

## JRC SCIENCE FOR POLICY REPORT

# Particle Number (PN) - Portable Emissions Systems (PEMS)

*Heavy Duty Vehicles  
Evaluation phase at the  
Joint Research Centre  
(JRC)*

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**Title** Particle Number (PN) - Portable Emissions Measurement Systems (PEMS): Heavy Duty Vehicles Evaluation phase at the Joint Research Centre (JRC)

#### Abstract

JRC evaluated the feasibility of using PN-PEMS systems for Heavy Duty Vehicles (HDV) applications. The main evaluation phase took place between February and June 2016. One Compressed Natural Gas (CNG) vehicle and three vehicles equipped Diesel Particulate Filters (DPF) and Selective Catalytic NOx Reduction (SCR) were tested. The key conclusion of the evaluation phase is that PN-PEMS testing for HDV is feasible. However, low ambient temperatures were challenging for the instruments regarding their robustness. Re-testing of the commercial instruments in September with a DPF and SCR equipped vehicle showed that most of the issues were resolved. The PN-PEMS instruments measurement uncertainty is around 30% at the moment. Similar uncertainty (35%) was found when comparing the best performing system with the reference system at the dilution tunnel (CVS); i.e. PEMS method uncertainty.

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## **Executive summary**

### **Policy context**

New emission standards (Euro VI) were introduced in Europe in 2013 for heavy-duty engines. Euro VI legislation includes a Portable Emissions Measurement System (PEMS) based test at type approval, followed by an on-road in-service conformity (ISC) test of the heavy-duty vehicle (HDV), which is devised as a measure to verify the emissions of the vehicle through its useful life. The gaseous pollutants NO<sub>x</sub>, HC and CO are assessed with PEMS. For many years Particulate Matter (PM) PEMS testing was evaluated (i.e. collecting mass onto a paper filter), but due to its inadequate sensitivity and resulting low benefit vs. envisaged costs, there were many concerns for its introduction into the regulation. In September 2015 it was decided to evaluate the (PN) method (i.e. real time counting of the number of solid particles) for ISC. In the beginning of 2016, the Commission adopted a new Regulation introducing measurement of Particle Number (PN) during the type-approval assessment as from September 2018.

The kick-off meeting for the PN-PEMS for Heavy Duty Vehicles Pilot Study was held in Ispra (Italy) on the 22<sup>nd</sup> of October 2015. After the kick-off meeting, DG-GROW requested JRC to conduct a feasibility study of using PN-PEMS for HDV (AA 2016). Although JRC did already in 2014 and 2015 the feasibility study of PN-PEMS for light-duty vehicles (Riccobono et al. 2014, Giechaskiel et al. 2014, 2015a), for HDV wider conditions had to be examined (e.g. CNG vehicles, -7°C to +35°C, regenerations etc.). JRC evaluated four PN-PEMS instruments (based on the light-duty specifications) in the lab and on the road from February until June 2016 (main evaluation phase). In September 2016 five commercial instruments were further evaluated (second evaluation phase). The second evaluation phase was conducted in order to check the improvements of the systems for the exhaust of heavy-duty vehicles. ACEA provided some of the vehicles tested. Instrument manufacturers provided the PN-PEMS which were based on the draft technical specifications of the light-duty RDE regulation (to be voted as a 3<sup>rd</sup> package until at end of 2016).

This report summarizes the findings of the JRC evaluation, which are useful not only for the HDV regulation but also for the upcoming light-duty vehicles RDE regulation regarding robustness at low and high ambient temperatures and regeneration events.

### **Key conclusions**

The key conclusion of the evaluation phase is that available PN-PEMS are technically robust (e.g. for regenerations, urea particles) and testing with the equipment is feasible for HDV. However, low ambient temperatures were challenging for the instruments regarding their robustness. Re-testing of the commercial instruments showed that for most of the instrument most of the issues were resolved. The PN-PEMS instruments measurement uncertainty is around ±30% (at the emission levels of 6x10<sup>11</sup> p/kWh), and is in-line with the theoretically expected from the technical specifications of the instruments. Slightly higher uncertainty (±35%) was found by comparing the best performing instruments with the reference system at the full dilution tunnel (CVS). This reflects the PN-PEMS procedure uncertainty, which includes the PN-PEMS instrument uncertainty).

### **Quick guide / Experimental**

Tests were conducted at the facilities of JRC (VELA 7). Six of the vehicles tested were trucks (one of category N2 and five N3) equipped with the latest technology of aftertreatment devices like Diesel Particulate filters (DPF) and Selective Catalyst

Reduction of NO<sub>x</sub> (SCR). One vehicle was garbage collector with a CNG (Compressed Natural Gas) engine. All vehicles tested were Euro VI certified. The test cycles consisted of cycles similar to the type approval cycles, but also long cycles similar to those conducted during the In-Service Conformity (ISC). Different load steady state points for the validation of CO<sub>2</sub> predicted by VECTO were also tested.

The PN-PEMS were sampling from the tailpipe. The climatic room was adjusted at temperatures between -7°C and +35°C. All CO<sub>2</sub> related tests were conducted at 20°C. The exhaust gas was connected to the full dilution tunnel where the reference PN system was measuring (as in the HDV regulation) (always at 20°C). In addition a reference PN system was connected to the tailpipe to investigate the uncertainties introduced by the sampling location. However, the PN system at the tailpipe was close to the dilution tunnel thus pressure pulsations, thermophoretic and diffusion losses, agglomeration effects etc. had probably a small effect at this system than at the PN-PEMS. This instrument was always at 20°C in order to exclude any temperature effects.

From the four PN-PEMS that were tested at the main evaluation phase, three had a particle detector based on the Diffusion Charging (DC) principle and one on the Condensation Particle Counter (CPC) as in the reference systems. In the final evaluation phase three DC and two CPC based instruments were tested.

The differences between PN-PEMS and the reference PN system at the tailpipe give the measurement uncertainty of the PN-PEMS. The difference between the two reference PN systems gives in a degree the uncertainty of the location (i.e. EFM uncertainty, time misalignment, particle losses etc.). Comparison of the PN-PEMS with the reference system at the dilution tunnel gives the uncertainty of the PN-PEMS procedure.

## **Main findings**

The findings of the main evaluation phase are:

- The (integrated) emission levels of the lab ISC cycles and on-road tests of the DPF equipped vehicles were  $<6 \times 10^{11}$  p/kWh (the current Euro VI limit) measured with the reference system at the dilution tunnel (PMP\_CVS). Higher emissions were observed only during some of the high load cycles, where passive regeneration occurred, and during some cold start cycles after regeneration.
- For two vehicles that were tested for a period of  $>1$  month, for each of them the 'mean' emissions were  $5.3 \times 10^{11}$  p/kWh and  $2.6 \times 10^{11}$  p/kWh.
- The two PN reference systems; one connected to the dilution tunnel with Constant Volume Sampling (CVS) as required by the legislation and the other at the tailpipe, had differences within  $\pm 15\%$ . The small difference between the two reference systems at different sampling locations indicated that the measured emissions were most probably accurate enough. Calibration uncertainties could further increase this value by another 10% for other cases. The system at the tailpipe was considered the basis of comparisons in order to evaluate mainly the measurement uncertainty of the instruments and not uncertainties of the exhaust flow meter or the time misalignment.
- The PN system at the tailpipe was close to the dilution tunnel thus pressure pulsation, thermophoretic and diffusion losses, agglomeration effects etc. had probably a small effect. Installation of the PN system directly at the tailpipe of the heavy-duty vehicles could result in higher emissions compared to the system at the dilution tunnel.
- The fraction of sub-23 nm particles of the DPF equipped vehicles was low ( $<10\%$ ) for integrated emission levels  $>3 \times 10^{11}$  p/kWh. For lower emission levels it was higher: the most possible explanation is formation of small nanoparticles from the injected urea. There were also indications that some of the difference was due to lower detection efficiency of these particles of the 23 nm CPC (Condensation Particle Counter) of the reference system. In absolute levels the emissions even

considering these sub-23 nm particles remained well below  $6 \times 10^{11}$  p/kWh. For the CNG engine the sub-23 nm fraction was 30-50% for the hot cycles and even higher (double) at cold start part of the cycles.

- The best performing instrument at temperatures  $>0^{\circ}\text{C}$  was a CPC (Condensation Particle Counter) based instrument. It had differences to the tailpipe reference system within 25%. The real time signals also matched very well with the reference system. The detection limit ( $<1 \times 10^9$  p/kWh) was comparable with the reference system and could easily measure the very low emissions of DPF equipped vehicles. It had no issues during regeneration events (both passive and active) and measured accurately. At low ambient temperatures it showed spikes and then stopped working. This system was not tested with the CNG vehicle.
- The best performing DC (Diffusion Charging) based instrument had differences on the order of 30% with the reference system. The real time signals matched quite well with the tailpipe reference system. The detection limit was around  $1 \times 10^{11}$  p/kWh. The system, which has specifications  $5\text{-}30^{\circ}\text{C}$ , had warnings and errors outside this temperature range (it also degraded fast when it was used at low ambient temperature).
- The other two DC based instruments had issues and the agreement with the reference systems was not satisfactory.

The findings of the second evaluation phase of the updated instrument with a DPF equipped vehicle are:

- The best performing instrument of the main evaluation phase (CPC based) was also the best performing instrument in the second phase. It had differences to the reference system within 15% (integrated results over a cycle). It also had excellent agreement of the real time signals with the tailpipe reference system. Again at low ambient temperatures showed artificial spikes.
- The second CPC-based system had an offset of 30% (measuring lower) compared to the tailpipe reference system (bias). The differences from the mean had small variability of 12% (precision, expressed as standard deviation of the differences).
- The best performing DC-based system of the first phase showed similar behaviour as in the first phase. The measurements above the limit agreed perfectly with the tailpipe reference system (differences within 10%). The measurements  $>1 \times 10^{11}$  p/kWh were around 50% higher than the reference system at the tailpipe. Although the system is specified for temperatures  $>5^{\circ}\text{C}$ , it could measure accurately and without warning also at  $0^{\circ}\text{C}$ . The  $-7^{\circ}\text{C}$  tests were also possible by putting the instrument in the cold room half an hour before the test (i.e. not leaving it overnight at  $-7^{\circ}\text{C}$ ).
- One of the DC-based systems that had issues in the main campaign had very good results in the second phase. The results were within 20% of the tailpipe reference instrument for emission levels  $>1 \times 10^{11}$  p/km. There were no issues for low or high ambient temperatures.
- One DC-based system didn't have good results also in the second phase. Calibration in the laboratory showed that this system was not compliant with the draft technical specifications. It is not clear why the real time signals matched quite well with the reference system but only after applying a correction factor.

### **Related and future JRC work**

Based on the results of the evaluation phase, OEMs can start gaining their own experience. Testing with cracked DPF, low ambient temperatures, biofuels etc is also highly recommended. JRC can support in this direction, especially the testing of CNG engines where more experience with PN-PEMS would be desirable.

What hasn't been investigated in this report is the sensitivity of the PN-PEMS to shocks, vibration, aging, variability in temperature and air pressure as well as electromagnetic

interferences and other impacts related to on-road vehicle and PN-PEMS operation. Dedicated tests should be conducted.

# 1 Introduction

New emission standards (Euro VI) were introduced in Europe in 2013 for heavy-duty vehicles (HDV). The Euro VI Regulation (EC) No 595/2009 and the implementing Regulation (EC) 582/2011 introduced a procedure for PEMS testing as a mandatory part of the type approval legislation in order to check the conformity of heavy-duty engines with the applicable emissions certification standards during the normal life of those engines: the so-called "In Service Conformity" (ISC) requirements. In addition, Euro VI engines also have to verify the off-cycle in-use emissions already at type approval (PEMS demonstration test). At the moment only the gaseous pollutants NO<sub>x</sub>, HC and CO are required with PEMS. No Particulate Matter (PM) requirement was introduced as there were no instruments that could measure PM in real time.

The PM-PEMS Evaluation Program was launched in 2008 by the European Commission to assess the potential of portable instruments to measure particulate emissions on-board of vehicles. The PM-PEMS program was a voluntary program, receiving contributions from the European Joint Research Centre (JRC), some portable emissions instrument manufacturers (AVL, Sensors Inc, Horiba) and the European association of heavy-duty engines manufacturers (ACEA).

The laboratory evaluation program at JRC identified and recommended the candidate principles for PM measurements: A filter holder for the measurement of the PM of the trip plus a real time sensor to 'convert' the PM to a second by second PM signal (Bonnell et al. 2010, Mamakos et al. 2011a, b, 2013).

To support the PM-PEMS Pilot Program, JRC conducted a Pre-Pilot Program with the collaboration of one of the ACEA's member, IVECO, and PM instrument manufacturers. The aim of this activity was to look into all the logistic necessary to mount both the gaseous and PM-PEMS equipment in a HDV, and to check for the system good functioning (Mendoza et al. 2015). The Pre-Pilot program was run at the JRC Vela 7 and on-road around the JRC Ispra site. One gaseous PEMS and four candidate PM-PEMS instruments were operated together on the same vehicle and the experience was shared with all the participants on the PM-PEMS Pilot program.

The second phase of the process was launched with the on-road measurement of PM with the updated instrumentation recommended in the validation program (PM-PEMS Pilot Program). This was a manufacturer-run with several members of ACEA and member states supplying test data from different locations with support of test equipment suppliers and JRC (Perujo & Mendoza 2015).

The main conclusions of the PM-PEMS Evaluation Program were that PM-PEMS measurement instruments are ready, the analysis can follow the procedure performed to analyse the gaseous pollutants, but concerns were raised for regeneration events and most importantly about the detection limit of the method and the resulting low benefit vs. envisaged costs (Perujo et al. 2015).

The (solid) Particle Number (PN) method due to its superior sensitivity was thought as an alternative already in 2009, although there were no available instruments at that time (Giechaskiel et al. 2011).

At the end of September 2015, in a HDV-PEMS meeting, it was decided to evaluate the Particle Number (PN) method. The kick-off meeting for the PN-PEMS for Heavy Duty Vehicles Pilot Study was held in Ispra (Italy) on the 22nd October 2015. This study was the outcome of discussions within the HDV-PEMS group and the opinion expressed by Member States to proceed fast with the validation in the Heavy Duty Vehicles of a PN-PEMS measurement and protocol. In the beginning of 2016, the Commission adopted a

new Regulation introducing measurement of Particle Number (PN) during the type-approval assessment as from September 2018.

The suggested overview of the study was:

### **Phase I (Months 1-2): Technical specifications**

Definition of draft technical specifications (based on the findings of the light-duty vehicles evaluation program). Agreement on test plan and availability of vehicles and instruments.

### **Phase II (Months 3-8): Evaluation at the JRC**

Experimental evaluation at the JRC both in the laboratory (HDV Chassis Dyno) and on the road. At least two PN-PEMS (based on condensation particle counter (CPC) and diffusion charger (DC) principles) should be measuring in parallel with the reference instruments at the tailpipe and the dilution tunnel.

The vehicles would be provided by ACEA and they should be at least one N2, one N3 and one M3 (all Euro VI). If more Euro 6 vehicles would be available they could be added and tested. The vehicles should be equipped with the most typical after-treatment devices, e.g. DPF, SCR. Regenerations should be possible to be triggered.

The ambient temperatures should cover at least 0°C to 35°C (with possible extension to lower temperatures). The test cycles should be type-approval equivalent, and ISC similar.

### **Phase III (Months 5-12): PN validation program**

Independent evaluation from participants (OEMs, MS) to the programme. A wide range of vehicles should be covered with special attention to CNG engines, dual fuel, hybrids etc. The ambient conditions should cover a wide range (0°C to 35°C, with possible extension to lower temperatures). Two PN-PEMS instruments measuring in parallel is obligatory.

After the kick-off meeting of the HDV PN-PEMS evaluation program at the end of October 2015, DG-GROW requested JRC to conduct the feasibility study of using PN-PEMS for HDVs (AA 2016). JRC did in 2014 and 2015 the feasibility study of PN-PEMS for light-duty vehicles (Riccobono et al. 2014, Giechaskiel et al. 2014, 2015a) and ran an inter-laboratory correlation exercise with two PN-PEMS (Riccobono et al. 2016). For HDV wider conditions (-7°C to +35°C, regenerations etc.) and different technologies than at the light-duty vehicles (e.g. CNG vehicles, DPF vs GDIs) had had to be examined. JRC evaluated some PN-PEMS instruments in the lab and on the road from February until June 2016. In September 2016 the updated instruments were tested. This phase was a transition between the JRC evaluation phase and the OEMs validation phase, because the OEM actively participated at the evaluation of the results. ACEA provided some of the vehicles tested. Instrument manufacturers provided the PN-PEMS which were based on the draft technical specifications of the light-duty RDE regulation (to be voted as a 3<sup>rd</sup> package at the end of 2016).

This report summarizes the findings of the JRC evaluation, which are useful not only for the HDV regulation but also for the upcoming light-duty vehicles RDE regulation regarding robustness at low and high ambient temperatures and regeneration events.

## 2 Experimental methods

Due to the urgency of the PN-PEMS project, it was combined with other projects. Table 1 summarizes the projects that were running in parallel and the tested vehicles. The vehicles included N2 and N3 trucks and a CNG garbage collector.

In this report only the PN-PEMS results will be discussed.

**Table 1: Overview of projects and tested vehicles (all Euro VI).**

No	Vehicle (approximate)	Period	<b>PN-PEMS</b>	PMP	Cold start	CO <sub>2</sub>
1	Truck N3, 13L, 340 kW	February	<b>Y</b>	Y	Y	Y
2	Garbage collector, CNG	March	<b>Y</b>	Y	N	N
3	Truck N3, 13L, 340 kW	Mid March	<b>Y</b>	Y	Y	Y
4	Truck N3, 8L, 240 kW	Mid April	<b>N</b>	Y	N	N
5	Truck N2, 5L, 180 kW	Mid May	<b>Y</b>	Y	Y	N
6	Truck N3, 8L, 240 kW	June	<b>Y</b>	Y	N	Y
7	Truck N3, 13L, 340 kW	End June	<b>N</b>	Y	N	Y
8	Truck N3, 13L, 340 kW	Mid September	<b>Y</b>	Y	Y	Y

### 2.1 VELA 7 facilities and setup

Chassis dyno measurements were performed at the Heavy Duty Chassis dynamometer of the Vehicle Emissions Laboratory (VELA 7) of the European Commission's Joint Research Centre (JRC). Figure 1 shows an overview of the VELA 7 facilities.

The two roller chassis dynamometer (Zoellner GmbH, Germany) has been designed to host even 4-wheel drive heavy-duty vehicles (trucks and buses) of up to 30 tons in weight, 12 m in length, and 5 m in height. Maximal test speed is set at 150 km/h. The test cell can be conditioned between -30°C and +50°C with relative humidity of 15-95% providing the ability to test vehicles under extreme conditions. The constant-volume sampler (CVS) for full exhaust dilution (AVL, Graz, Austria) is equipped with 4 Venturis of 10, 20, 40, and 80 m<sup>3</sup>/min in order to achieve a maximum air flow of 150 m<sup>3</sup>/min. Dilution air is taken from the test cell, conditioned to 22°C, and filtered through high-efficiency particulate air (HEPA) and activated charcoal filters. The climatic test cell of VELA 7 has an air circulation system that provides enough number of cell air changes ( $\geq 15$ ) in order to allow the testing of vehicles fueled with different types of fuels.

