCs at different laboratories could result in deviations between the PN measurements performed at tailpipe and at CVS. According to UN-ECE Regulation 83 the Particulate Number Counter (PNC) (in this case the CPC) shall have counting efficiency at particulate sizes of 23 nm (±1 nm) of 50 per cent (±12 per cent). In order to assess the effect of the CPC counting efficiency differences on total particle emissions we consider two CPCs, one with high counting efficiency at 23 nm (60% as the one at laboratory 2) and one with low counting efficiency (38%). The shape of the counting efficiency curve is based on the following three parameter equation (Stolzenburg, M. and McMurry, 1991)

$$\eta = a - \exp\left(\frac{b - Dp}{c}\right)$$

where D_p is the particle diameter.

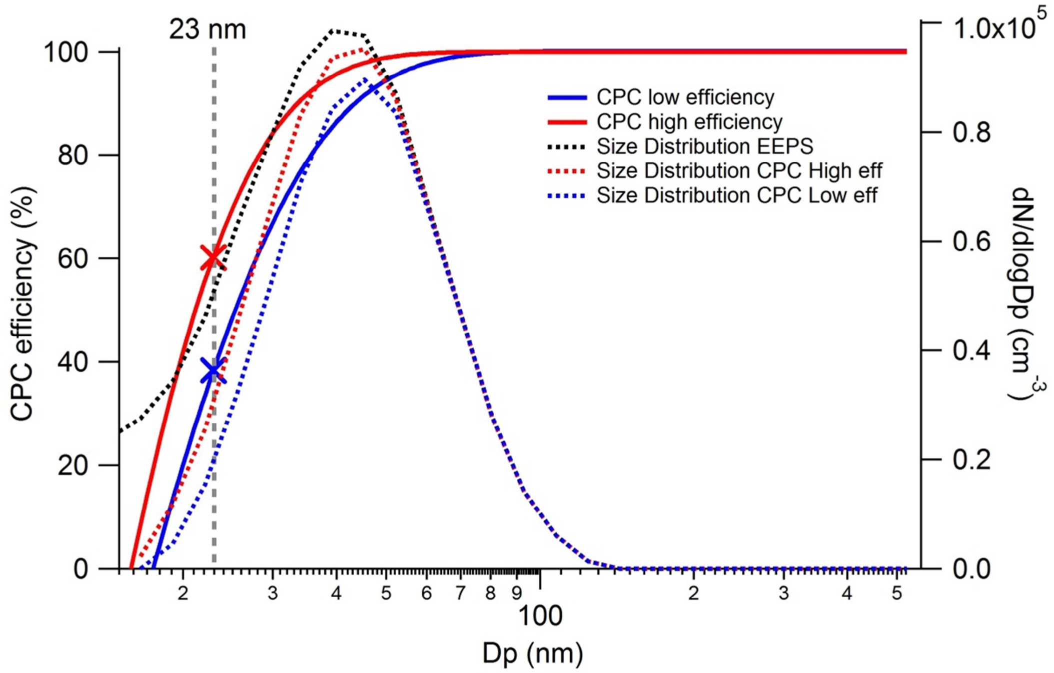


Figure 50 Counting efficiency curves of two CPCs, both compliant to UN-ECE Regulation 83 but at the extreme of the allowed efficiency ranges, example of size distribution measured with EEPS and size distributions detected by the CPCs (rhs axis).

We then calculated the total number of particles detected by the two CPC (high efficiency and low efficiency) multiplying the second by second PN size distributions measured with an Engine Exhaust Particle Sizer (EEPS) for a NEDC and a WLTC test performed at the JRC (Figure 51). Results show that for the NEDC cycle the CPC with low efficiency measures 6% less particles of the high efficiency CPC independently of the cycle phase (UDC and EUDC). For the WLTC cycle the deviation between the two CPCs is 7% independently of the cycle phase (low, medium, high and extra high phases).