An AVL i60 AMA 4000 system was used for the analysis of gaseous emissions. A Heated Flame Ionization Detector (HFID) was employed for measuring exhaust gas concentrations of THC and CH<sub>4</sub>. A Heated Non-Dispersive Infrared sensor (NDIR) was used for CO<sub>2</sub> and CO emissions. A Heated ChemiLuminescence Detector (CLD) measured exhaust NO<sub>x</sub>. Pollutants were measured downstream of the exhaust aftertreatment system of the truck.

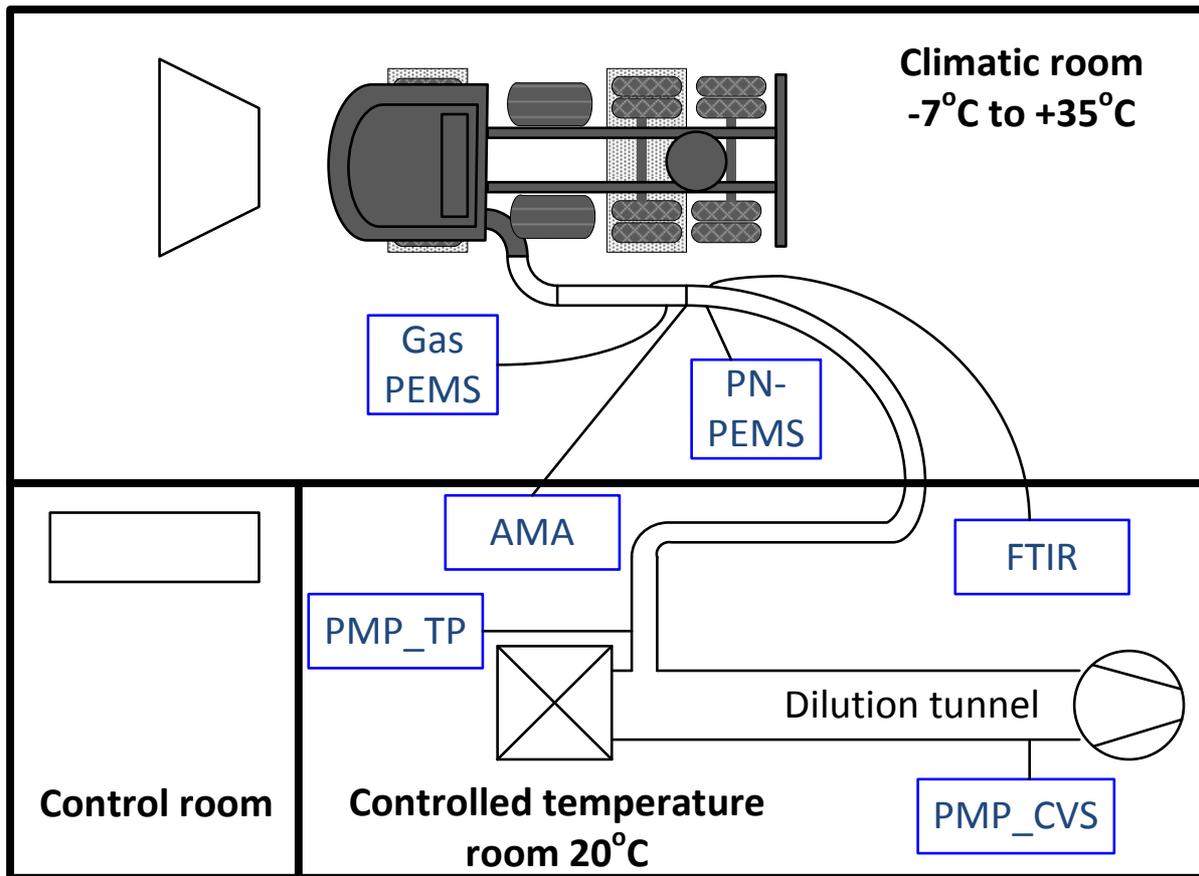


Figure 1: VELA 7 facilities.

The Gas-PEMS system used both in the lab and on-road was the Semtech-DS manufactured by Sensors, Inc. and it consisted of tailpipe attachment, heated exhaust lines, an exhaust flow meter (EFM) (4" or 5" depending on the vehicle tested, see Table 3), exhaust gas analyzers, data logger to vehicle network, a global positioning system (GPS), and a weather station for ambient temperature and humidity. All data was recorded at a frequency of 1 Hz and the whole system added further ~100 kg of instrumentation to the vehicle. A generator was used to produce current for the needs of the PEMS. The Semtech DS measured exhaust gas concentrations of unburned hydrocarbons (THC) by HFID, carbon monoxide (CO) and carbon dioxide (CO<sub>2</sub>) by a NDIR, and nitrogen monoxide (NO) and nitrogen dioxide (NO<sub>2</sub>) by a non-dispersive ultraviolet sensor (NDUV). The oxides of nitrogen (NO<sub>x</sub>) were calculated by the sum of the concentrations of NO and NO<sub>2</sub>. The measurement principles and accuracy from the Semtech DS were in-line to those described by current legislation for this type of testing. As a standard procedure, test runs preparation included routine calibration of pollutant analyzers (zero and span of gases).

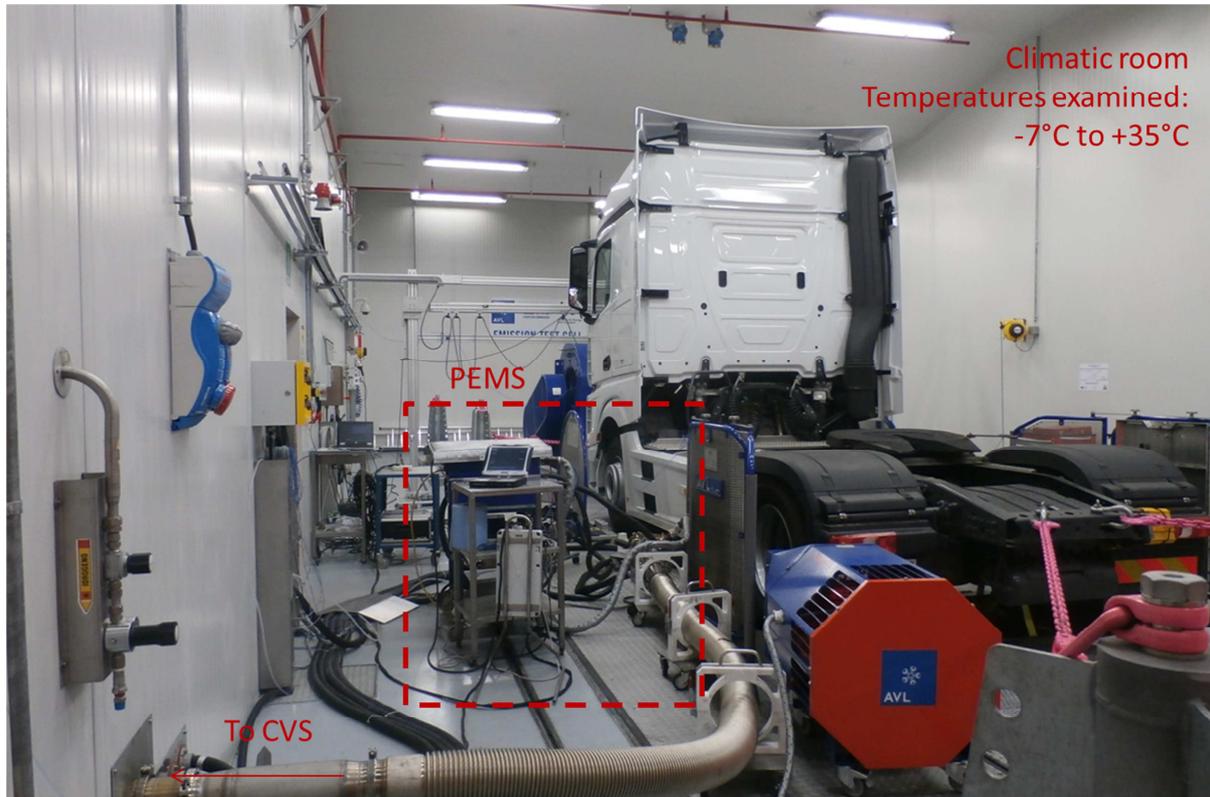
The AVL SESAM FTIR (Fourier Transform Infrared spectrometer) was used to monitor a selection of unregulated gaseous emission, including nitrogen species like nitric oxide (NO), nitrogen dioxide (NO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O), NH<sub>3</sub>, and oxygenated compounds like formaldehyde, acetaldehyde, and ethanol. The instrument created an infrared broadband spectrum that was used to detect the spectral information about the exhaust gas sample for all gas components simultaneously. The absorption spectrum (intensity/wavelength) was calculated from the measured interferograms (intensity/time) by means of the Fourier transformation.

The calculation of the engine work output over each sub-cycle was based on the instantaneous engine torque and rpm values which were recorded via the vehicle's OBD (On-Board-Diagnostics) system as well as on the nominal torque for each truck. A cross validation with the instantaneous work values retrieved from the chassis dyno system or a torquemeter installed either at the shaft or at the wheels was also performed and confirmed the accuracy of the calculation. The ratio of work/distance for the various cycles and vehicles can be seen in Table 2. With the exception of the SICO cycles the ratio was close to one. These ratios were used to convert p/km to p/kWh when no OBD (power) data existed.

**Table 2: Ratio of work to distance for various cycles and vehicles.**

kWh/km	V1	V2	V3	V4	V5	V6	V7
ISC	1.00	0.90	1.27	0.78	1.53		
WHVC	1.10		0.78		1.49	1.01	1.41
SICO	2.54		1.89	2.76			
On-road	1.10		1.17				

No gaseous pollutants results will be presented in this report, with a few exceptions where PN behavior is discussed.



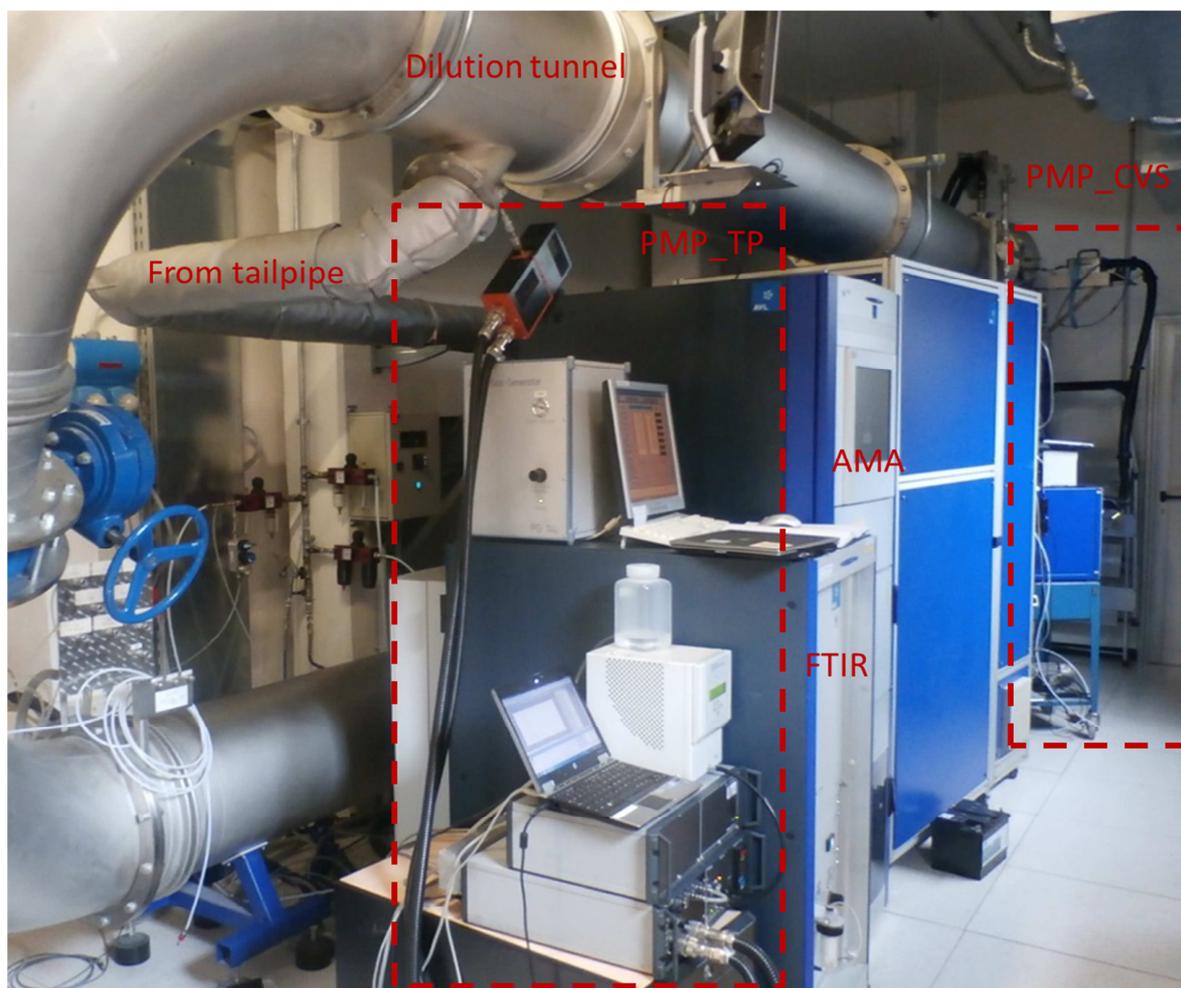
**Figure 2: Example of a vehicle and the PEMS in the climatic room.**

## 2.2 Reference PN systems

A PN measurement system compliant with the heavy duty engines (UN-ECE Reg. 49) regulations was used (AVL APC 489) at the dilution tunnel (Giechaskiel et al. 2010).

The Volatile Particle Remover (VPR) of the system consists of a hot dilution (HD) at 150 °C and an evaporation tube (ET) at 350 °C. The system was calibrated by the manufacturer and the dilution including the particle losses (as average of 30, 50 and 100 nm) is called Particle number Concentration Reduction Factor (PCRF). Typically, a primary PCRF of 25 and a secondary of 10 were used.

Downstream of the thermal pre-treatment system a TSI butanol CPC 3790 with 50% counting efficiency at 23 nm ( $d_{50\%}=23$  nm) is measuring. In parallel a TSI butanol CPC 3772 ( $d_{50\%}=10$  nm) is used in order to investigate the presence of particles <23 nm. Note that HD+ET with a CPC  $d_{50\%}=23$  nm is the protocol defined in the Particle Measurement Program (PMP) and used for the regulatory measurements. From now on this system will be mentioned as PMP\_CVS.



**Figure 3: Typical setup of the reference systems in the controlled temperature dilution tunnel room.**

The instrument used to measure (solid) PN emissions from the tailpipe was the Nanomet 1 from Testo which is compliant with UNECE Regulation 49. The instrument consists of a hot dilution at 150 °C, an evaporation tube at 350 °C, a secondary dilution at ambient temperature and a CPC (TSI 3790) with  $d_{50\%}=23$  nm. The Particle number Concentration

Reduction Factor (PCRF) chosen was approximately 720 (primary 180 and secondary 4), as given by the manufacturer. This value, which was used in the calculations for this report, is 10% higher than our measured PCRF in the lab with monodisperse aerosol of 30 nm, 50 nm and 100 nm soot particles. From now on this system will be mentioned as PMP\_TP. This system was not placed in the climatic chamber but was connected just before the mixing of the exhaust gas with the dilution air in the dilution tunnel room. This way it was always measuring at 20°C ambient temperature and thus unaffected by changes of the climatic room temperature. On the other hand, as this system was close to the dilution tunnel, pressure pulsation, thermophoretic and diffusion losses, agglomeration effects etc. had probably a small effect. Installation of the PN system directly at the tailpipe of the heavy-duty vehicles could result in higher emissions compared to the system at the dilution tunnel. Thus the differences between the two systems at tailpipe and dilution tunnel could be higher in other cases.

For our setup (9 m tubing in the climatic room plus 6 m insulated in the controlled temperature dilution tunnel room of 120mm) the mean residence time was 1 s for the HDV measured (mean flow rate around 7 m<sup>3</sup>/min) and thus the diffusion losses negligible. The thermophoretic losses should be <15% as the exhaust temperatures at 20°C ambient temperature were around 250°C. The agglomeration losses should also be negligible due to the low levels of the DPF equipped vehicles.

## 2.3 PN-PEMS

The PN-PEMS were connected to the tailpipe after the exhaust flow meter EFM (Figure 4).

PN-PEMS #1 (AVL) consists of a VPR and a DC (modified particle detector, Partector, from Naneos). The VPR is connected to the tailpipe with a short (0.9 m) heated line at 150°C. The VPR consists of a two stage dilution with an evaporation tube and a catalytic stripper in between (both set at 300°C). The primary dilution is 2:1, and the secondary 5:1 (3:1 in the second evaluation phase). For the upstream dilution the dilution air is heated at 150°C. The downstream dilution is performed with dilution air at 60°C, to minimize nucleation potential. The diluted sample is transferred to the DC in a 1.3 m heated line at 60°C. The sampling rate is 0.7 l/min. A sample probe heater at 100°C was added at the second evaluation phase (Figure 5).

PN-PEMS #2 (modified NPET, HORIBA) consists of a VPR and a CPC. The VPR consists of two cold dilution stages with a dilution ratio of 10:1 each and a heated catalytic stripper at 350°C in between. The first diluter utilizing dried dilution air is located directly at the sample probe followed by a 4 m heated line at 60°C that brings the diluted aerosol to the main cabinet. Downstream of the VPR an isopropyl alcohol-based CPC with  $d_{50\%}$  at 23 nm is used to detect the particles. The CPC is optimized for on-road measurements and has an environmental operating temperature ranging from -10°C to +40°C. At the second evaluation phase the commercial version OBS-ONE-PN was used.

PN-PEMS #3 (Nanomet 3-PS, Testo AG) consists of a VPR and a DC (Diffusion Size Classifier miniature, DiSC mini). The VPR consists of a heated sampling line at 100°C, a heated rotating disk diluter (primary and total PCRF used in this campaign around 30 as calibrated by the manufacturer), and an evaporation tube at 300°C. A unique characteristic of the device is that the DC has two electrometers and can estimate a mean particle size based on their ratio. The charged particles first flow through a diffusion stage. Some of the particles are captured in this stage and generate a current  $I_{diff}$ , while the remaining particles flow into a second stage that is equipped with a HEPA filter. Here, all particles are captured, and a current  $I_{filter}$  is measured with an electrometer. The ratio  $I_{filter}/I_{diff}$  is a measure of the average particle size, because smaller particles undergo larger Brownian motion, and are therefore more likely to be captured in the diffusion stage. The instrument gives particle number concentration based on the currents it measures and an estimated mean particle size.