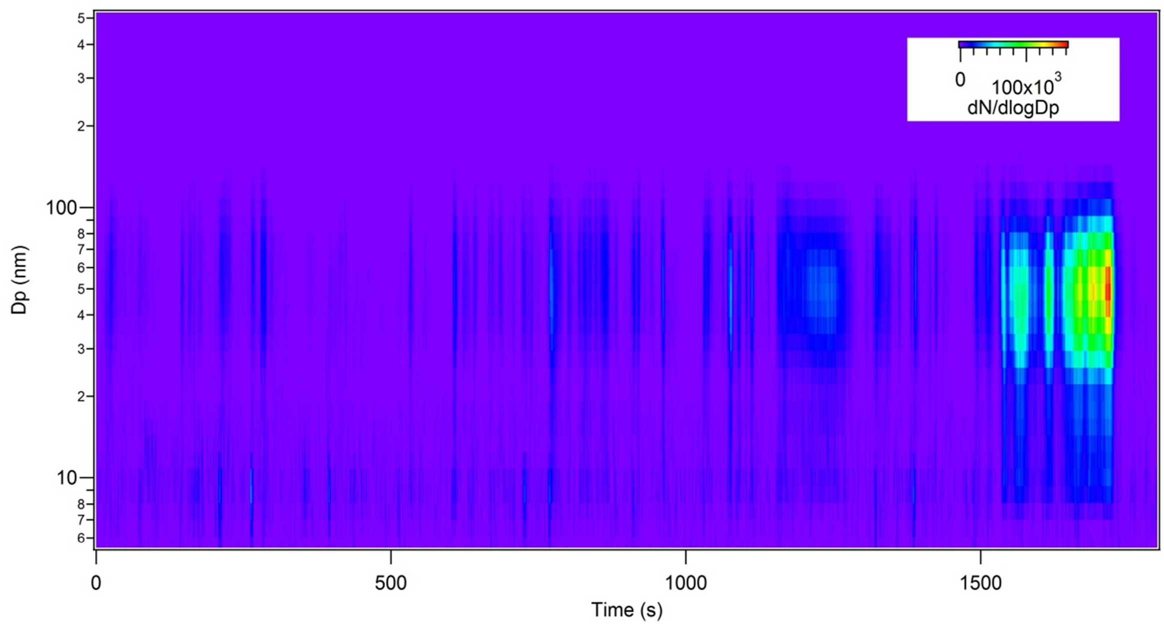


Figure 51 Particle size distribution during a WLTC test at JRC measured with EEPS at CVS.

6 Conclusions

The PN-PEMS Inter-Laboratory Comparison Exercise assessed the accuracy and precision of the PN-PEMS. Two PN-PEMS and a PMP compliant system circulated among seven European laboratories. All systems were connected to the tailpipe and were compared with the reference systems at the CVS of the laboratories.

The average deviation of the diffusion charger based PN-PEMS (NanoMet 3 from Testo) to the reference system at the tailpipe was 10.4% ± 11.9% (range -15.7% to 30.8%). The average deviation of the CPC based system (Mod-NPET from Horiba) to the PMP at tailpipe was -8.0% ± 9.5% (range -27.4 to 7.8).

The average deviation of NM3 to PMP systems measuring at CVS was 6.3% ± 20.0% (range -38.6% to 35.5%) and of Mod-NPET was -12.4% ± 18.2% (range -40.6% to 35.4%). These deviations resulted in line with the deviation of the reference PMP system measuring at the tailpipe to the PMP reference systems measuring at the CVS. Part of the deviations are due to particle transformation occurring between the tailpipe and the CVS for laboratories that had long transfer lines from tailpipe to CVS, but calibration uncertainties of the CVS systems are another important source of the deviations observed between the instruments. It is worth to highlight that these deviations were assessed with a single Golden Vehicle (even if in several laboratories), thus additional deviations are expected when assessing the performance of the PN-PEMS with different vehicles as shown in a Giechaskiel 2014 and Giechaskiel 2015.

The effect of extreme ambient temperatures (-7°C and 30°C) on the performance of the PN-PEMS has been assessed with additional temperature controlled dynamometer tests at the JRC. PN-PEMS showed deviations from PMP CVS comprised between +15% and -15% indicating that the PN-PEMS are not affected by ambient temperature. All instruments measuring at tailpipe failed during the night soak tests at -7°C. The recommendation to safely run tests at extremely cold ambient temperature is to keep the instrument warm with thermo covers or install the instruments just before the start of the test avoiding the soaking at extremely cold temperatures.

Both PN-PEMS showed a percentage of error free tests of 85% on dynamometer tests (failed 9 tests over 61 normal ambient temperature NEDC and WLTC tests). NM3 showed a percentage of error free tests of 87% for RDE road tests, while for Mod-NPET resulted of 55% mainly due to maintenance time.

The ratio between the PN emissions measured with the two PN-PEMS is similar for dynamometer tests and for road tests. In particular RDE tests showed a ratio between the two PN-PEMS ranging between -17% and +42% (with an average of 21%) while during the dynamometer tests the ratio ranged between -17% and +52% (with an average of 20%). These results indicate that the performance of the PN-PEMS can be considered stable when moving the instruments from laboratory to road tests.

Distance specific PN emissions on road resulted only marginally higher than PN emissions in the laboratory: Deviations between the integrated second by second road tests and the laboratory tests are 10% for NM3 and 16% for Mod-NPET. Comparing RDE Mowing Average Window PN emissions with laboratory emissions, deviations are reduced to 3% for NM3 and 4% for Mod-NPET. These values are in the same range (or smaller) of the statistical uncertainty showed by the PN-PEMS during the dynamometer tests suggesting that for the specific assessed technology there are not significant deviations between the PN emissions measured in the laboratory and the PN emissions measured under real driving conditions.

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List of abbreviations and definitions

APC	AVL Particle Counter
CPC	Condensation Particle Counter
CS	Catalytic Stripper
CVS	Constant Volume Sampling
DC	Diffusion Charging
DPF	Diesel Particulate Filter
ECM	Engine Control Module
ESP	Electronic Stability Control
EFM	Exhaust Flow Meter
ET	Evaporation Tube
EUDC	Extra-Urban Driving Cycle
GDI	Gasoline Direct Injection
GPF	Gasoline Particulate Filter
JRC	Joint Research Centre
GV	Golden Vehicle
ICLE	Inter-Laboratory Comparison Exercise
MAW	Moving Average Window
NEDC	New European Driving Cycle
NO_x	Nitric Oxides
PCRF	Particle Concentration Reduction Factor
PEMS	Portable Emission Measuring Systems
PM	Particulate Matter
PMP	Particle Measurement Programme
PN	Particle Number
PNC	Particle Number Counter
OBD	On-board diagnostics
PNC	Particle Number Counter
RDE	Real Driving Emissions
RH	Relative Humidity
TWC	Three way catalyst
UDC	Urban Driving Cycle
VPR	Volatile Particle Remover
WLTC	World Light Duty Test Cycle
WLTP	World Light Duty Testing Procedures

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Annexes

Annex 1. ILCE laboratory guide

PN-PEMS
Inter-Laboratory Comparison Exercise

Laboratory guide and test procedure

Introduction

This guide is aimed to provide information to the participating laboratories on the test procedure to be followed for the PN-PEMS Inter-laboratory Comparison Exercise (ILCE).

The ILCE aims to gain information on the reproducibility and repeatability of the performance of the PN-PEMS.

Laboratories participating to the ILCE are responsible for the instruments and car in case of accident.

Golden Vehicle

The golden vehicle (GV) is a VW Golf TSI 1.2l, 63 kW. The registration certificate of the golden vehicle is reported in Annex 1.

Preparation of the vehicle

The chassis dynamometer controller shall be adjusted to simulate the inertia of the test vehicle. The inertia shall be set to 2750 lbs with the following road load coefficients: F1= 74 N, F2= 0.48 N/(km/h), F3= 0.0304 N/(km/h)^2 (as provided by the GV manufacturer). These values shall be verified on the dyno.

The reference fuel shall be ordered from Total: 2x50 liter tanks of reference fuel RF-02-08 E5 from batch PCZ030081G. The reference fuel shall be used for both dyno and road tests. Prior to the first dynamometer preconditioning the GV shall be refuelled to 50% of full scale.

The GV shall be fuelled to 100% prior to the start of the road tests.

Tires shall be inflated as following
Front tyres pressure: 2.4 bars
Rear tyres pressure: 2.7 bars

Prior to the start of each test (both dyno and on road) deactivate the Start/Stop and the ESP following the procedure described below.

Instrumentation

The GV will arrive already equipped with the following instrumentation:

- Gas-PEMS (including ECU logger)
- PN-PEMS DC (Diffusion charging based)
- PN-PEMS CPC (CPC based)
- PMP system (only for dyno tests)

All the instruments shall be sampling at tailpipe. The three PEMS will come already installed on the vehicle and will measure during all tests, while the PMP need to be installed (sampling port downstream of the in the test cell and will measure only during the dyno tests.

The user's manuals of the instruments will be provided to each participating laboratory before the start of the ILCE. A JRC engineer will support the execution of the experimental work.

The extracted flow by the PEMS and PMP shall be considered in the automation dyno system.
The total extracted flow rate by the PEMS and the PMP system is 13 l/min.

Laboratories participating to the ILCE should provide gas cylinders for calibration of CO, CO_2, NO and NO_2

CO cylinder range 1000 - 30000 ppm, optimal 10000 ppm

CO_2 cylinder range 2 - 20%, optimal 16%

NO cylinder range 1000 - 2000 ppm, optimal 1500 ppm

NO_2 cylinder range 10 - 500 ppm, optimal 200 ppm

Dynamometer test procedure

Preconditioning shall be performed only at the end of day 0 and day1: NEDC preconditioning (NEDC+EUDC) for next day cold NEDC test.

All the WLTC tests should start with engine coolant temperature reaches 95 (±1) °C (based on ECU data) or engine oil temperature reaches 75 (±1) °C.

Test cell temperature shall be set at 23 °C and RH to 50%.

The hood of the vehicle shall be kept closed during the tests.

Please be careful when securing the rear wheels on the dyno, due to the heavy instruments and batteries inside the car the bottom of the car is very low.

TABLE 9 - TEST MATRIX

<table>
<tr><th>Day 0</th><th>Day 1</th><th>Day 2</th><th>Day 3</th><th>Day 4</th><th>Day 5</th></tr>
<tr><td rowspan="5">Preparation of the GV in the dynamometer test cell
+
WLTC
+
Coast Down
+
WLTC warm (optional)
+
NEDC preconditioning (NEDC+EUDC)</td><td>NEDC cold</td><td>NEDC cold</td><td rowspan="2">Road test 1</td><td rowspan="2">Road test 3</td><td rowspan="5">Preparation of the GV for shipping</td></tr>
<tr><td>WLTC warm</td><td>WLTC warm</td></tr>
<tr><td>WLTC warm</td><td>WLTC warm</td><td rowspan="3">Road test 2</td><td rowspan="3">Road test 4

(optional)</td></tr>
<tr><td>WLTC warm</td><td>WLTC warm (optional)</td></tr>
<tr><td>NEDC preconditioning (NEDC+EUDC)</td><td>WLTC warm (optional)</td></tr>
</table>

The minimum amount of test per laboratory is 2 NECD cold, 5 WLTC warm and 3 road tests. The tests can be run in the preferred order.

There is no need to record emissions during day one unless want to speed up the exercise and perform some optional WLTC warm.

The gear shift strategy file (WLTC_ShiftPoints_GoldenVehicle.xlsx) has been loaded on the ftp server folder .

Road test procedure

Road tests shall follow the RDE test procedure (specific draft) that will be distributed to each laboratory prior the beginning of the ILCE. At least three successful road tests shall be performed by each laboratory. In case of test failure, tests shall be repeated.

Laboratories can perform the tests on already tested road trips or a new road trip can be designed with the support of JRC. Please confirm if you already have your own preferred test road trips.