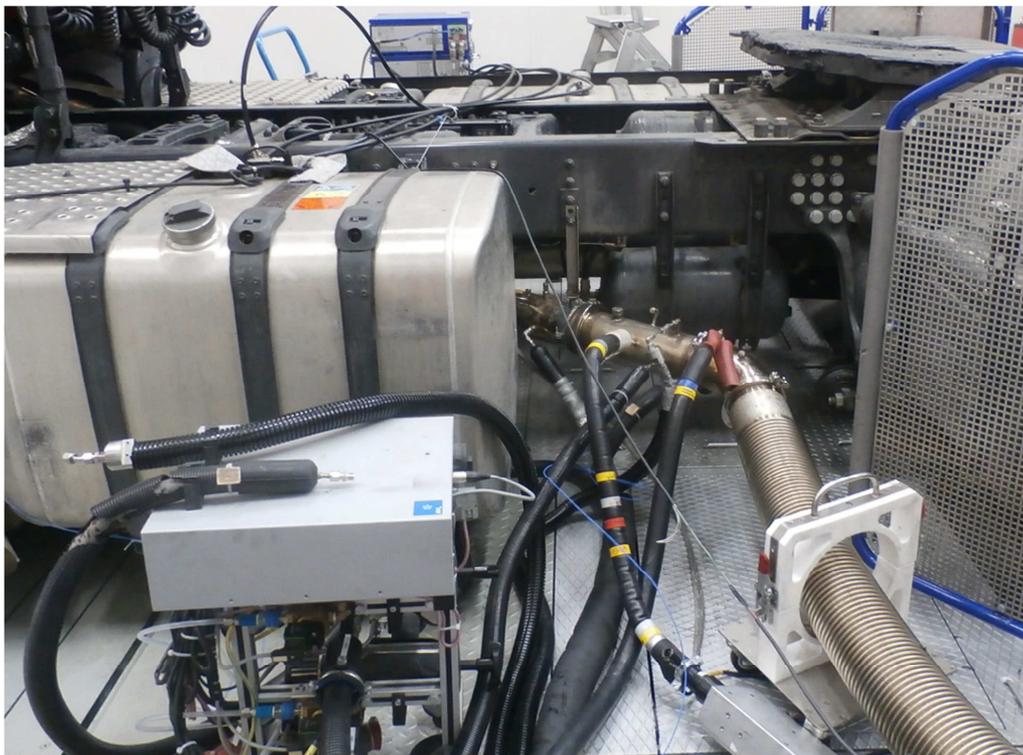
PN-PEMS #4 (PPS, Pegasor): No unit was delivered to JRC for the HDV campaign.

PN-PEMS #5 (Sensors): No unit was delivered to JRC for the HDV campaign.

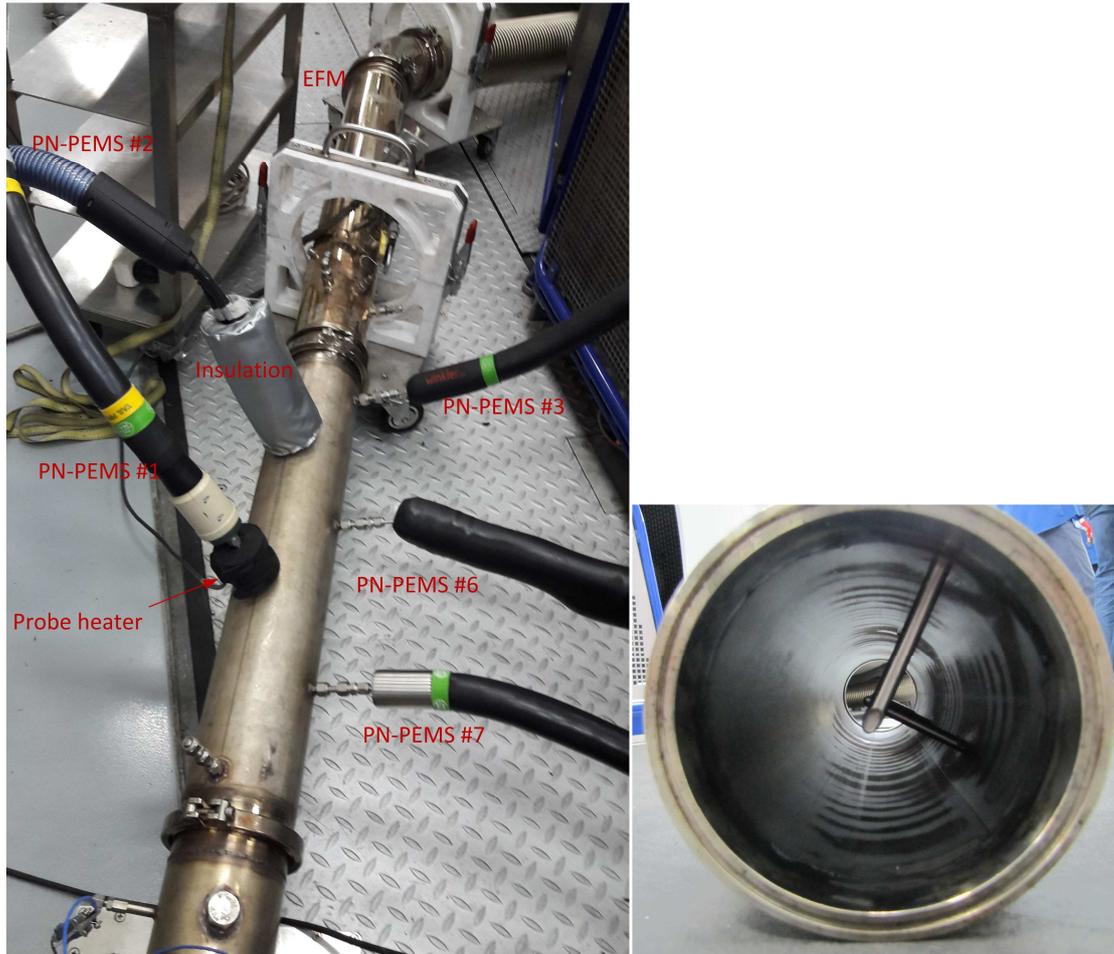
PN-PEMS #6 (NanoPEM-10, Shimadzu) is a 6 stage electro mobility analyser without sheath flow. The cut-off size is 23 nm. For the tailpipe tests, the sample was drawn into a heater (350°C) and diluted 10 times (DF=10). Then it was drawn through a heated line (190°C) to the main unit. The total concentration [ $\text{p}/\text{cm}^3$ ] was given by the manufacturer's software.

PN-PEMS #7 (MAHA-AIP GmbH & Co.) consists of a VPR and a CPC, thus is very similar to a PMP system. It has a short sampling line (0.5 m) heated at 100°C. The primary diluter is an orifice diluter also heated at  $>100^\circ\text{C}$ , with a dilution of approximately 100. The evaporation tube is kept at 300°C, then a secondary dilution follows at ambient temperature (dilution approximately 10:1). The CPC is a 3007 TSI CPC with saturator and condenser temperatures adjusted to obtain a cut-off at 23 nm. The unit was available only at the second evaluation phase.

The calibration results of the PN-PEMS at JRC can be seen in the Chapter 12.



**Figure 4: Example of setup of PEMS (main evaluation phase).**



**Figure 5: Example of setup of PN-PEMS (second evaluation phase). On the right the positioning of the sampling probes. Probes facing away from the flow.**

## 2.4 Sampling position influence

A limited number of tests were conducted with PN-PEMS #2 at the end of the main evaluation campaign sampling from the centerline or from the tube wall (no probe). The differences of the PN-PEMS from the PMP system at the tailpipe can be seen in Figure 6. It seems that lower concentration is measured when there is no probe. The topic was not investigated in detail but indicates that a probe should be used when particles are sampled. All systems in this report were connected to the tailpipe with a probe in the tube reaching the centreline (but facing away from the flow).

In the second phase the probes had a distance of 1.5 tube diameters (approximately 15 cm) to each other and with an angle of 75 degrees to each other. In order to confirm that there was no influence of the sampling the first instrument (PN-PEMS #2) was moved to the last position and then at the first again. The normalized to the reference instrument results can be seen in Figure 7. There is no measurable effect from the sampling location. Similarly small or no influence is expected by the location for the main evaluation phase.

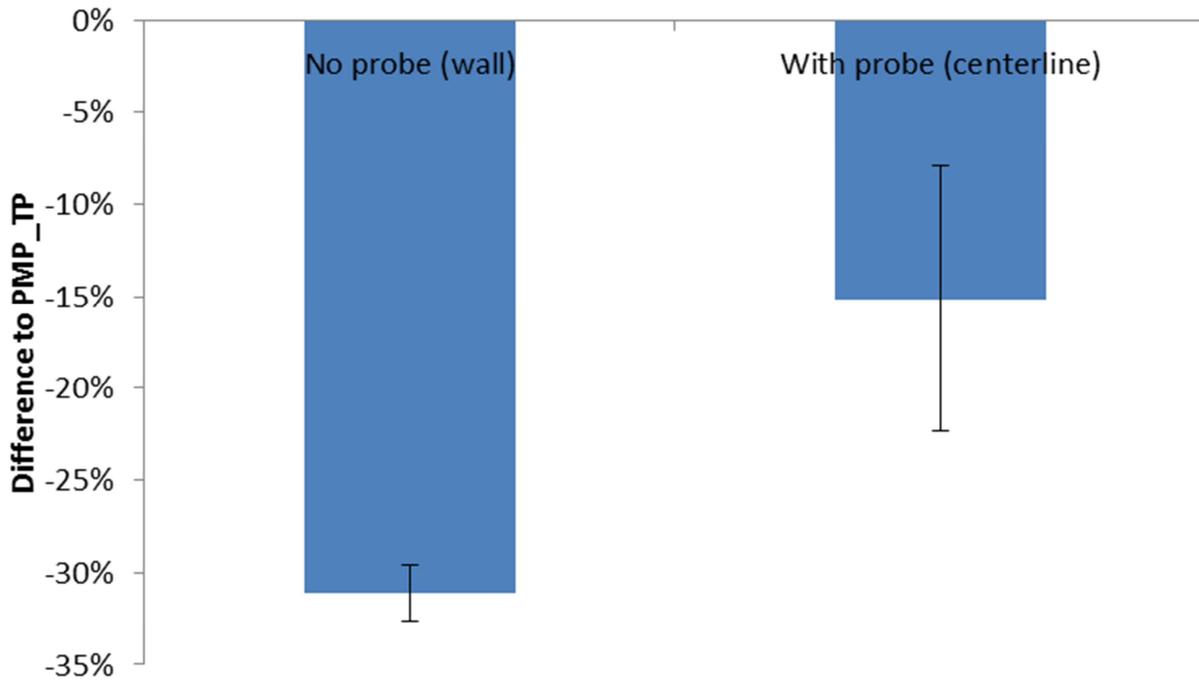


Figure 6: Effect of sampling probe.

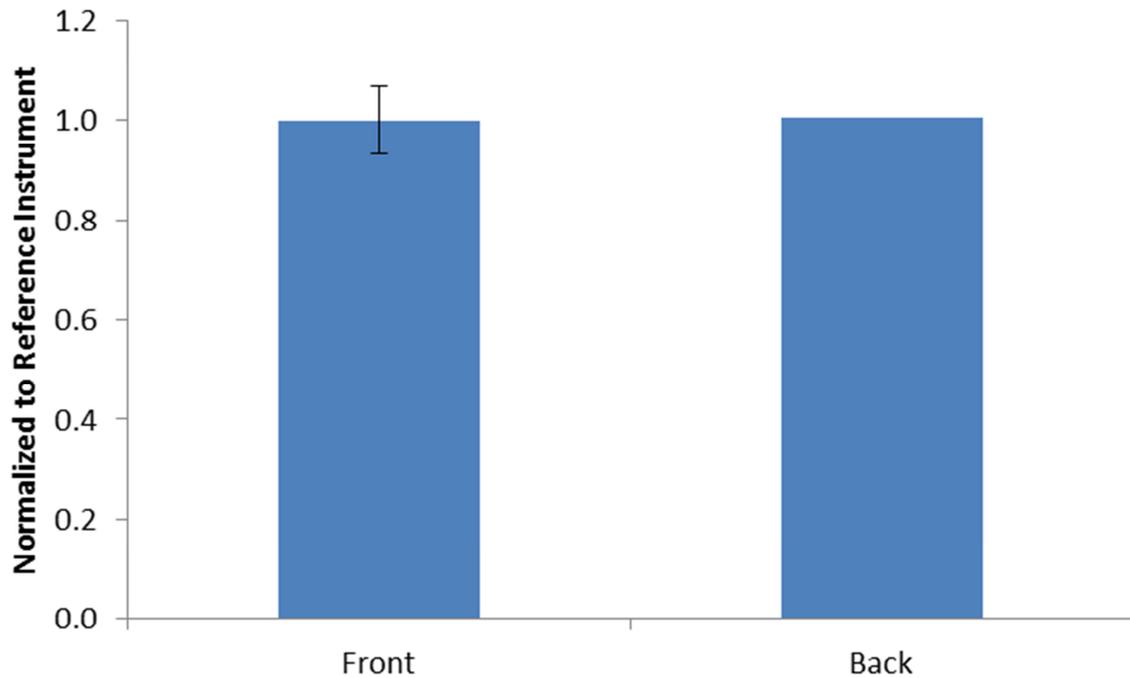


Figure 7: Influence of position on results. See Figure 5: Front refers to position of PN-PEMS #2 and Back refers to position of PN-PEMS #7.

## 2.5 Test cycles

Various test cycles were tested in the laboratory:

- **WHVC (World Harmonized Vehicle Cycle)** that is the equivalent of the engine World Harmonized Test Cycle (WHTC) to a vehicle cycle for the chassis dynamometer. The duration of the WHVC test is 1800 s. The test includes three segments, representing urban, rural and motorway driving. No slopes were added in most of the cases, thus the work of this cycle in many cases was different to the type approval work of the WHTC.
- **Regional Delivery** which is a distance-based cycle where the actual speed of the vehicle at any moment in time is produced by the simulator, and is a function of the vehicle characteristics (weight, resistances, and available power) and the modeled behavior of the driver. Such an approach is considered much more realistic for evaluating the performance of a multitude of different HDV without overlooking their optimal performance conditions. In order to match realistic conditions more closely, the Regional Delivery cycle features additionally the slope as a function of the traveled distance.
- **SICO:** Constant Speed test with predefined combinations of engine rpm and real time measured wheel torque (predefined test cycle in VECTO consisting of constant speeds for optional later validation of the CO<sub>2</sub> result produced for a HDV).
- **ISC (In-Service-Conformity)** cycle which consists of urban (30%/15%), rural (30%/30%) and motorway (40%/55%) parts of approximately 150 km (>2.5 h duration) in this order (percentages excluding idle as time/distance shares) for the N3 vehicles. For the N2 vehicle the shares were urban (45%/25%), rural (25%/30%) and motorway (30%/45%). In the second evaluation phase an ISC that consisted of rural (25%/10%), motorway (15%/20%) and urban and rural (25%/25%) and motorway (40%/45%) parts was also used for the N3 vehicle.

The on-road tests around the JRC site were performed to simulate real-world emissions. A mixed route of total distance of approximately 200 km which consists of urban, rural and highway parts was driven during on-road test. The scope was to obtain a mix of operating conditions similar to those of the chassis dynamometer tests. Cold start in the following figures refers to the first 1200 s of the ISC cycle (when the engine was cold).

For the on-road tests only the gas PEMS was used with the 5" EFM and one or two PN-PEMS (#2 always and #1 or #3).

## 2.6 Protocol

The test protocol can be seen in Table 3 and the tests conducted in Table 4.

## 2.7 Calculations

For the systems at the CVS, the CVS flow rate and the work produced were used to calculate the emissions in p/kWh. For the systems at the tailpipe, the particle concentration was time aligned with the exhaust flow rate and then they were multiplied with each other. The sum was divided with the work to give p/kWh. The exhaust flow in all tests presented was estimated from the difference of the total flow of the dilution tunnel minus the dilution air flow. These flows were inter-calibrated weekly.

The flow rate extracted by the instruments was approximately 20-30 lpm (11 lpm the gas analyzer, 6.5 lpm the FTIR, 1-10 lpm the PN-PEMS). This flow is <1% of the mean vehicles' flow rate during a test (<2% at idle). And was not considered in the calculations.

For many tests the exhaust flow meter (EFM) was connected to the tailpipe and the flow rates measured by the EFM and the estimated by the CVS were compared (Figure 8).

The flow rate of the EFMs (both 4" or 5") was also used to estimate the emissions of the PMP-TP. The cycle average results had less than 5% difference. Thus no correction was applied to the flowrate.