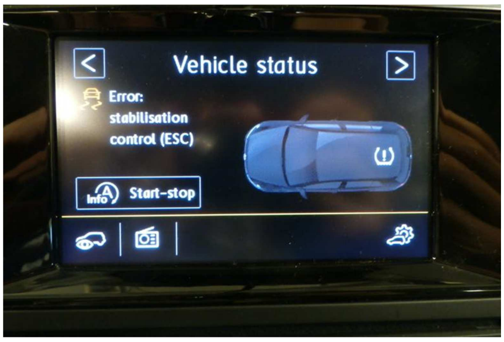
PEMS shall be warmed up while connected to the power grid, in order to allow for the maximum duration of the battery during the road tests.

Vehicle setup

Press the button on the left side of the gear lever to deactivate the Start/Stop system.

Procedure to deactivate ESP:

Click the option button  in the bottom right corner of the front panel



Click on Activated and set ASR off.

Annex 2. Compliance certificate of the reference fuel

TOTAL ADDITIFS ET CARBURANTS SPECIAUX
Place du Bassin - 69700 Givors- France
Tél: +33 4 72 49 84 10 - Fax: +33 4 72 49 84 20

DESIGNATION : CEC RF-02-08 E5		Analysis : 28618
	Batch : PCZ030081G	Date : 03/06/15
COMPLIANCE CERTIFICATE ☒		BULLETIN OF ANALYSIS ☐

UNLEADED GASOLINE	SPECIFICATIONS	UNITS	RESULTS	METHODS
PHYSICAL DATA				
Density 15 °C	743.0 - 756.0	kg/m3	752,7	NF EN ISO 12185
Reid Vapour Pressure	560 - 600	mbar	571	EN ISO 13016-01
DISTILLATION				
IBP		°C	35.1	EN-ISO 3405
5 % Vol		°C	49.0	EN-ISO 3405
10 % Vol		°C	52.4	EN-ISO 3405
20 % Vol		°C	57.2	EN-ISO 3405
30 % Vol		°C	63.6	EN-ISO 3405
40 % Vol		°C	82.7	EN-ISO 3405
50 % Vol		°C	96.9	EN-ISO 3405
60 % Vol		°C	105.8	EN-ISO 3405
70 % Vol		°C	114.3	EN-ISO 3405
80 % Vol		°C	129.2	EN-ISO 3405
90 % Vol		°C	174.7	EN-ISO 3405
95 % Vol		°C	181.2	EN-ISO 3405
FBP	190.0 - 210.0	°C	192,7	EN-ISO 3405
Residue	2.0 maxi	%v/v	0,5	EN-ISO 3405
Losses		%Vol	0.2	EN-ISO 3405
E 70 °C	24.0 - 44.0	%v/v	33,6	EN-ISO 3405
E 100 °C	48.0 - 60.0	%v/v	52,8	EN-ISO 3405
E 150 °C	82.0 - 90.0	%v/v	84,7	EN-ISO 3405
E 180 °C		%Vol	94.3	EN-ISO 3405
COMPOSITION				
Saturates	Report	%Vol	56.7	ASTM D 1319
Ethanol content	4.7 - 5.3	%v/v	5,0	EN 13132
Olefins	3.0 - 13.0	%Vol	6,6	ASTM D 1319
Aromatics	29.0 - 35.0	%Vol	31,7	ASTM D 1319
Benzene	1.0 maxi	%Vol	<0,1	EN 12177:98
OCTANE NUMBER				
RON	95.0 mini	index	96,8	ISO 5164 = JIS K2280 = ASTM D 2699
MON	85.0 mini	index	86,6	ISO 5163 = JIS K2280 = ASTM D2700
COMBUSTION				
Lower Calorific Value		kcal/kg	10080	GC-calculated
Lower Calorific Value		MJ/kg	42.365	ASTM D240
Lower Calorific Value	Report	kcal/kg	10227,38	ASTM D 3338
C/H ratio		ua	6.395	GC / Calculated
%C, %H, %O	Report	%Mass	84.9/13.3/1.8	GC / Calculated
0/C ratio		ua	0.022	GC / Calculated
COMPLEMENTARY DATA				
Sulfur content	10.0 maxi	mg/kg	3,0	EN ISO 20846 / EN ISO 20847 / EN ISO 20884
Oxidation Stability	480 mini	minutes	>528	ISO 7536
Copper Strip Corrosion at 50 °C	1 maxi	merit	1a	ISO 2160 = ASTM D130
Phosphorus content	1.3 maxi	mg/l	<0,2	ASTM D 3231
Unwashed Gums		mg/100ml	4	ISO 6246 / ASTM D381
Existent Gum	4 maxi	mg/100ml	2	ISO 6246
Lead content	5.0 maxi	mg/l	<5,0	EN 237-96
Water content	0.015 maxi	%Vol	<0,015	ASTM E 1064
Appeareance		couleur	Clear and bright	
Manganese Content		mg/l	<0.25	ASTM D 3831
Silicium Content		mg/kg	<0,10	ICP / AES
OXYGENATES				
Methanol content		%Vol	<0.17	ASTM D 4815
MTBE content		%Vol	<0.17	ASTM D4815
ETBE content		%Vol	<0.17	ASTM D4815
Others oxygenates components content		%Vol	<0.17	EN 1601:1997
Oxygen content	Report	%m/m	1,84	EN 1601:1997

Notes : Ne doit pas contenir d'additifs détergents et dispersants. / Detergents and dispersants additives must not be added

Givors, le 04/06/15 Tommy VERNAY		Confidential Document. External distrubution under agreement of RM/SPE/ACS The interpretation of results meets NF EN ISO 4259 Norm

Date specs : 04/06/12 Rév: 4

02/10/15

Annex 3. RDE tests characteristics

Test ID		Lab 1 Road 01	Lab 1 Road 02	Lab 1 Road 03	Lab 2 Road 01	Lab 2 Road 02	Lab 2 Road 03	Lab 3 Road 01	Lab 3 Road 02	Lab 3 Road 03	Lab 3 Road 04
TRIP CHARACTERISTICS		VALID	VALID	VALID	VALID	VALID	**INVALID**	**INVALID**	VALID	VALID	VALID
Total trip distance	km	78.18	83.44	79.18	74.50	74.60	72.55	87.60	76.61	76.84	76.78
Total trip duration	min. [90-120]	95	100	96	94	95	**87**	**130**	98	101	102
Urban distance	km [>16]	28.83	30.35	28.01	26.43	27.75	25.99	32.80	28.88	27.21	28.29
Rural distance	km [>16]	26.32	27.12	26.40	23.40	23.25	26.54	29.29	26.17	23.11	24.65
Motorway distance	km [>16]	23.02	25.96	24.76	24.66	23.60	20.02	25.50	21.56	26.52	23.84
Urban distance share	% [29-44]	36.88	36.38	35.38	35.48	37.20	35.82	37.45	37.69	35.41	36.85
Rural distance share	% [23-43]	33.67	32.50	33.35	31.42	31.17	36.58	33.44	34.16	30.07	32.11
Motorway distance share	% [23-43]	29.45	31.12	31.27	33.10	31.63	27.60	29.11	28.15	34.51	31.05
Urban average speed	km/h [15-40]	27.73	27.83	27.32	26.14	26.86	28.65	20.99	26.61	23.63	24.89
Rural average speed	km/h	75.50	76.88	74.14	75.09	73.10	76.87	76.75	75.06	76.03	74.13
Motorway average speed	km/h	113.68	113.15	113.56	104.07	105.00	104.61	115.47	109.96	116.00	107.13
Total trip average speed	km/h	49.13	49.87	49.50	47.76	47.34	50.25	40.45	47.01	45.63	45.38
Motorway speed above 145 km/h	% [<3% mot. time]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Motorway speed above 100 km/h	min [>=5]	9.73	10.13	10.30	8.93	8.28	6.95	12.18	10.10	12.85	10.38
Urban stop time	% [6-30]	27.00	25.08	24.05	23.54	21.91	20.00	**31.05**	15.59	24.54	21.38
Start and end elevation difference	m [<=100m]	40.80	39.80	52.00	59.60	15.90	4.40	25.50	6.00	8.40	2.10
Cumulative positive elevation gain	m/100km [<1200m]	636.29	603.92	661.33	447.84	442.69	463.94	822.22	910.34	886.81	904.83
MAW RESULTS		VALID	VALID	VALID	VALID	VALID	VALID	VALID	VALID	VALID	VALID
Total number of windows	-	3817	4087	3816	3796	3903	3430	4869	3928	3673	4016
Number of urban windows	-	1253	1348	1090	1051	1170	946	2522	1713	1486	1815
Number of rural windows	-	1705	1682	1978	1948	1882	1741	1500	1256	1214	1173
Number of motorway windows	-	859	1057	748	797	851	743	847	959	973	1028
Share of urban windows	% [>15]	32.83	32.98	28.56	27.69	29.98	27.58	51.80	43.61	40.46	45.19
Number of rural windows	% [>15]	44.67	41.15	51.83	51.32	48.22	50.76	30.81	31.98	33.05	29.21
Number of motorway windows	% [>15]	22.50	25.86	19.60	21.00	21.80	21.66	17.40	24.41	26.49	25.60
Share of normal urban windows	% [>50]	100.00	100.00	92.39	94.67	87.26	100.00	85.65	100.00	100.00	100.00
Number of normal rural windows	% [>50]	84.52	78.66	55.31	92.40	99.15	100.00	87.27	90.84	93.82	93.69
Number of normal motorway win.	% [>50]	80.44	85.53	77.14	76.79	94.95	77.39	95.99	100.00	94.66	100.00
Urban severity index	%	4.90	4.43	9.55	17.94	21.15	8.73	13.83	3.47	8.18	-2.19
Rural severity index	%	17.37	18.93	29.28	7.57	3.75	5.61	6.71	8.40	5.34	3.18
Motorway severity index	%	10.63	8.08	16.49	-18.70	-12.85	-17.07	12.07	8.33	2.91	1.56
OVERALL TRIP DYNAMICS		VALID	VALID	VALID	VALID	VALID	VALID	VALID	VALID	VALID	VALID
Urban RPA	m/s2	0.20	0.22	0.24	0.17	0.16	0.16	0.18	0.15	0.19	0.14
Rural RPA	m/s2	0.12	0.14	0.13	0.10	0.08	0.09	0.09	0.10	0.10	0.08
Motorway RPA	m/s2	0.10	0.09	0.10	0.03	0.03	0.05	0.12	0.13	0.10	0.09
Urban 95th percentile Speed*Acc	m2/s3	14.59	14.63	14.80	11.83	10.97	11.45	9.93	9.78	10.62	8.95
Rural 95th percentile Speed*Acc	m2/s3	21.36	22.21	19.50	17.09	15.16	15.71	16.59	18.86	21.02	14.40
Motorway 95th percentile Speed*Acc	m2/s3	20.55	18.34	20.15	11.41	16.00	15.25	19.96	20.75	26.36	14.93