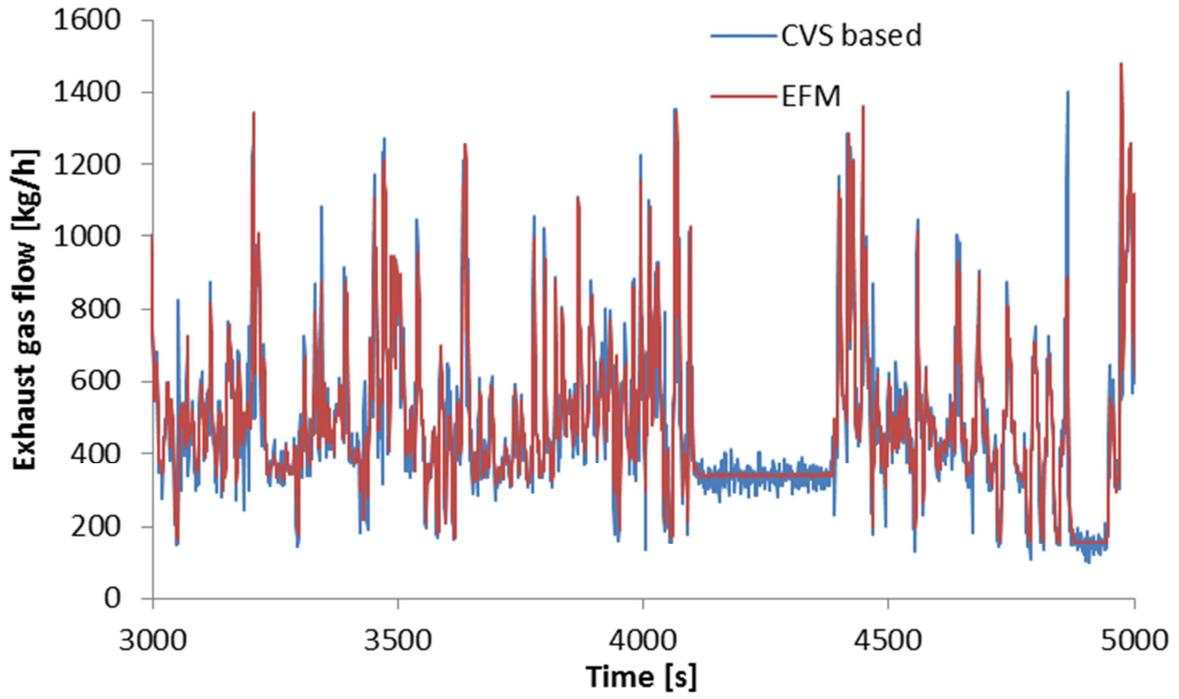
**Table 3: Testing period of PN emissions and available PN-PEMS instrumentation.**

Period		#1	#2	#3	#6	EFM	Comments
<b>V1</b>							
3/2-29/2	Lab	Y	Y1, Y2	Y1	N	5"	27 tn
7/3-11/3	On-road	N	Y2	Y1	N	5"	27 tn
14/3	Lab	N	Y2	Y1	N	5"	regeneration
<b>V2</b>							
16/3-23/3	Lab	N	N	Y2	Y	4"	20 tn, <3000 km
<b>V3</b>							
24/3-1/4	Lab	N	N	Y2	Y	4"	20 tn, low temp, no OBD
8/4-12/4	Lab	Y	Y3	N	Y	4"	27 tn, torquemeter
13/4-15/4	Lab	Y	Y3	N	Y	N	27 tn, torquemeter*
21/4-6/5	On-road	Y	Y3	N	N	5"	27 tn
12/5	Lab	Y	Y3	N	N	5"	27 tn, repeat
<b>V4</b>							
28/4-4/5	Lab	N	N	N	N	N	Only CVS
<b>V5</b>							
18/5-31/5	Lab	Y	Y3	N	Y	4"	9 tn
<b>V6</b>							
9/6-13/6	Lab	N	Y3	N	N	4"	13 tn
<b>V7</b>							
27/6-28/6	Lab	N	N	N	N	5"	CVS
<b>V8</b>							
5/9-16/9	Lab	Y2	Y4	Y3	Y2	5"	27 tn, PN-PEMS #7

\* 12/4 Error: Exhaust gas System Faulty (then warning). 16/4 repair at official workshop

**Table 4: Test cycles for each vehicle and number of repetitions.**

	<b>Cycle</b>	<b>-7°C</b>	<b>0°C</b>	<b>10°C</b>	<b>20°C</b>	<b>35°C</b>	<b>Cold</b>
V1	ISC	3	2		2	2	4
	WHVC		1		10		7
	Various				15		0
	On-road			5			2
V2	ISC	1	1	1	2		3
	WHVC					1	0
	Various				2		0
V3	ISC	1	1		1		2
	WHVC	1			8	1	2
	Various		2		24		0
	On-road			1	5		3
V4	ISC	4					2
	Various	3			2		0
V5	ISC	2	2		2	1	3
	WHVC				4		2
V6	WHVC				3		0
	Various				5		0
V7	WHVC				3		1
	Various				9		0
V8	ISC	2	1		2	1	6
	WHVC	4			4	2	0
	Various				5		0



**Figure 8: Example of comparison of exhaust flow estimated from the dilution tunnel (CVS) and an exhaust flow meter (EFM) (201604010\_1\_ISC).**

### 3 Main evaluation Phase: Reference systems

#### 3.1 Emission levels

An example of the emission levels of different cycles for vehicle V1 can be seen in Figure 9. The emission levels of the on-road tests and the hot cycles are  $<1 \times 10^{11}$  p/kWh. Higher emissions were measured during the SICO tests when the DPF was passively regenerating. High emissions were also measured during some cold WHVCs; the level of the cold start probably has to do with the DPF fill state from the tests the day before. Summing up the emissions during a period of approximately one month gave emission levels of  $5.3 \times 10^{11}$  p/kWh for vehicle V1. Similarly for vehicle V3 the emissions during a period of one and a half months were approximately  $2.6 \times 10^{11}$  p/kWh.

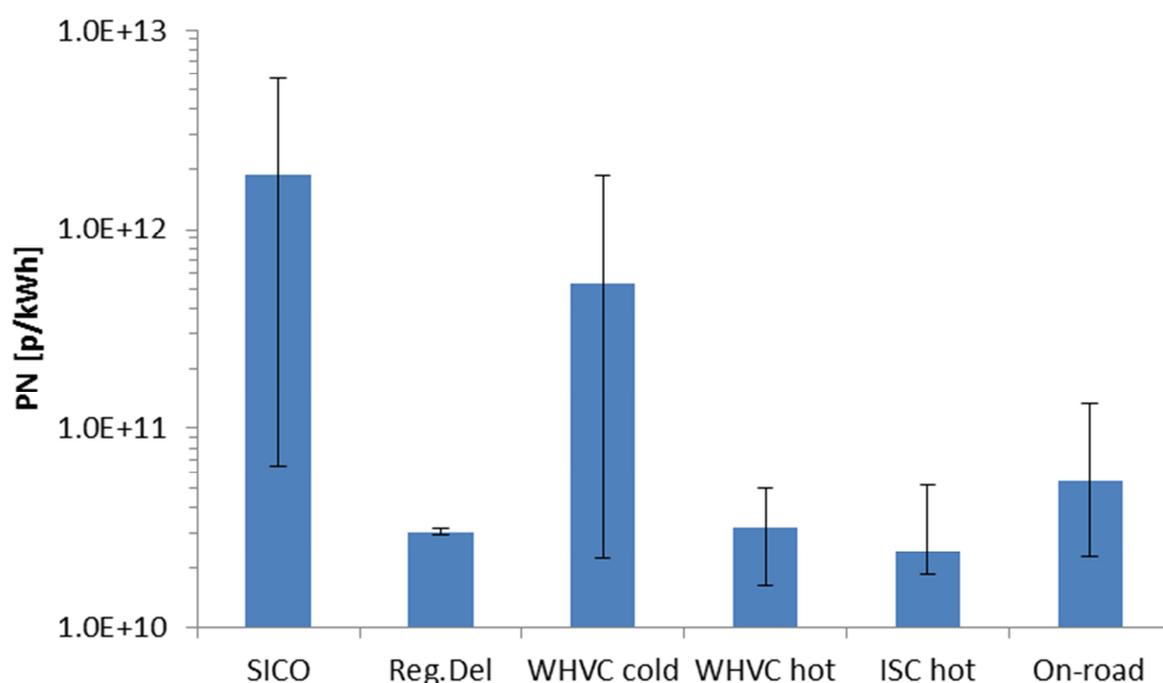


Figure 9: Emission levels of V1 for various cycles. Error bars indicate max-min values.

The tests were conducted depending on the needs of the various projects and thus there was no dedicated protocol to ensure similar DPF fill state and testing conditions. Thus the repeatability of the measurements was not good, as seen in Figure 9. An example of continuously running Regional Delivery cycles can be seen in Figure 10. Between the two days two WHVC cycles were also conducted. The emissions were low, but then at one of the cycles the DPF regenerated and the emissions were high. The emissions remained high during the next cycle due to the low soot cake in the DPF. The bad repeatability (big error bars) of the measurements has no effect on the conclusions of this report: All PN-PEMS were measuring in parallel with the reference PN systems and the differences are evaluated on a cycle by cycle basis.

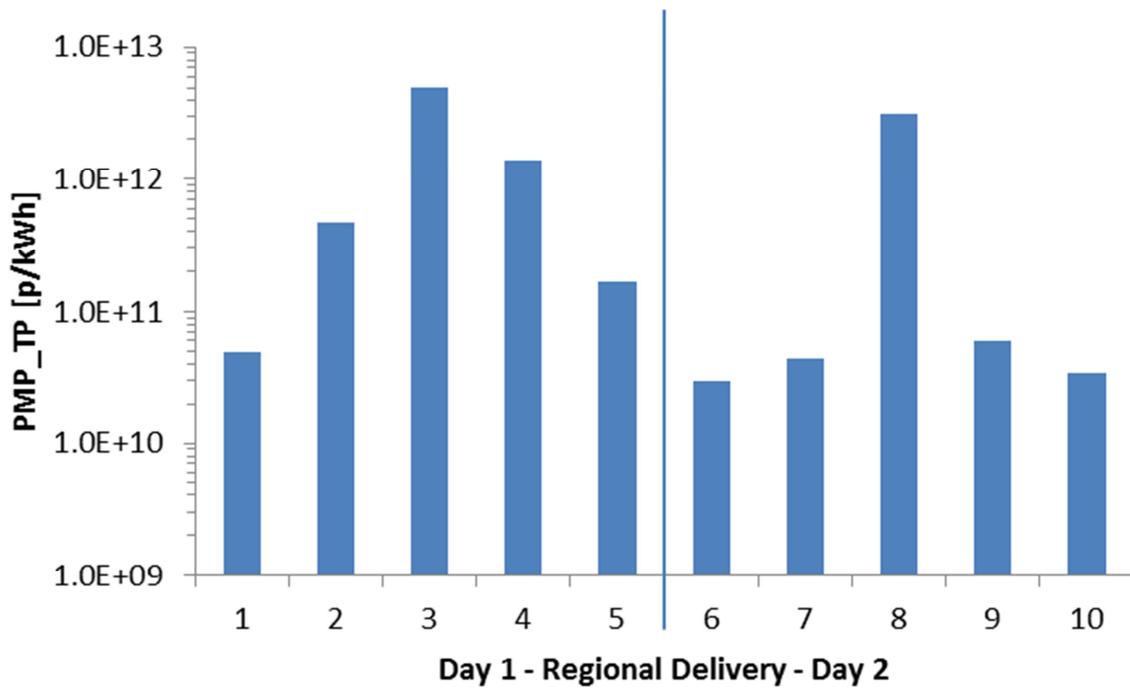


Figure 10: Repeatability of Regional Delivery Cycles.

The emission levels of all vehicles for some test cycles can be seen in Figure 11. Vehicle V2 (CNG) had high emissions probably because it was new and there were oil particles. The rest vehicles (all DPF equipped) were below the  $6 \times 10^{11}$  p/kWh limit with a few cold start WHVC exceptions; these cold start WHVCs were conducted the day after the SICO cycles which generated the DPF and thus the DPF efficiency was relatively low. The important message from this figure is that a wide range of emissions was examined.

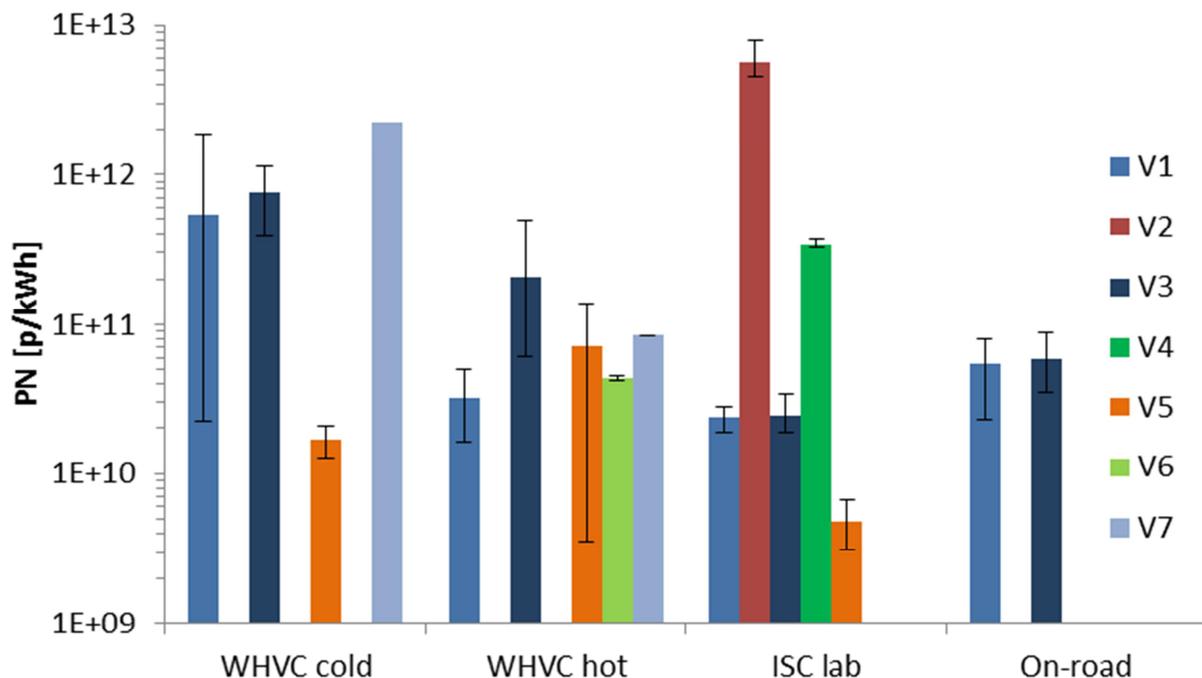


Figure 11: Emission levels at different cycles of different vehicles.

### 3.2 PMP\_CVS vs. PMP\_TP

The correlation of the PMP\_TP to the PMP\_CVS can be seen in the following figures for the various vehicles (Figure 12 for vehicle V1, Figure 13 for vehicle V2, Figure 14 for vehicle V3, Figure 15 for vehicle V5). In general, the agreement is within 15% with only a few cases exceeding this difference and there is no dependency of the ambient temperature in the climatic room, as it should, because the PMP\_TP was installed in a room with controlled temperature of 20°C.

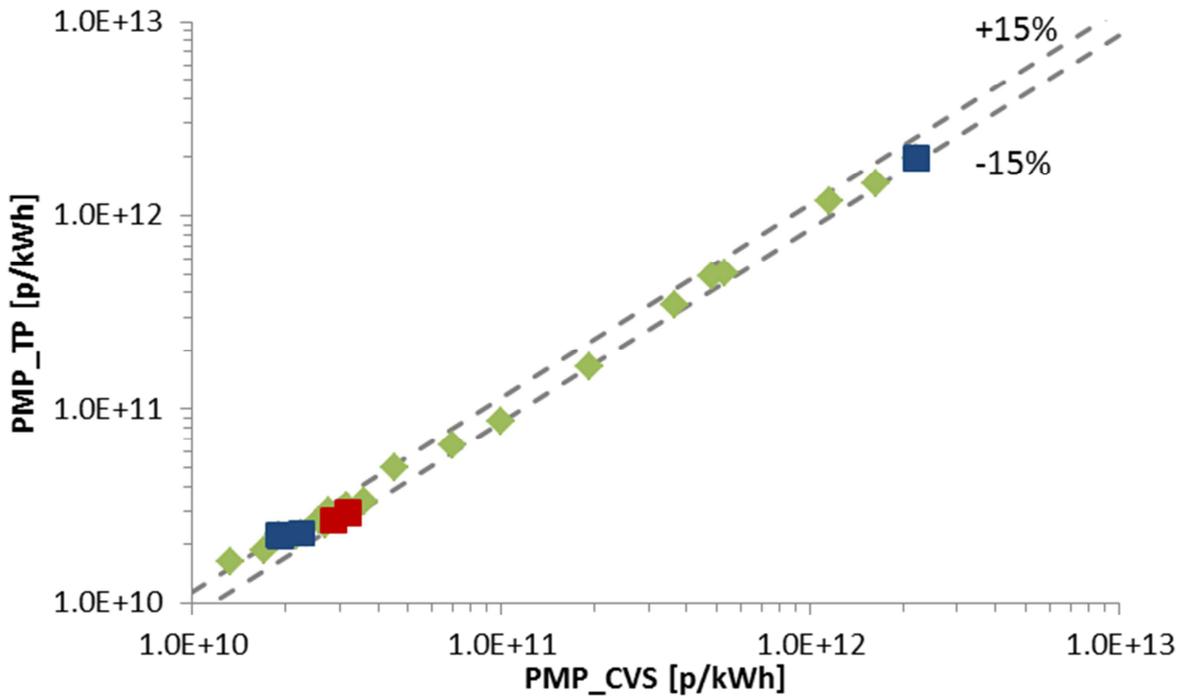


Figure 12: Correlation of PMP\_TP to PMP\_CVS for vehicle V1. Blue points tests at -7°C, red points tests at +35°C.

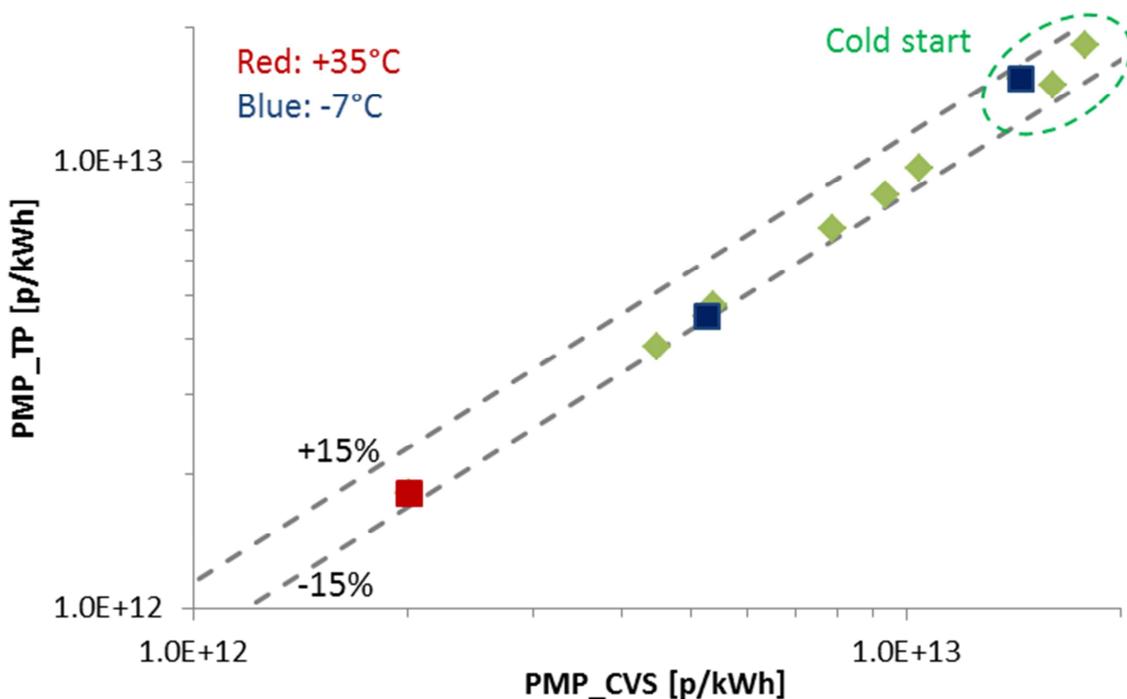


Figure 13: Correlation of PMP\_TP to PMP\_CVS for vehicle V2. Blue points tests at -7°C, red points tests at +35°C.