Test ID		Lab 4 Road 01	Lab 4 Road 02	Lab 4 Road 03	Lab 5 Road 01	Lab 5 Road 02	Lab 5 Road 03	Lab 5 Road 04	Lab 6 Road 01	Lab 6 Road 02	Lab 6 Road 03
TRIP CHARACTERISTICS		VALID	VALID	VALID	VALID	VALID	**INVALID**	VALID	**INVALID**	VALID	VALID
Total trip distance	km	87.37	87.45	91.07	82.30	82.22	82.65	82.46	116.20	93.53	93.48
Total trip duration	min. [90-120]	110	104	117	102	110	105	111	**136**	112	112
Urban distance	km [>16]	31.35	29.38	33.91	33.07	31.74	36.86	34.67	33.52	32.79	35.80
Rural distance	km [>16]	28.73	30.05	29.48	26.12	26.19	24.61	28.62	41.21	26.96	25.78
Motorway distance	km [>16]	27.29	28.02	27.69	23.10	24.29	21.18	19.17	41.48	33.77	31.90
Urban distance share	% [29-44]	35.88	33.59	37.23	40.18	38.61	**44.60**	42.04	**28.84**	35.06	38.30
Rural distance share	% [23-43]	32.88	34.37	32.37	31.74	31.86	29.77	34.71	35.46	28.83	27.58
Motorway distance share	% [23-43]	31.24	32.04	30.40	28.07	29.54	25.63	23.25	35.69	36.11	34.12
Urban average speed	km/h [15-40]	25.95	26.90	25.72	29.29	25.34	30.08	26.93	25.33	28.03	29.54
Rural average speed	km/h	74.30	74.72	74.99	71.74	72.58	72.73	73.49	74.43	70.55	72.05
Motorway average speed	km/h	111.27	115.16	117.81	112.54	108.60	109.09	106.18	105.60	106.10	105.93
Total trip average speed	km/h	47.49	50.33	46.78	48.45	44.76	47.01	44.40	51.20	50.01	49.96
Motorway speed above 145 km/h	% [<3% mot. time]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Motorway speed above 100 km/h	min [>=5]	10.98	12.48	13.47	9.32	8.45	6.92	6.53	18.63	18.48	15.78
Urban stop time	% [6-30]	25.27	22.49	24.37	17.34	21.31	10.72	14.85	27.44	17.45	13.70
Start and end elevation difference	m [<=100m]	5.90	9.00	22.80	35.00	38.90	22.90	35.00	43.90	54.10	96.30
Cumulative positive elevation gain	m/100km [<1200m]	287.84	299.30	462.72	951.08	945.08	951.73	929.35	362.75	348.46	397.45
MAW RESULTS		VALID	VALID	VALID	**INVALID**	**INVALID**	**INVALID**	**INVALID**	VALID	VALID	VALID
Total number of windows	-	4141	4141	4707	4284	4667	4623	4775	5683	4755	4873
Number of urban windows	-	910	1069	1657	1069	1429	1322	1773	1634	1744	1828
Number of rural windows	-	2161	2005	1964	2579	2600	2872	2443	2391	1904	1914
Number of motorway windows	-	1070	1067	1086	636	638	429	559	1658	1107	1131
Share of urban windows	% [>15]	21.98	25.82	35.20	24.95	30.62	28.60	37.13	28.75	36.68	37.51
Number of rural windows	% [>15]	52.19	48.42	41.73	60.20	55.71	62.12	51.16	42.07	40.04	39.28
Number of motorway windows	% [>15]	25.84	25.77	23.07	**14.85**	**13.67**	**9.28**	**11.71**	29.17	23.28	23.21
Share of normal urban windows	% [>50]	100.00	100.00	100.00	99.25	87.68	95.01	79.81	100.00	100.00	100.00
Number of normal rural windows	% [>50]	100.00	99.80	85.95	**44.20**	**40.46**	51.18	**40.65**	96.74	98.90	96.97
Number of normal motorway win.	% [>50]	100.00	100.00	98.25	90.41	86.68	91.14	100.00	100.00	100.00	100.00
Urban severity index	%	0.95	4.38	7.79	8.70	23.44	13.80	19.34	6.39	5.15	3.63
Rural severity index	%	2.11	6.11	7.65	27.83	32.73	27.98	29.38	3.54	2.21	4.02
Motorway severity index	%	-11.83	-10.67	-12.22	-9.77	-9.12	-15.26	-10.48	-8.91	-9.60	-4.85
OVERALL TRIP DYNAMICS		VALID	VALID	VALID	VALID	VALID	VALID	VALID	VALID	**INVALID**	VALID
Urban RPA	m/s2	0.17	0.18	0.18	0.17	0.20	0.19	0.19	0.22	0.19	0.17
Rural RPA	m/s2	0.09	0.09	0.09	0.11	0.13	0.14	0.13	0.06	**0.05**	0.06
Motorway RPA	m/s2	0.08	0.08	0.07	0.07	0.07	0.07	0.09	0.03	**0.02**	0.04
Urban 95th percentile Speed*Acc	m2/s3	10.45	9.99	9.73	13.82	15.28	14.97	13.30	13.44	11.33	10.12
Rural 95th percentile Speed*Acc	m2/s3	16.76	15.54	14.43	19.44	20.04	21.75	19.39	16.51	14.26	14.71
Motorway 95th percentile Speed*Acc	m2/s3	18.31	17.47	18.42	19.72	19.28	18.98	19.07	15.28	14.32	12.24

Test ID		**Lab 7 Road 01**	**Lab 7 Road 02**	**Lab 7 Road 03**	**Lab 7 Road 04**	**Lab 7 Road 05**	**Lab 1 Road 04**	**Lab 1 Road 05**	**Lab 1 Road 06**	**Lab 1 Road 07**	**Lab 1 Road 08**	**Lab 1 Road 09**
TRIP CHARACTERISTICS		VALID	**INVALID**	VALID	**INVALID**	**INVALID**	VALID	**INVALID**	**INVALID**	VALID	VALID	**INVALID**
Total trip distance	km	83.74	80.19	83.74	83.01	81.58	92.72	93.67	92.77	89.67	93.12	95.44
Total trip duration	min. [90-120]	110	103	105	107	**121**	118	**121**	**124**	105	108	**122**
Urban distance	km [>16]	30.36	26.07	28.69	27.46	28.63	39.10	36.91	36.74	32.28	35.75	35.77
Rural distance	km [>16]	24.26	24.83	26.61	28.88	26.29	28.35	31.92	30.92	29.39	25.02	25.79
Motorway distance	km [>16]	29.11	29.29	28.45	26.68	26.66	25.27	24.83	25.11	28.00	32.35	33.88
Urban distance share	% [29-44]	36.26	32.51	34.26	33.07	35.10	42.17	39.41	39.61	36.00	38.39	37.48
Rural distance share	% [23-43]	28.97	30.96	31.77	34.79	32.23	30.57	34.08	33.33	32.78	26.87	27.02
Motorway distance share	% [23-43]	34.77	36.53	33.97	32.14	32.68	27.25	26.51	27.07	31.23	34.74	35.50
Urban average speed	km/h [15-40]	24.69	23.70	25.76	23.90	20.23	28.56	26.74	25.63	28.77	30.21	25.27
Rural average speed	km/h	75.75	75.57	75.60	76.00	74.52	76.28	75.51	74.81	77.23	74.31	75.66
Motorway average speed	km/h	102.15	101.69	102.41	103.27	103.98	112.45	116.24	112.85	112.26	118.71	121.01
Total trip average speed	km/h	45.63	46.72	48.04	46.45	40.30	47.17	46.45	44.82	51.18	51.95	46.87
Motorway speed above 145 km/h	% [<3% mot. time]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.56	0.00	0.00
Motorway speed above 100 km/h	min [>=5]	9.93	9.72	9.73	9.85	11.15	10.45	10.90	10.53	10.88	13.70	14.52
Urban stop time	% [6-30]	27.21	**31.57**	25.09	**30.73**	**36.34**	22.40	26.32	27.64	25.33	20.70	27.61
Start and end elevation difference	m [<=100m]	3.70	11.80	15.60	21.50	35.10	17.90	19.80	11.90	56.30	58.00	33.30
Cumulative positive elevation gain	m/100km [<1200m]	801.52	805.98	862.31	815.87	763.76	649.98	636.22	640.22	807.08	835.38	730.39
MAW RESULTS		VALID	VALID	VALID	VALID	VALID	**INVALID**	**INVALID**	**INVALID**	**INVALID**	VALID	VALID
Total number of windows	-	4338	3848	4196	4035	4475	4920	4964	5033	4148	4635	4635
Number of urban windows	-	1138	1123	1180	896	1287	1332	1653	1460	1007	1734	1813
Number of rural windows	-	1985	1401	1809	1818	2104	2602	2297	2565	2109	1983	1810
Number of motorway windows	-	1215	1324	1207	1321	1084	986	1014	1008	1032	918	1012
Share of urban windows	% [>15]	26.23	29.18	28.12	22.21	28.76	27.07	33.30	29.01	24.28	37.41	39.12
Number of rural windows	% [>15]	45.76	36.41	43.11	45.06	47.02	52.89	46.27	50.96	50.84	42.78	39.05
Number of motorway windows	% [>15]	28.01	34.41	28.77	32.74	24.22	20.04	20.43	20.03	24.88	19.81	21.83
Share of normal urban windows	% [>50]	100.00	100.00	100.00	100.00	100.00	**100.00**	**95.64**	**100.00**	**87.39**	72.66	61.94
Number of normal rural windows	% [>50]	100.00	86.72	98.34	90.81	88.97	**41.93**	**47.98**	**48.50**	**8.87**	78.11	52.87
Number of normal motorway win.	% [>50]	100.00	96.53	95.86	97.20	90.41	78.40	77.51	79.66	68.41	73.09	75.49
Urban severity index	%	7.16	5.83	4.91	8.04	8.50	13.84	13.33	18.59	20.18	7.01	22.68
Rural severity index	%	-5.31	-5.99	-11.07	-4.76	-1.39	32.93	32.45	32.02	42.25	17.00	29.10
Motorway severity index	%	-1.90	-4.31	-3.71	-5.43	-1.55	17.29	17.40	16.20	25.57	13.09	13.69
OVERALL TRIP DYNAMICS		VALID	VALID	VALID	VALID	VALID	VALID	VALID	VALID	**INVALID**	VALID	VALID
Urban RPA	m/s2	0.19	0.21	0.18	0.19	0.20	0.20	0.22	0.22	0.24	0.19	0.21
Rural RPA	m/s2	0.08	0.07	0.07	0.08	0.10	0.14	0.13	0.13	0.17	0.11	0.13
Motorway RPA	m/s2	0.04	0.03	0.03	0.04	0.04	0.08	0.10	0.08	0.14	0.10	0.08
Urban 95th percentile Speed*Acc	m2/s3	12.02	12.84	11.45	12.10	11.79	13.32	13.63	14.57	**19.41**	11.02	12.72
Rural 95th percentile Speed*Acc	m2/s3	21.23	13.88	13.50	19.90	15.40	19.52	20.50	19.02	**27.24**	15.63	17.44
Motorway 95th percentile Speed*Acc	m2/s3	18.43	15.29	16.16	15.36	15.37	19.97	22.90	18.73	26.27	24.04	17.72