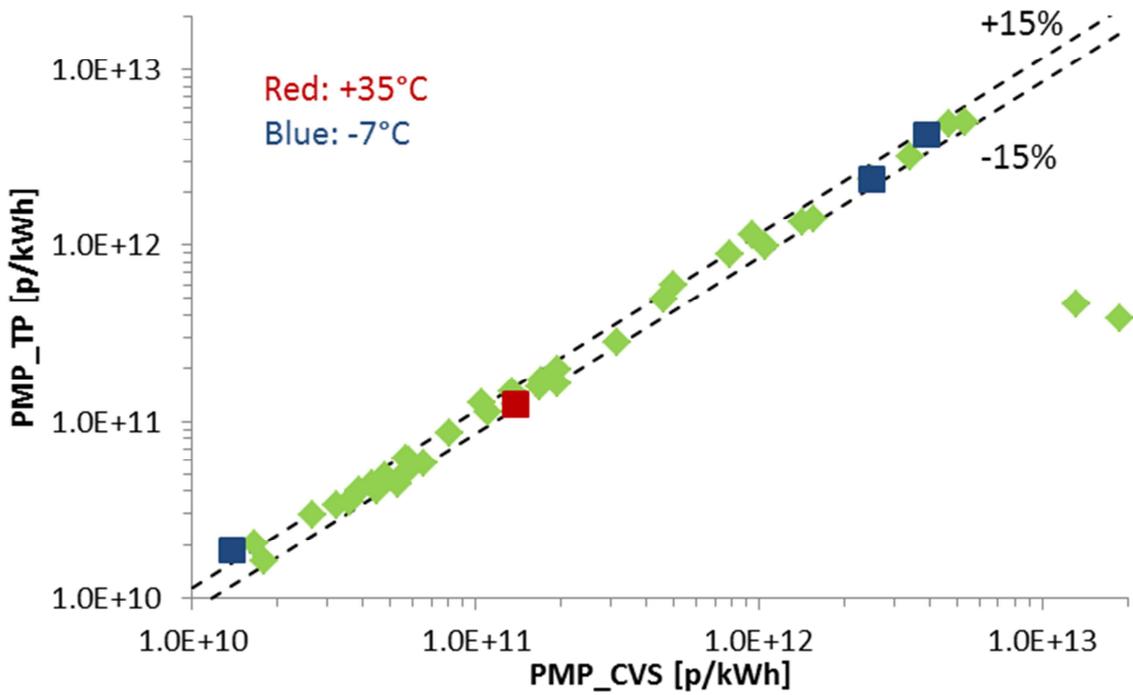


Figure 14: Correlation of PMP\_TP to PMP\_CVS for vehicle V3. Blue points tests at -7°C, red points tests at +35°C. The two outliers will be discussed separately.

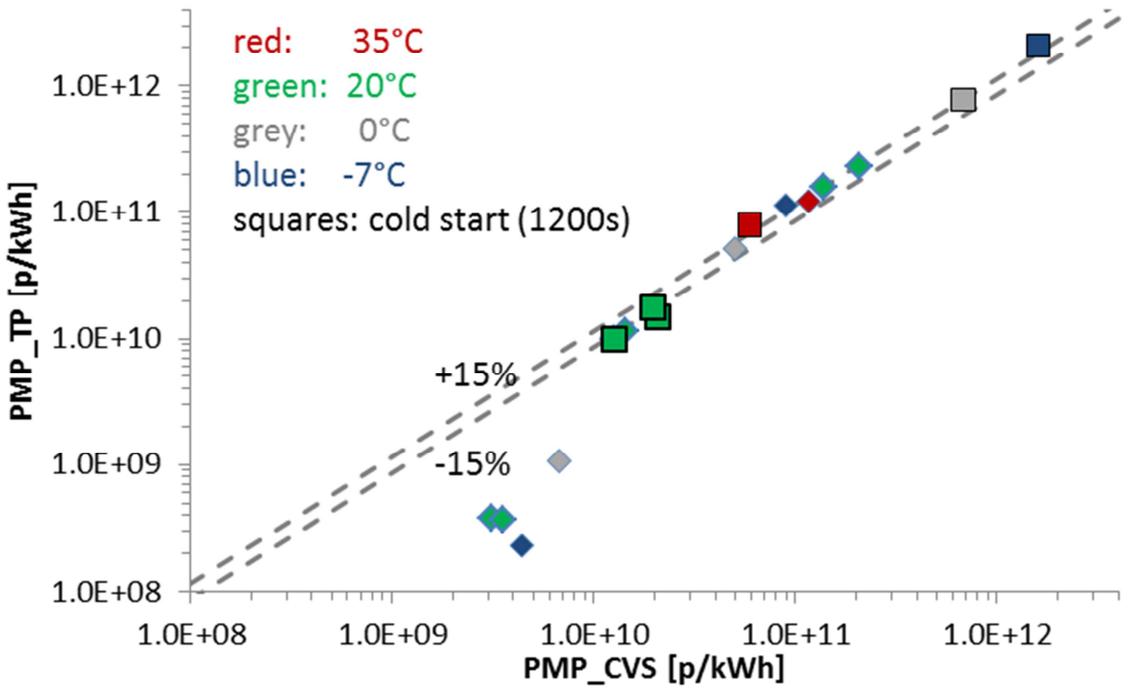
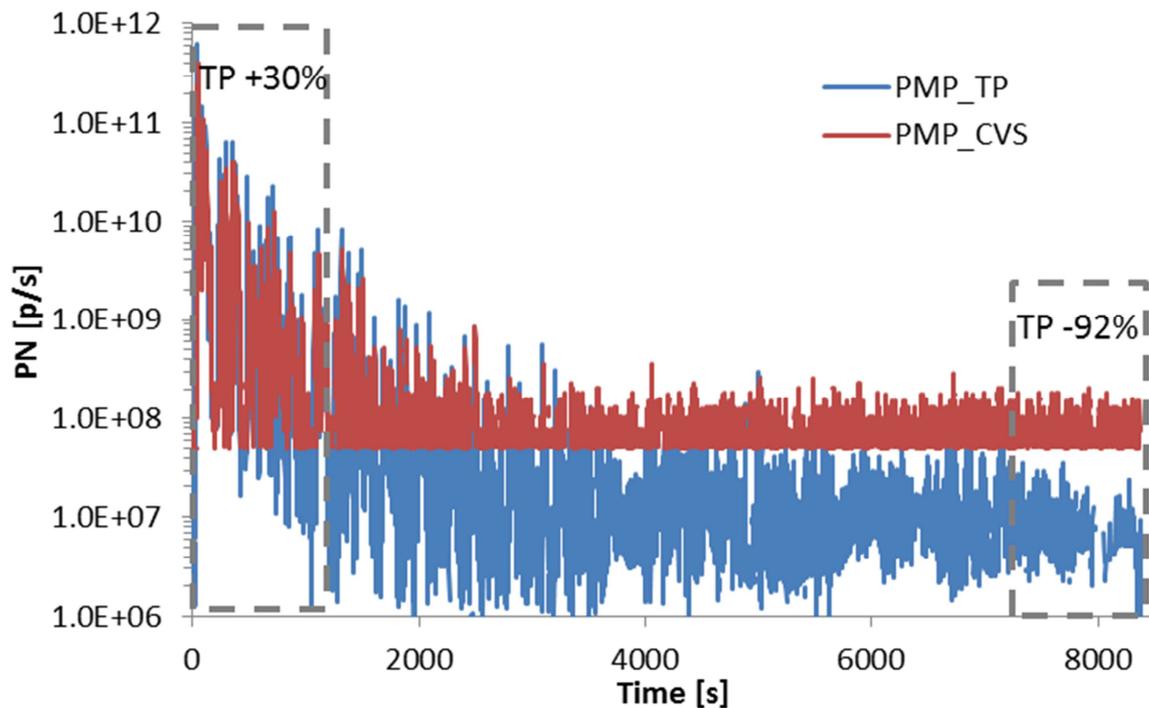


Figure 15: Correlation of PMP\_TP to PMP\_CVS for V5. Blue points tests at -7°C, red points tests at +35°C.

If the reference system was connected close to the vehicles and not the dilution tunnel probably the differences would be higher (higher influence from pressure fluctuations, thermophoretic or diffusion losses and agglomeration).

Bigger differences than 15% were observed when the concentrations were very low and the total emissions were  $<10^{10}$  p/kWh (Figure 15). In this case the relatively high background of the CVS results in a detection limit of the CVS around  $5 \times 10^9$  p/kWh ( $<100$  p/cm<sup>3</sup> at the CVS). This can be seen in Figure 16 where a cold start ISC cycle is shown. At the cold start part the PMP\_TP is measuring 30% higher (one of the few cases that the  $\pm 15\%$  was exceeded) than the PMP\_CVS, while in the last hot part 92% lower.



**Figure 16: Real time comparison of PMP\_CVS and PMP\_TP over a long cycle in the lab (Example vehicle V5) (20160520\_1\_ISC\_-7°C).**

Special discussion need the two outliers of Figure 14. These tests, which happened on the same day, showed low emissions with the PMP\_TP but high with the PMP\_CVS. The real time signals are shown in Figure 17 and Figure 18. The high emissions are due a spike during an acceleration at the PMP\_CVS test at both cases. There is no clear explanation for this behaviour. It could be a re-nucleation effect in the dilution tunnel as the exhaust gas cools down that couldn't be completely removed in the evaporation tube of the PMP system. The PMP system at the tailpipe samples hot exhaust thus this nucleation did not happened. The PN-PEMS also didn't show this high concentration of particles. These two tests were not considered in the analysis and comparison of the CVS results.

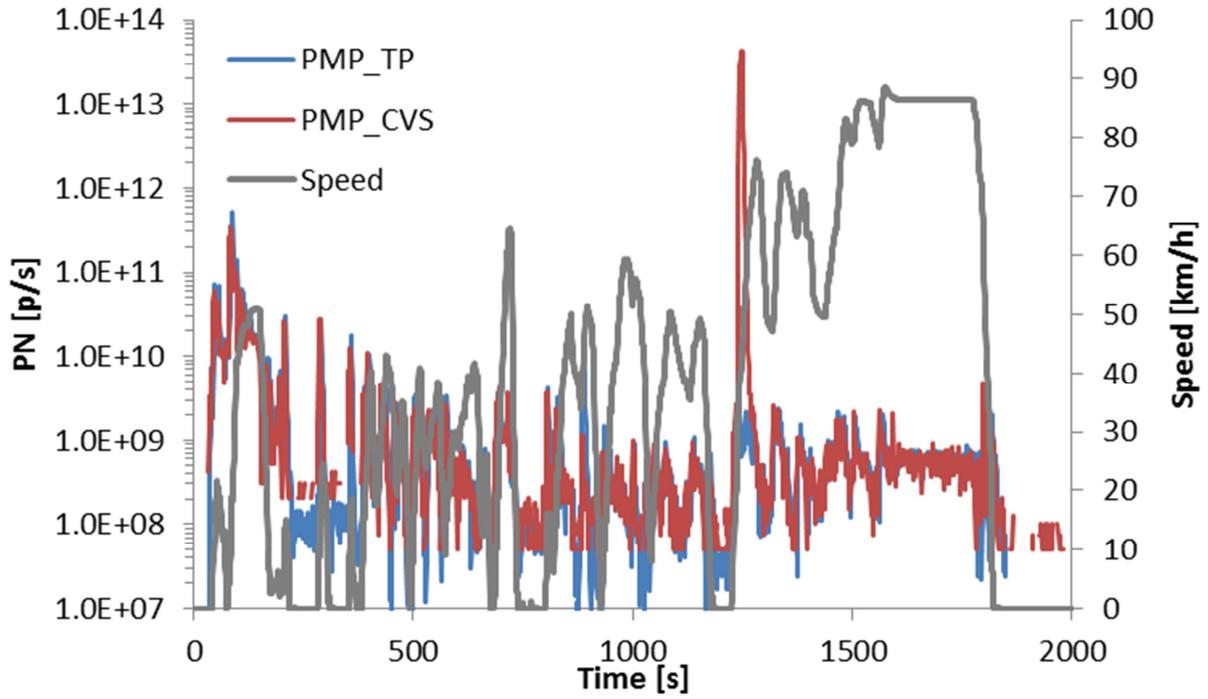


Figure 17: Real time comparison of PMP\_TP and PMP\_CVS (20160411\_01\_WHVC).

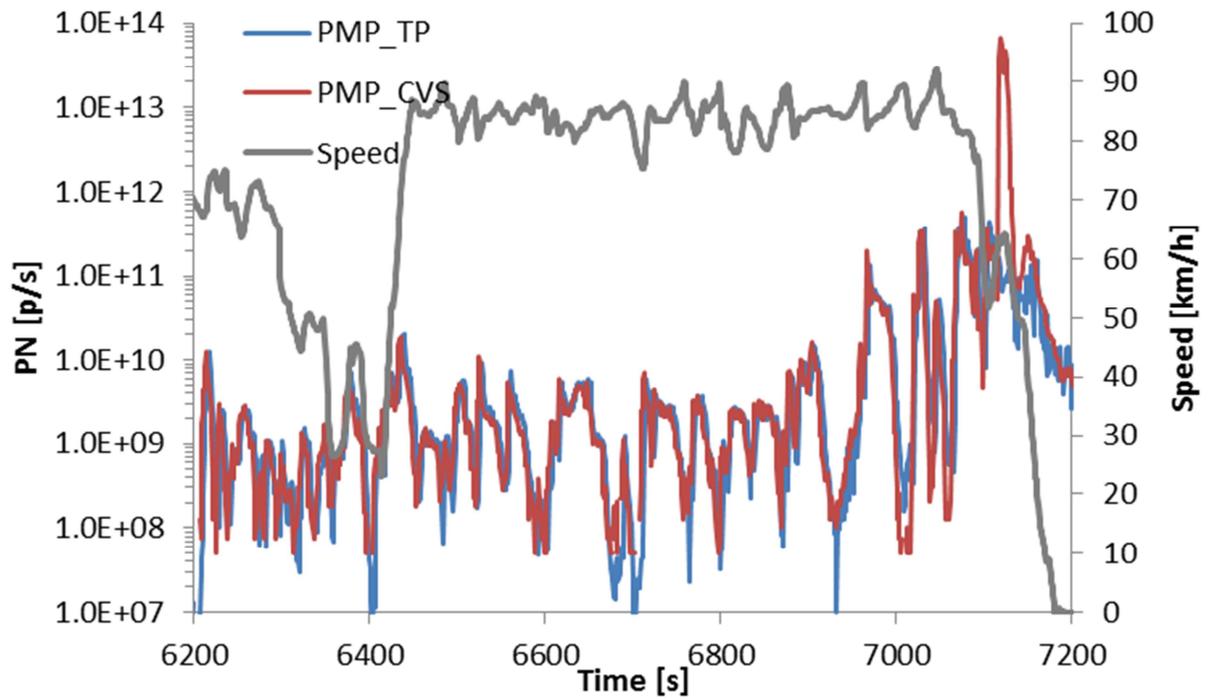


Figure 18: Real time comparison of PMP\_TP and PMP\_CVS (20160411\_04\_Region.Del.).

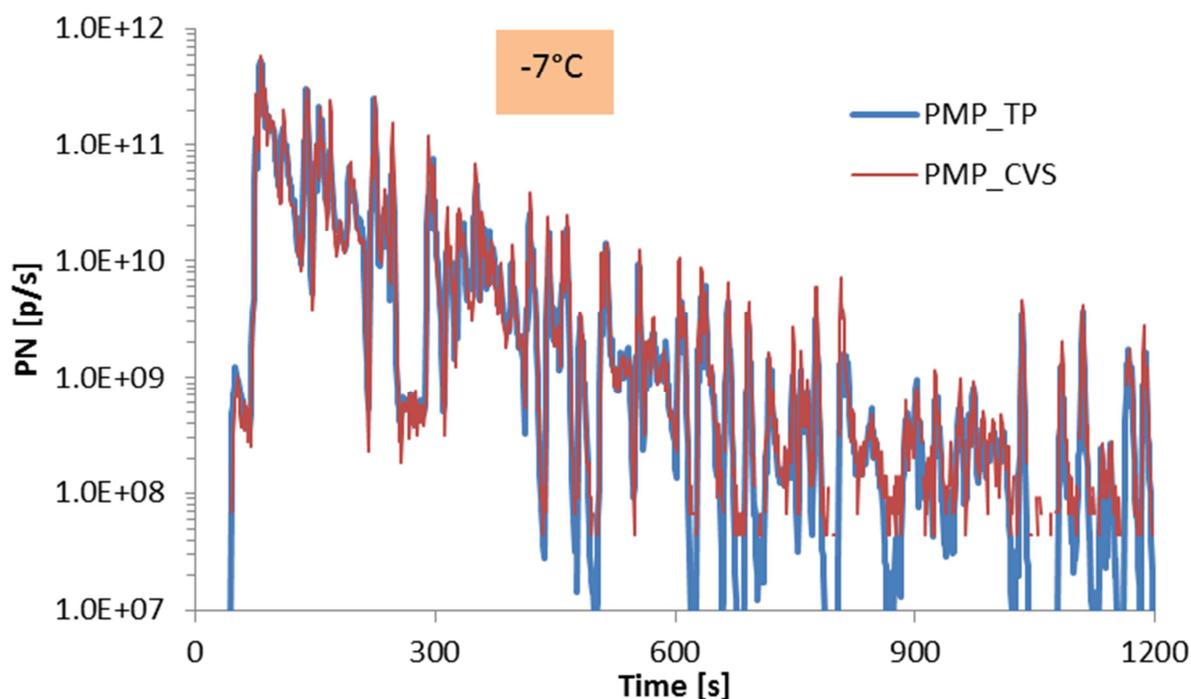
### 3.3 Cold start

Examples of cold start emissions (first 1200 s) with the PMP\_CVS and PMP\_TP systems are shown in Figure 19 for vehicle V1, Figure 20 for vehicle V3 and Figure 21 for vehicle V5. A summary of the differences of the PMP\_TP and PM\_CVS systems at the cold part of the cycle and the hot part is given in Table 5. The difference of PMP\_TP from PMP\_CVS is lower at the cold part than in the hot part, with a few exceptions that the emissions are below the background levels. This is in contrast to the light-duty exercise where the cold start emissions were in general higher at the tailpipe than at the CVS. Part of this difference can be explained by the position of the PMP\_TP system. In the light-duty exercise it was connected directly at the end of the vehicle's tailpipe, while in the heavy-duty exercise just before the CVS. Thus diffusion and agglomeration between the system at the tailpipe and the dilution tunnel were more significant in the light-duty exercise.