Annex 4. Additional tests

Additional dynamometer and RDE tests have been performed in May 2016 at the Berner Fachhochschule. The tests have been performed on the same Golden Vehicle with the same reference fuel but with different Gas-PEMS and PN-PEMS systems to the one used for the ILCE. Moreover no PMP Tailpipe measurement was available for these tests.

The Gas-PEMS used was a Semtech DS (Sensors Inc.) and the PN-PEMS was a NanoMet3 provided by the Berner Fachhochschule.

Figure 52 show the comparison between the distance specific PN emissions measured at the Berner Fachhochschule with the average emissions measured during the ILCE with the PMP CVS.

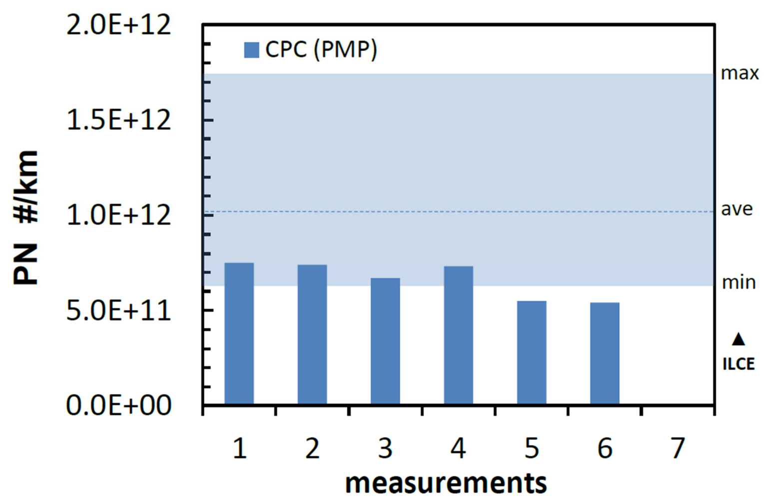


Figure 52 Distance specific PN emissions measured during the 7 WLTC dynamometer tests at the Berner Fachhochschule with the PMP CVS (blue bars). The blue dashed line indicate the average value of the PMP CVS results during the ILCE, blue bands indicate the maximum and minimum ILCE values.

Figure 53 shows the comparison of the distance specific PN emissions measured during 7 WLTC, 2 NEDC and 3 RDE tests performed at the Berner Fachhochschule with NanoMet3.

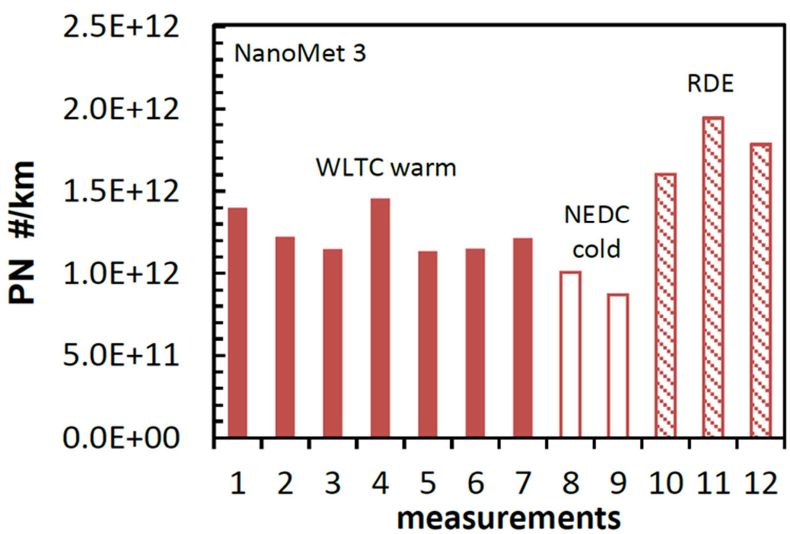


Figure 53 Comparison of the distance specific PN emissions at the Berner Fachhochschule with NanoMet3.

LD-NA-28136-EN-N

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doi:10.2790/562

ISBN 978-92-79-62296-0