**Table 5: Difference of PMP\_TP to PMP\_CVS for the cold part and hot part of the ISC cycle at different ambient temperatures.**

Vehicle	V1		V3		V5	
Temperature	-7°C	20°C	-7°C	20°C	-7°C	20°C
Cold start	-10%	-15%	+9%	+17%	+30%	-7%
Hot part	+15%	+5%	+34%	+43%	-43%*	-20%

\* due to higher background of the CVS



**Figure 19: Comparison of PMP\_TP with PMP\_CVS at the cold part of a cycle (V1) (20160217\_01\_ISC\_-7°C).**

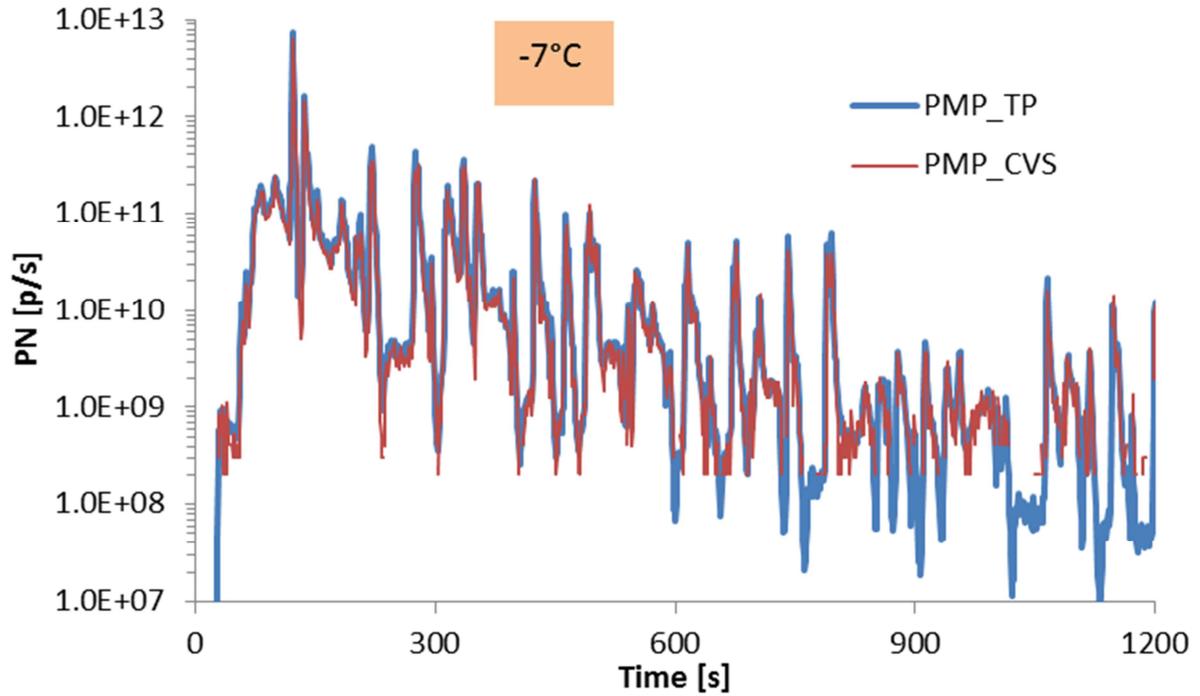


Figure 20: Comparison of PMP\_TP with PMP\_CVS at the cold part of a cycle (V3) (20160331\_01\_ISC\_ $-7^\circ\text{C}$ ).

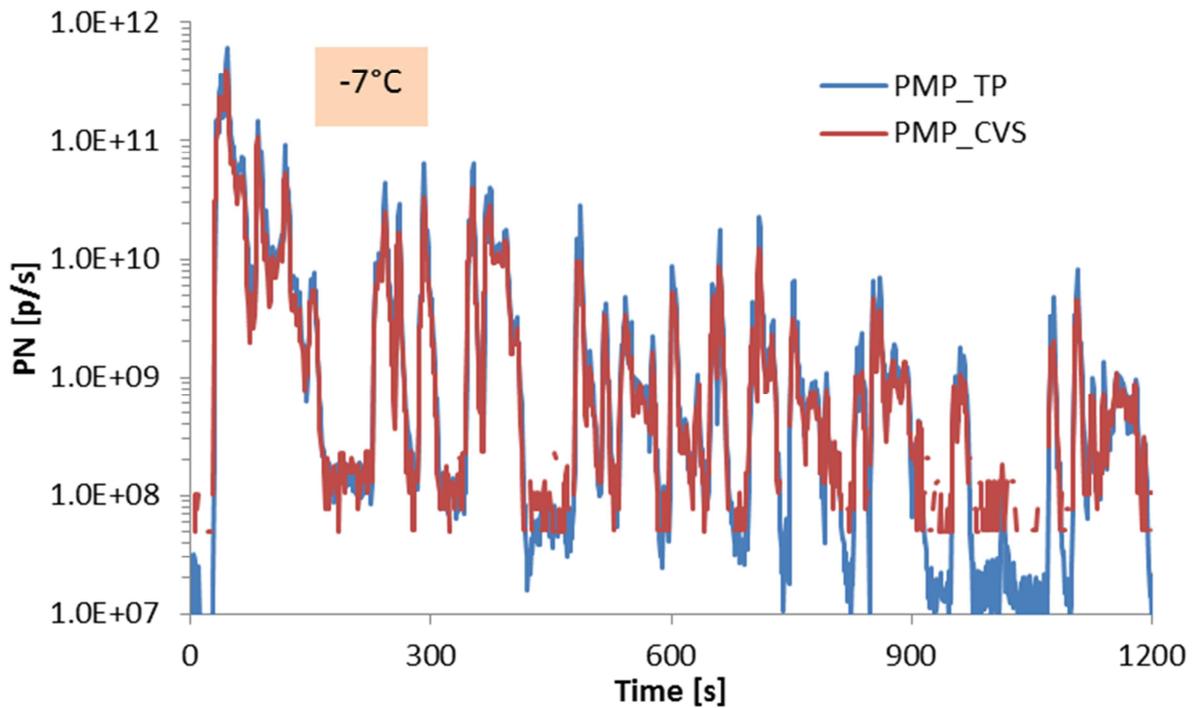


Figure 21: Comparison of PMP\_TP with PMP\_CVS at the cold part of a cycle (V5) (20160520\_01\_ISC\_ $-7^\circ\text{C}$ ).

### 3.4 Sub-23 nm fraction

The sub-23 nm fraction was estimated by comparing the concentrations of a 10 nm CPC and the 23 nm CPC measuring in parallel downstream of the VRP of the PMP\_CVS. This fraction might not be representative of the true sub-23 nm emissions as the losses <30 nm are not properly considered in the established regulated procedure.

Figure 22, Figure 24, and Figure 26 show the fraction as a function of the emission levels for the DPF equipped vehicles V1, V3 and V5 respectively. Figure 28 shows for the CNG vehicle V2. For the DPF equipped vehicles the fraction is low at high concentrations (<10%). However, quite often it was high at low concentrations (<1x10<sup>11</sup> p/kWh). Some possible reasons are:

- Drift of the 23 nm CPC (highly unlikely in this case, as the pulse height was monitored) (Figure 23).
- Low measured concentration that increases the measurement uncertainty of the CPCs (see Figure 25 and Table 6).
- Formation of particles due to urea injection (Figure 27).
- Potential material effect on the counting efficiency of the 23 nm CPCs.

For the CNG vehicle V2 (Figure 28) the assumption is that these are oil particles (or residuals) that have survived the evaporation tube temperature (350°C). Typically their size is around 20 nm thus a high fraction is measured at all tests. During cold start the fraction is even higher (Figure 29). One could argue that these particles are re-nucleated particles downstream of the evaporation tube. Dedicated tests at different PCRF (250 and 2500) didn't show any difference on the measured levels (within experimental uncertainty) indicating that the re-nucleation, if any, should be minimum. Note that 10% effect from changing the PCRF is at the high end of acceptable calibration uncertainty, but it should be mentioned that the used PCRF 2500 (250x10) is not calibrated by the manufacturer and it was set only to have a 10 fold increase of the PCRF.

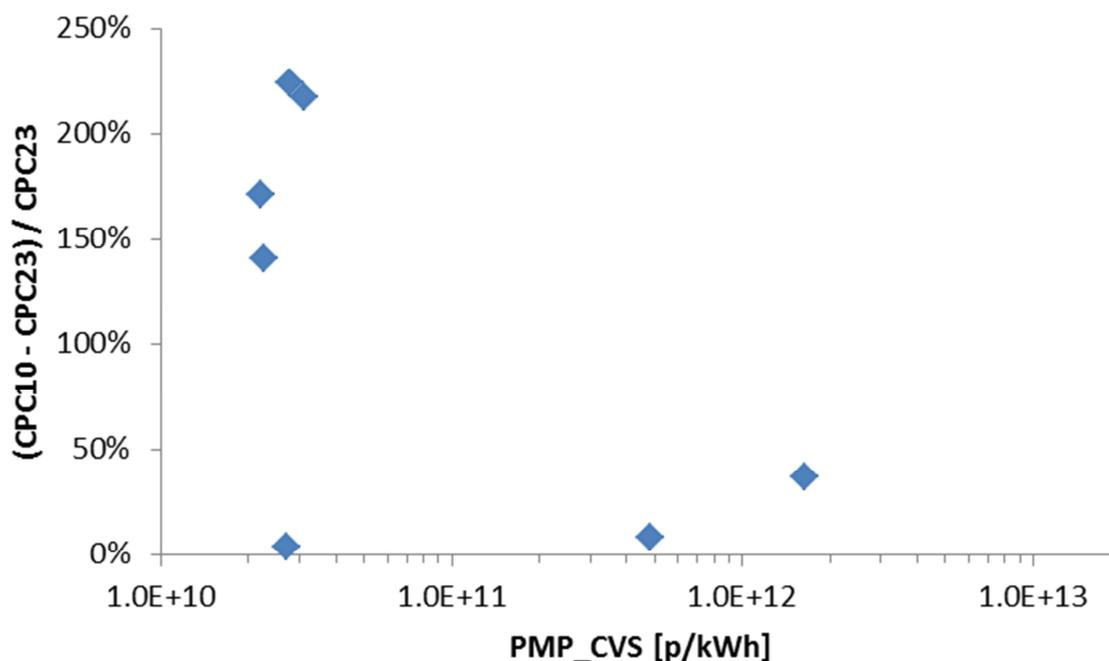


Figure 22: Sub-23 nm fraction of V1.

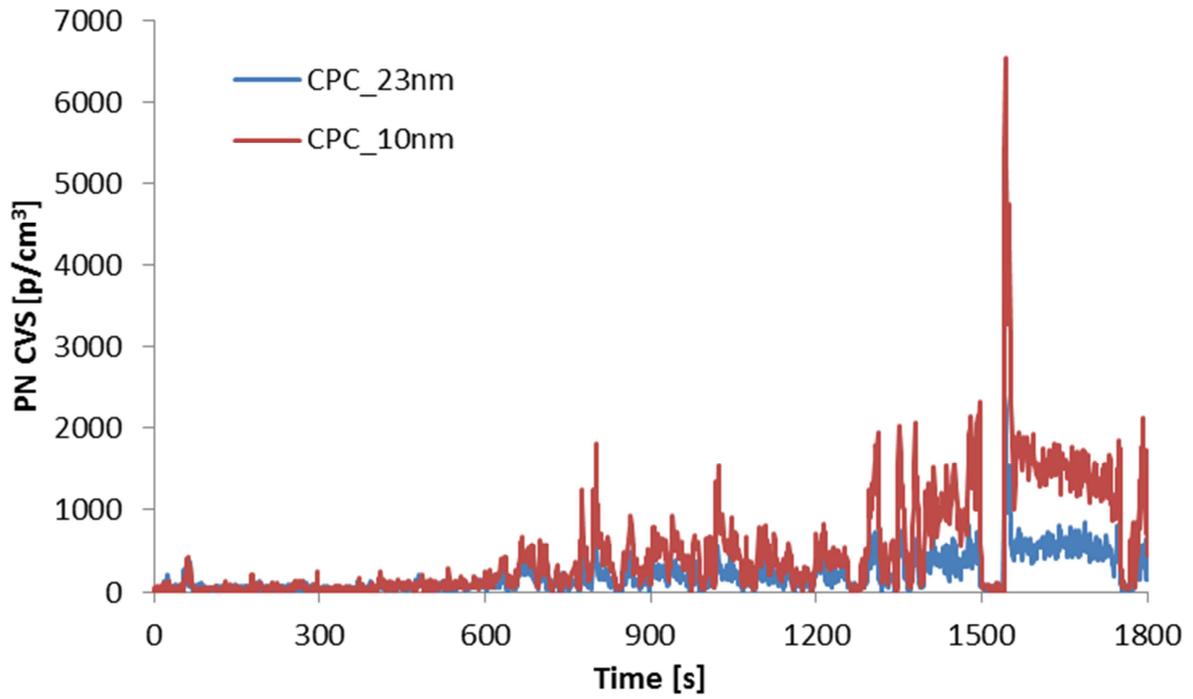


Figure 23: Real time concentration signals of the two CPCs. Concentrations refer to the CVS (20160224\_01\_WHVC cold).

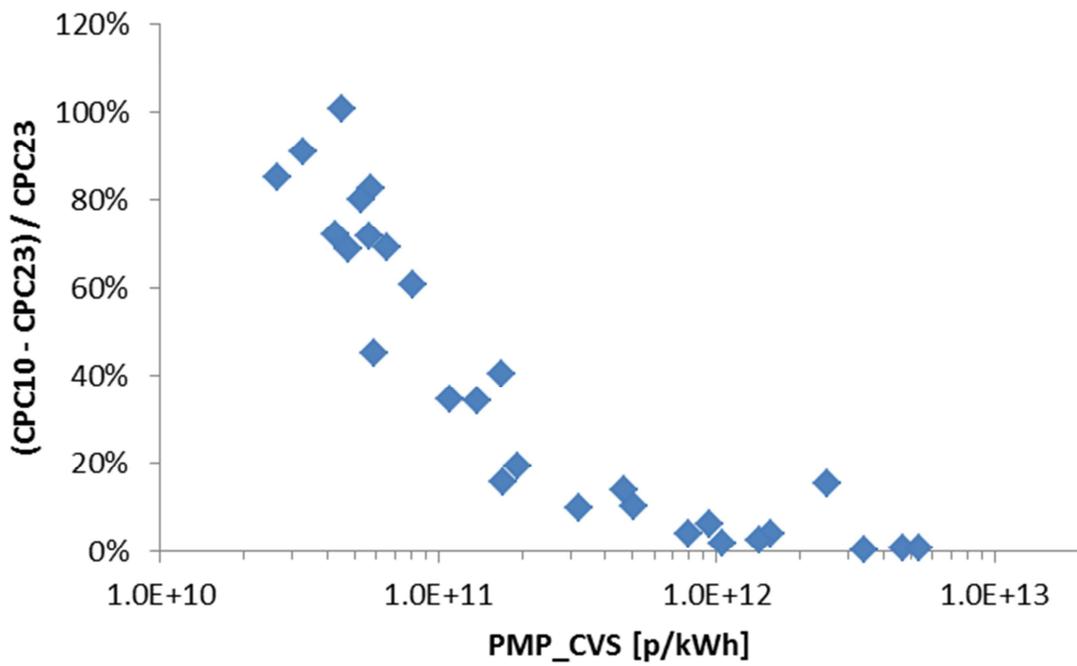


Figure 24: Sub-23 nm fraction of V3.

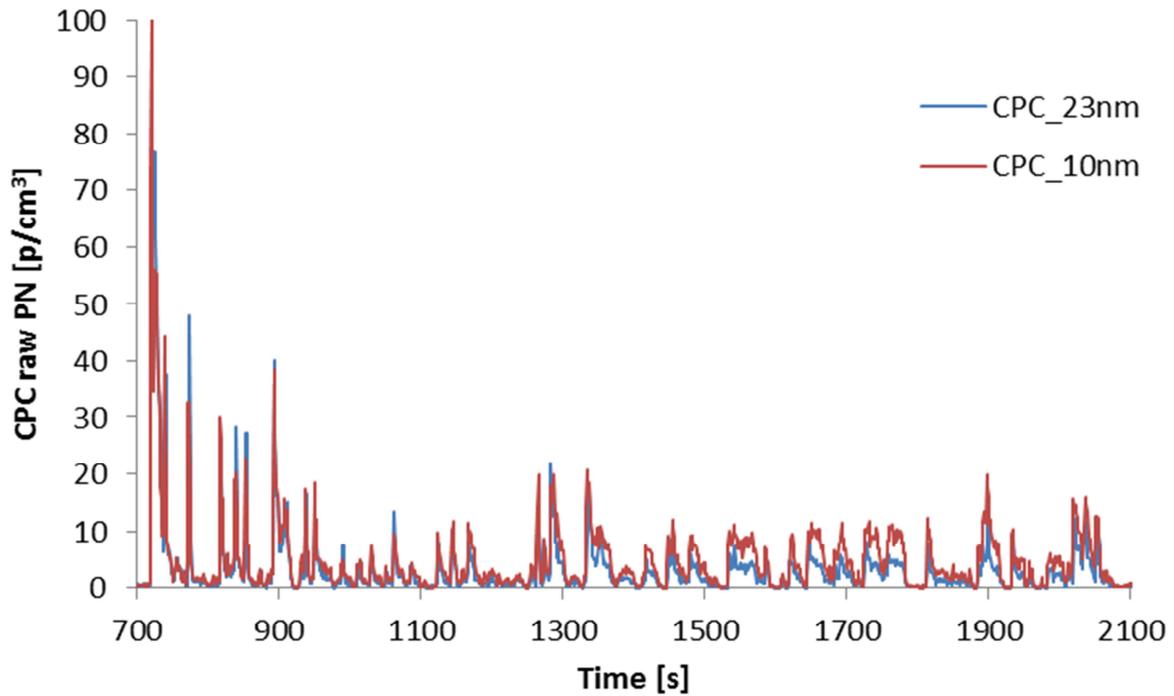


Figure 25: Typical measured raw concentration of CPCs (emissions around  $5 \times 10^{10}$  p/kWh) (20160512\_02\_Region.Del.).

Table 6: Count statistics error ( $n^{0.5}/n$ ) of a CPC based on the measured concentration  $n$ .

Concentration [p/cm <sup>3</sup> ]	1	10	100	1000	10000
Uncertainty	100%	32%	10%	3%	1%

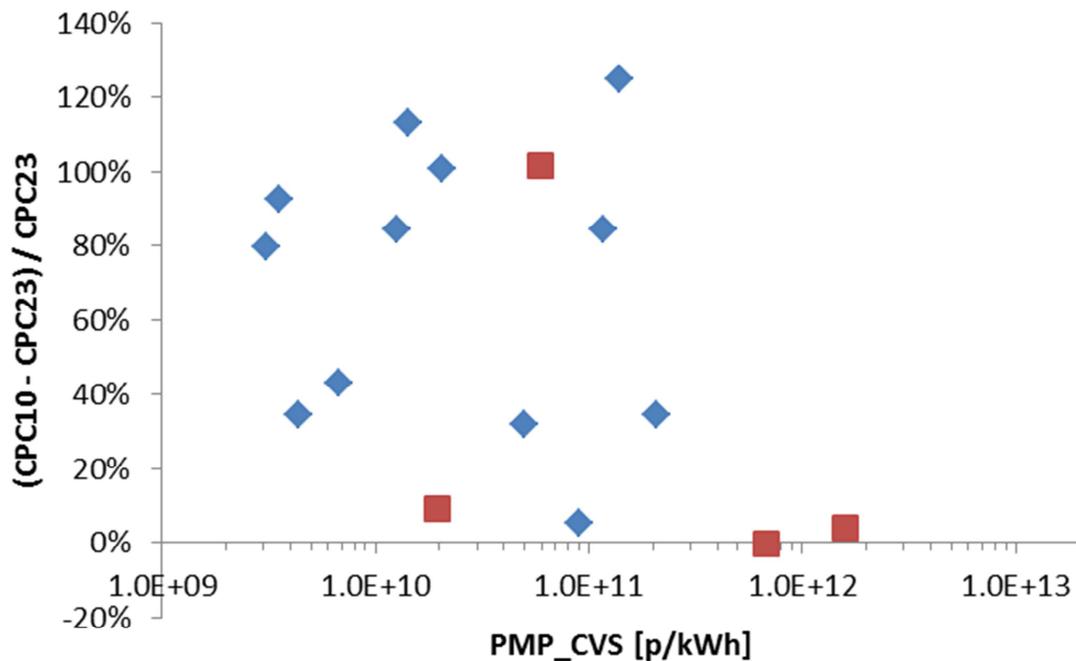


Figure 26: Sub-23 nm fraction of V5. Red squares are cold start tests (i.e. first 1200 s).

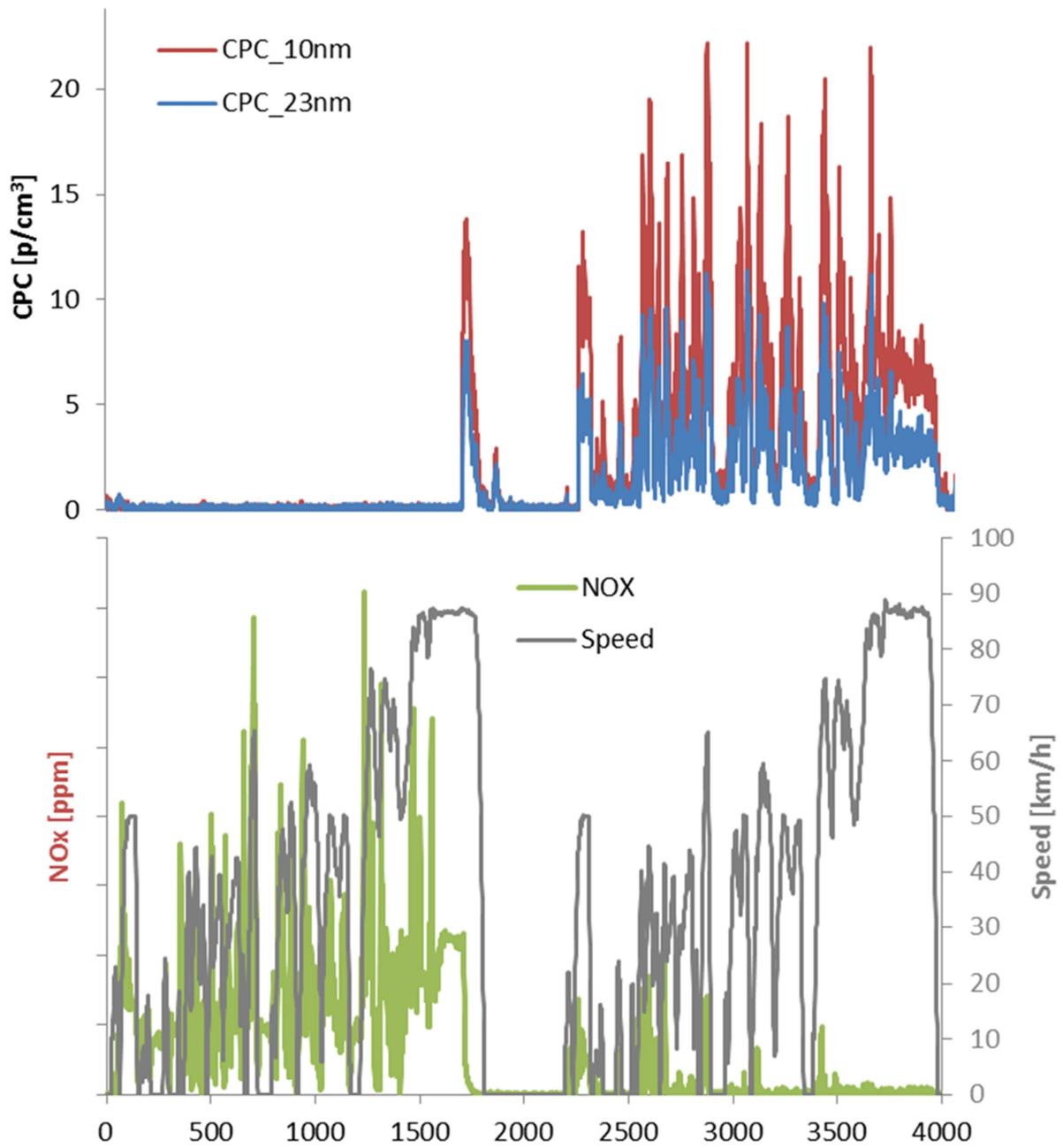


Figure 27: Real time concentrations of a) 10 nm and 23 nm PN and b) NOx. In panel b the speed profile is also shown. Vehicle V5.

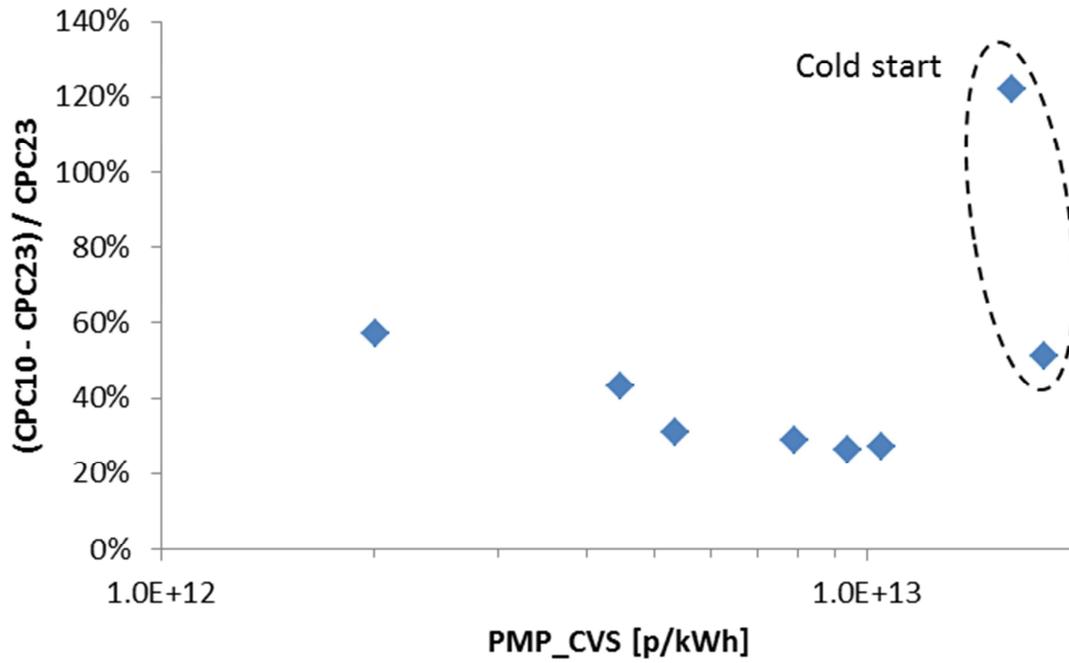


Figure 28: Sub-23 nm fraction of V2.

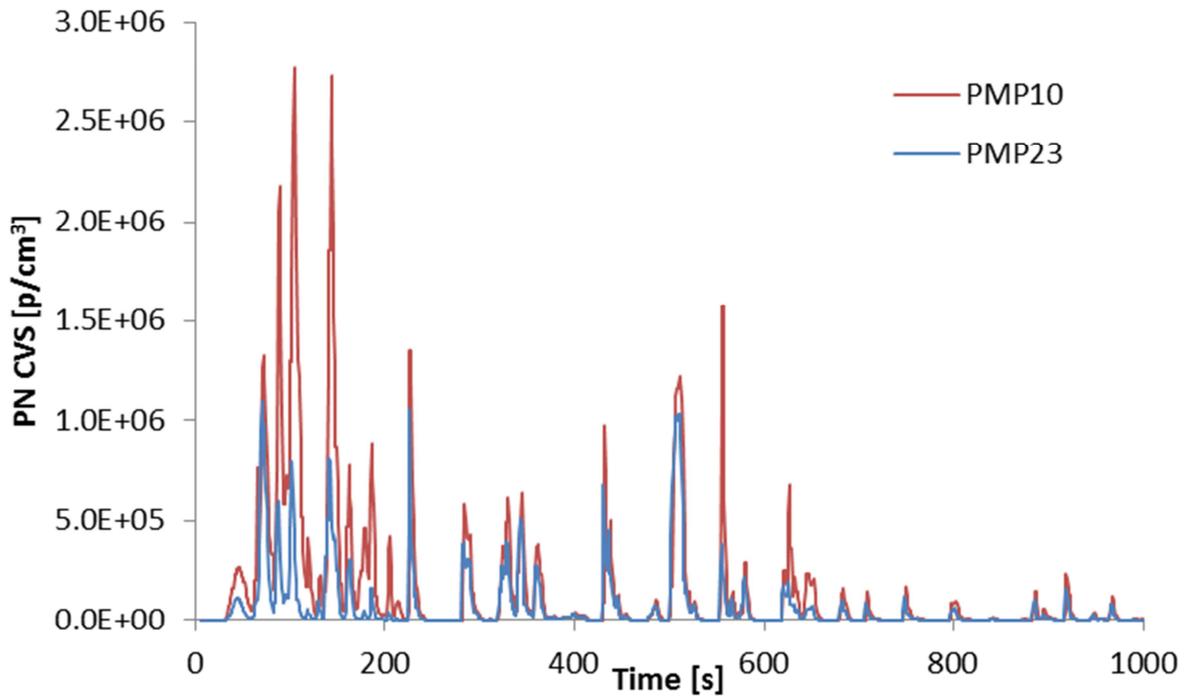
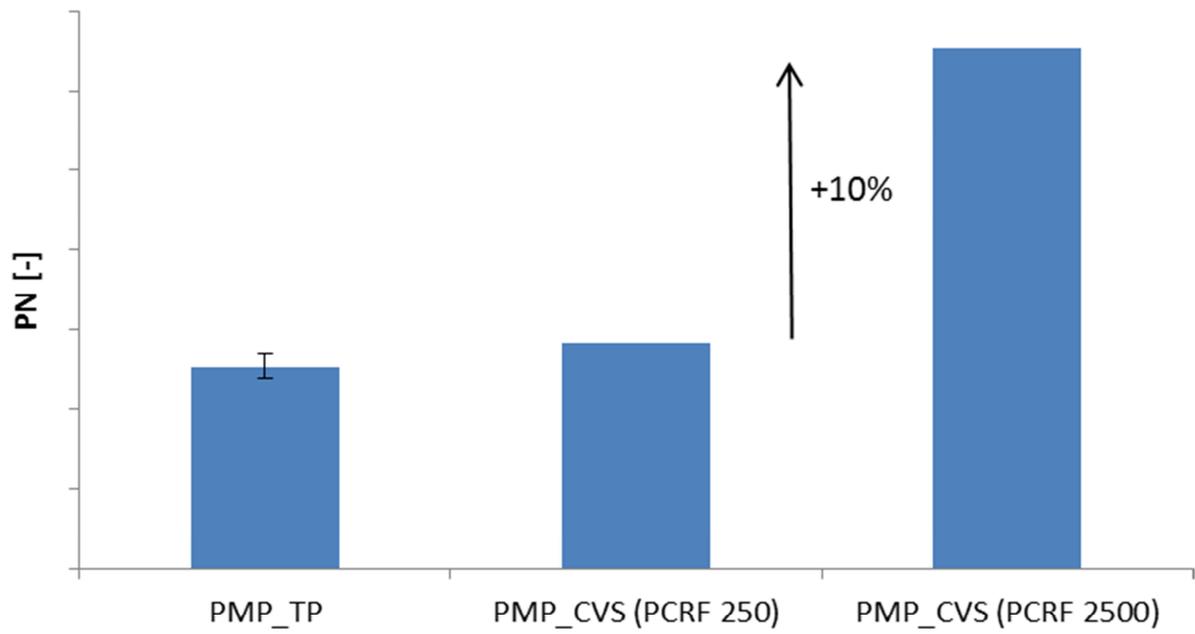


Figure 29: Typical measured concentration of CPCs (emissions around  $4 \times 10^{12}$  p/kWh for the whole cycle and  $1.5 \times 10^{13}$  p/kWh for the cold start part). Cold start at  $0^\circ\text{C}$  (20160323\_01\_ISC cold\_0°C).



**Figure 30: Difference of PMP\_CVS from PMP\_TP with different PCRFs. Exact levels not known due to lost OBD signal. Based on the distance the emission levels should be around  $5 \times 10^{12}$  p/kWh.**

## 4 Main evaluation phase: PN-PEMS #1: AVL

### 4.1 General

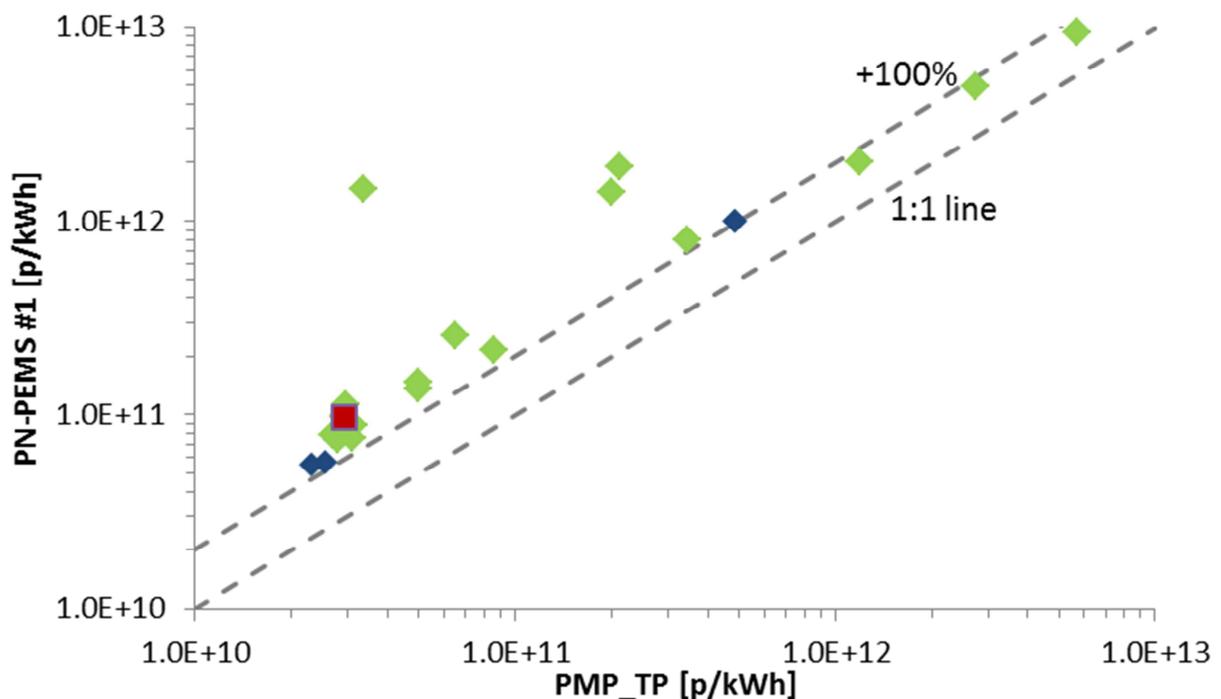
PN-PEMS #1 was available with vehicle V1. It was returned to the manufacturer to check the device and then it was used with vehicle V3 and V5.

### 4.2 Robustness

In general the device didn't have any issues during cold or hot ambient temperature tests. No indication of wear either. However, the results were not satisfactory: the device didn't have good correlation with the reference systems indicating sensitivity to pressure, humidity or particle size that will be discussed in the paragraphs below.

### 4.3 Accuracy

The comparison of PN-PEMS #1 with the PMP\_TP for vehicle V1 can be seen in Figure 31. In general there is a 100% overestimation of the emissions with some points overestimating the emissions one order of magnitude. These tests and five tests at -7°C which are not plotted had spikes of very high concentration.



**Figure 31: Comparison of PN-PEMS #1 with PMP\_TP for vehicle V1. Green points are tests at ambient temperature of 20°C. Blue points are tests at ambient temperature of -7°C (5 tests had artificial high spikes and are not plotted). Red points are tests at ambient temperature of 35°C.**

The results with vehicle V3 were not better (Figure 32). Although there were many points within 50%, there were others that were overestimating the emissions one order of magnitude. Similar behaviour was observed with V5 (Figure 33).

It is important to mention though that the low or high ambient temperature tests didn't cause any problems to the device. The possible reasons of the high deviations are discussed in the real time graphs in the next paragraph.

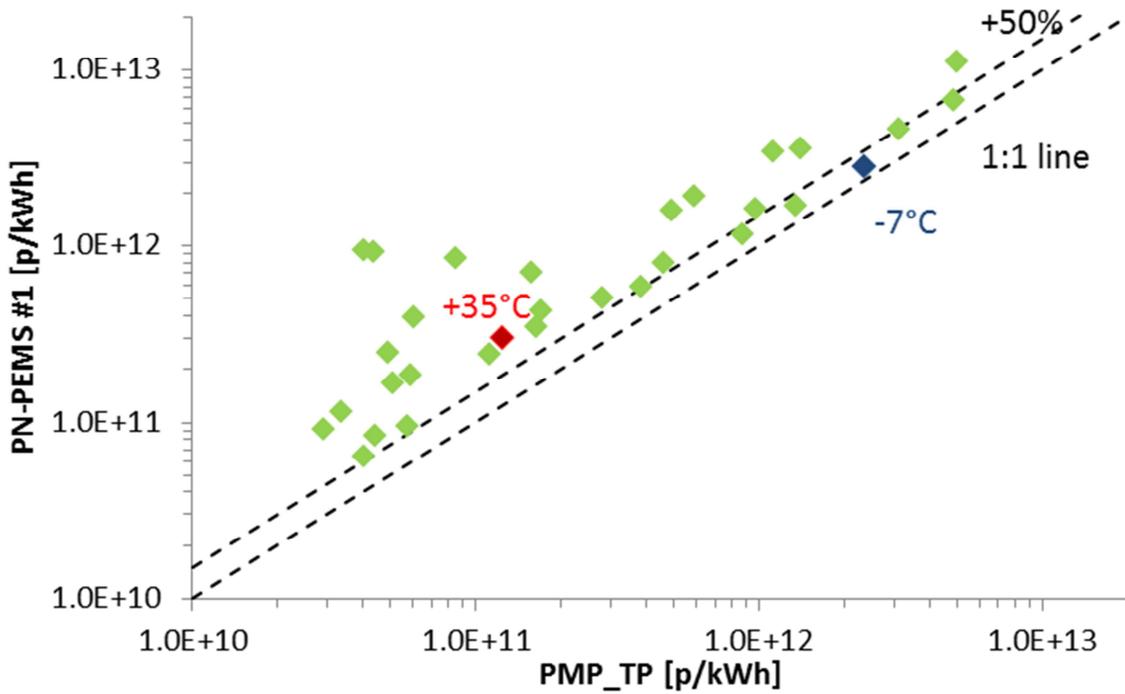


Figure 32: Comparison of PN-PEMS #1 with PMP\_TP for vehicle V3. Green points are tests at ambient temperature of 20°C. A test at -7°C is shown (blue point) and one at +35°C (red point); no more tests were conducted at extended ambient temperatures.

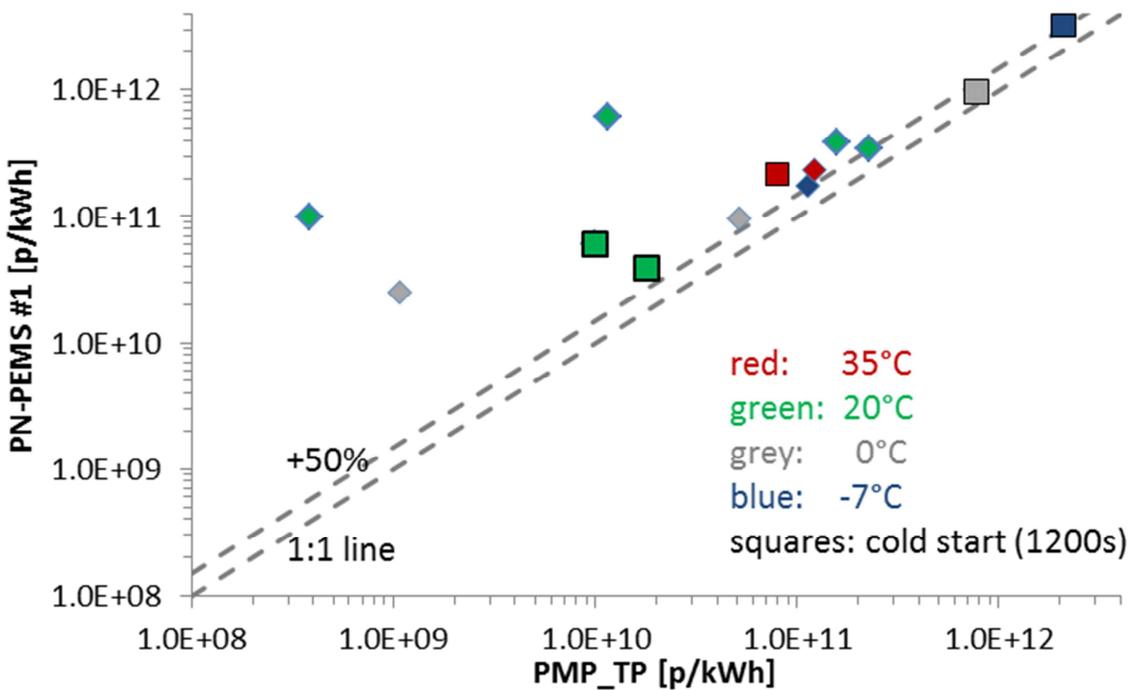
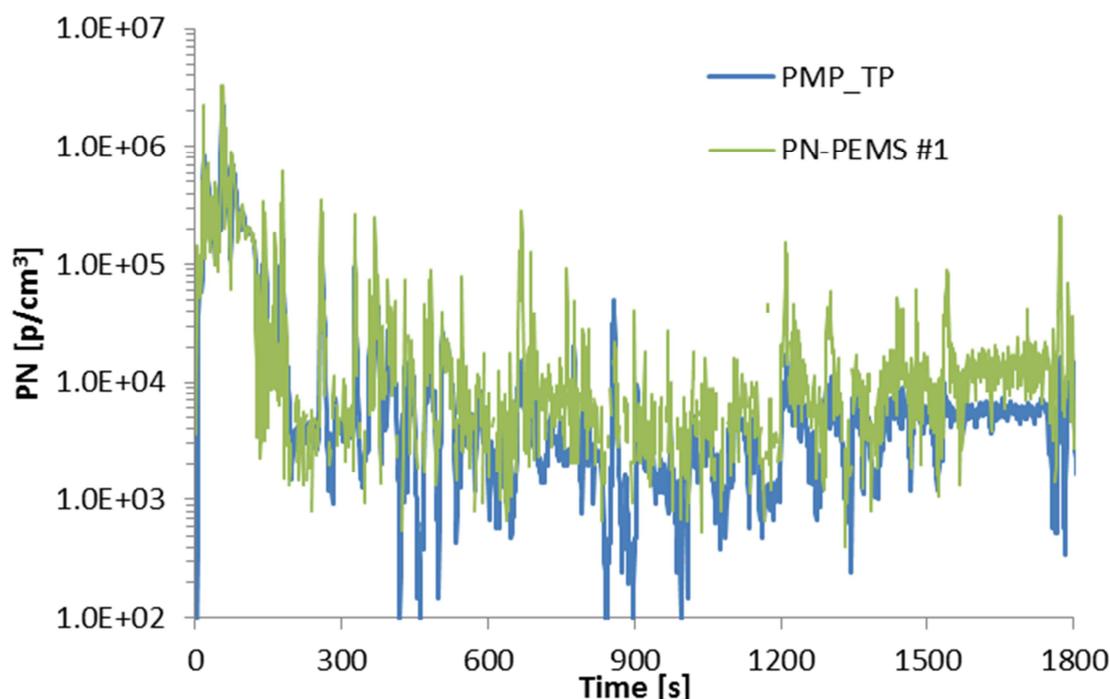


Figure 33: Comparison of PN-PEMS #1 with PMP\_TP for vehicle V5.

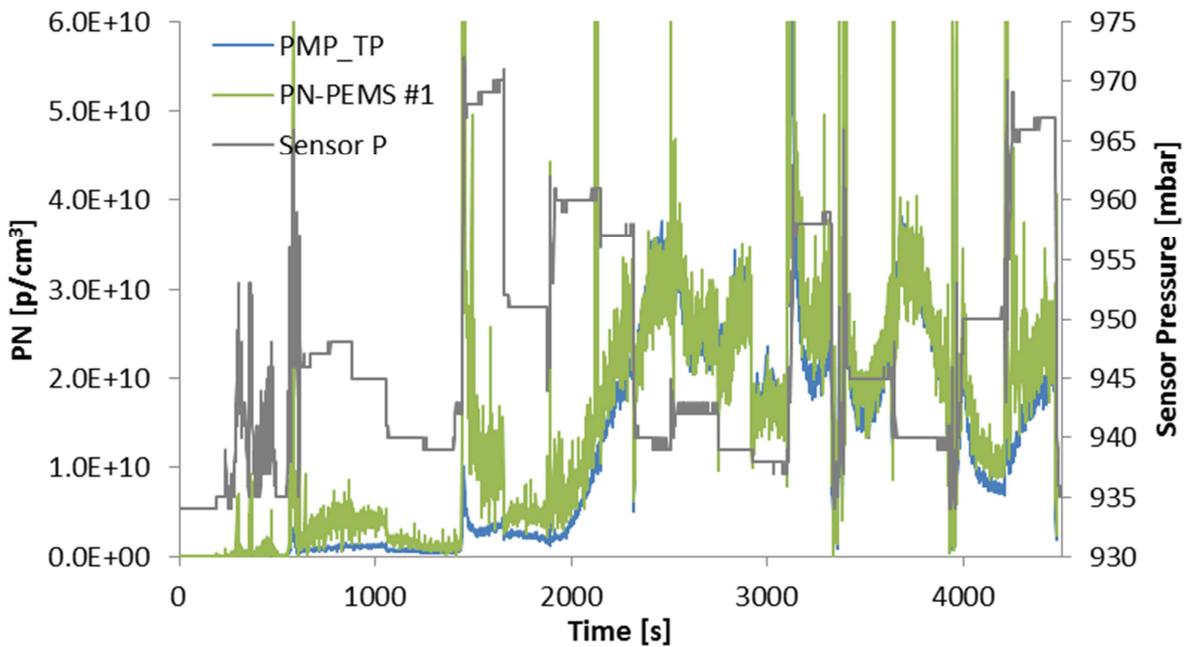
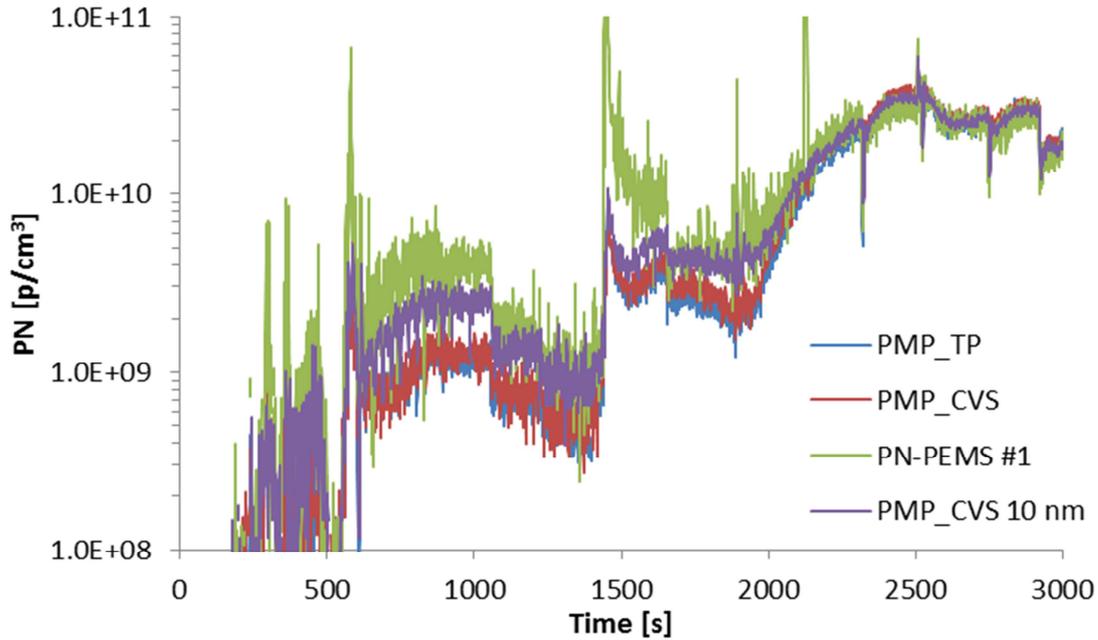
#### 4.4 Real time measurements

An example of a real time measurement of PN-PEMS #1 versus the PMP\_TP for vehicle V1 can be seen in Figure 34. At high concentrations (e.g. cold start) the agreement is good. Then the PN-PES has more spikes that reach 100000 p/cm<sup>3</sup>. At the end of the cycle the PN-PEMS is measuring higher than the PMP\_TP. Over this specific portion of the cycle the 10 nm CPC also registered more particle counts and this issue will be discussed in a later section. This was a test with, on average, good agreement between the two systems (36%).



**Figure 34: Real time comparison of PN-PEMS #1 with PMP\_TP over a cold start WHVC (vehicle V3) (20160411\_01\_WHVC cold). Difference over the cycle 36% (level  $3.3 \times 10^{11}$  p/kWh).**

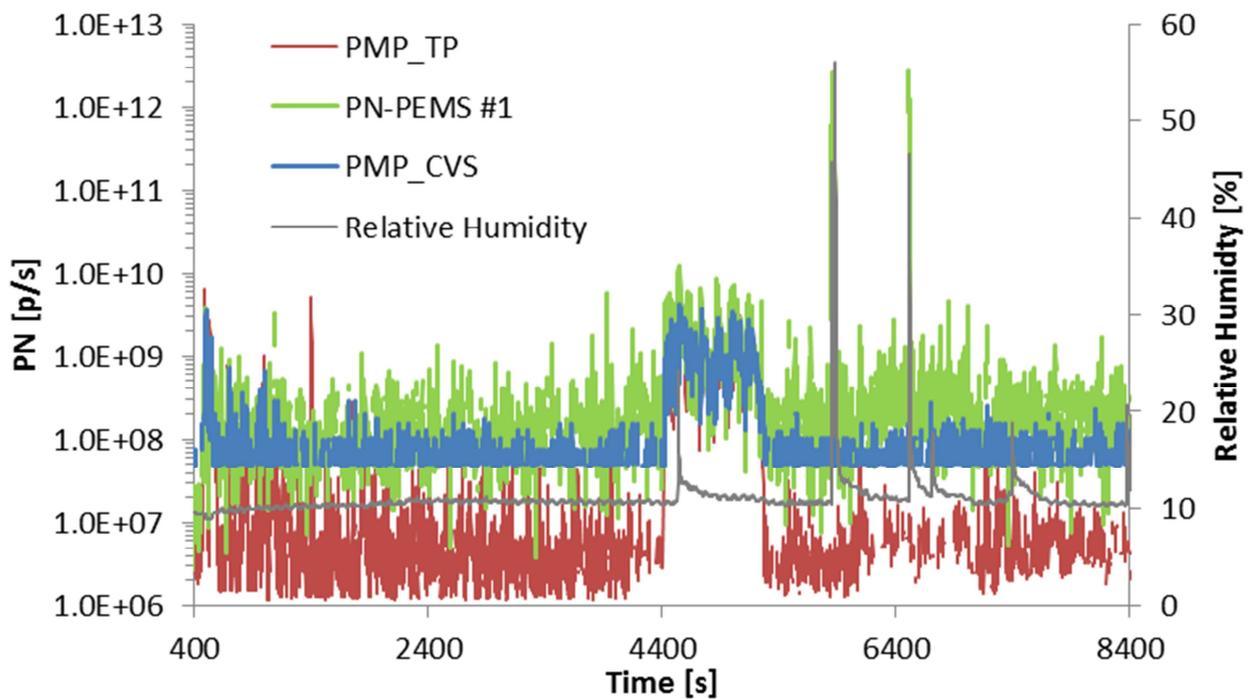
Another example during a SICO test with steady state points of high load can be seen in Figure 35. The PMP\_CVS of both the 23 nm and 10 nm CPCs are also given. The pressure at the particle detector of PN-PEMS is given in the second panel. The relative humidity at the detector was 10% to 16% and thus it is not plotted. A small dependency on the pressure and/or size of particles can be seen. The most important is that the rapid pressure changes result in huge spikes that affect the results. In this example without the spikes the difference of the PN-PEMS from the PMP\_TP is 30%, but including the spikes is 100%. It should be noted though that high pressure increases are not expected at typical chassis dynamometer testing and not on the road. Another interesting observations is that the higher emissions recorded by the PN-PEMS coincide with periods were the 10 nm CPC is also measuring higher. As the efficiency of the PN-PEMS for small particles is very low (<10% see Calibration chapter 11) it is possible that these particles are bigger that the 23 nm CPC cannot detect due to their structure or chemical composition.



**Figure 35: Real time comparison of PN-PEMS #1 with PMP\_TP over a SICO test (vehicle V3) (20160512-01-SICO).**

An ISC cycle is given in Figure 36. The emission levels are  $7.5 \times 10^9$  p/kWh. The PN-PEMS is measuring higher than the PMP\_TP because the emissions of the vehicle are at the background levels of the PN-PEMS. Nevertheless, this background level is quite close to the background level of the PMP\_CVS system. In this example there are two spikes of the PN-PEMS system that result in high average emissions for the cycle, close at the PN emissions limit of  $6 \times 10^{11}$  p/kWh. These two spikes are probably the result of a droplet entering the system, as the relative humidity at the detector of the PN-PEMS increases suddenly (without obvious reason from the engine operation). The difference of the PN-PEMS to the PMP\_TP is around 100% at the first part (first 1000 s) or the high emitting part of the cycle (around 4400-5400 s). At the low emissions parts of the cycle the PN-PEMS is measuring 6 times higher, but in absolute levels the difference is very small.

The overall emissions are  $7.5 \times 10^9$  p/kWh, the PN-PEMS measures  $5 \times 10^{11}$  p/kWh or  $2 \times 10^{10}$  p/kWh without these two spikes.



**Figure 36: Real time comparison of PN-PEMS #1 with PMP\_TP over an ISC cycle (vehicle V5) (20160519-01\_ISC cold).**

Another example with good agreement at the cold start, but noisy signal afterwards is given in Figure 37. In this case the ambient temperature was  $-7^{\circ}\text{C}$ . Although the difference is 20% at the cold start the PN-PEMS is measuring 18 times higher at the rest part of the cycle. The average cycle difference though is only 32%. Probably in this test there were condensates actually frozen at the inlet and causing this behaviour; the pressure downstream of the orifices of the device was not constant as it should be, but fluctuating.

In Figure 38, where the emissions are high, the difference of the PN-PEMS to the PM\_TP is 10%.

	PMP_CVS	PMP_TP	PN-PEMS	Diff to TP
Cold	1.18E+12	1.54E+12	1.24E+12	-19%
Rest	4.59E+09	2.61E+09	4.90E+10	1781%
All	6.83E+10	8.65E+10	1.14E+11	32%

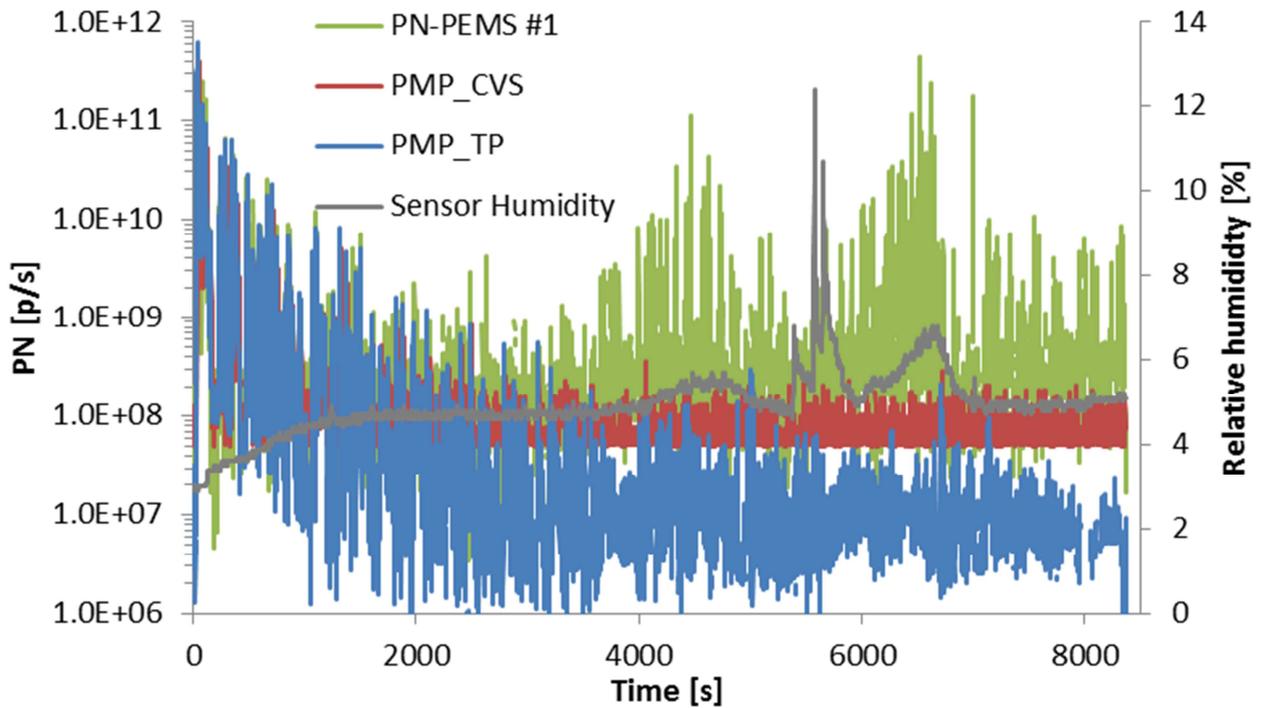


Figure 37: Real time comparison of PN-PEMS #1 with PMP\_TP over a cold start WHVC at -7°C (vehicle V5). (20160529\_01\_ISC cold\_-7°C)

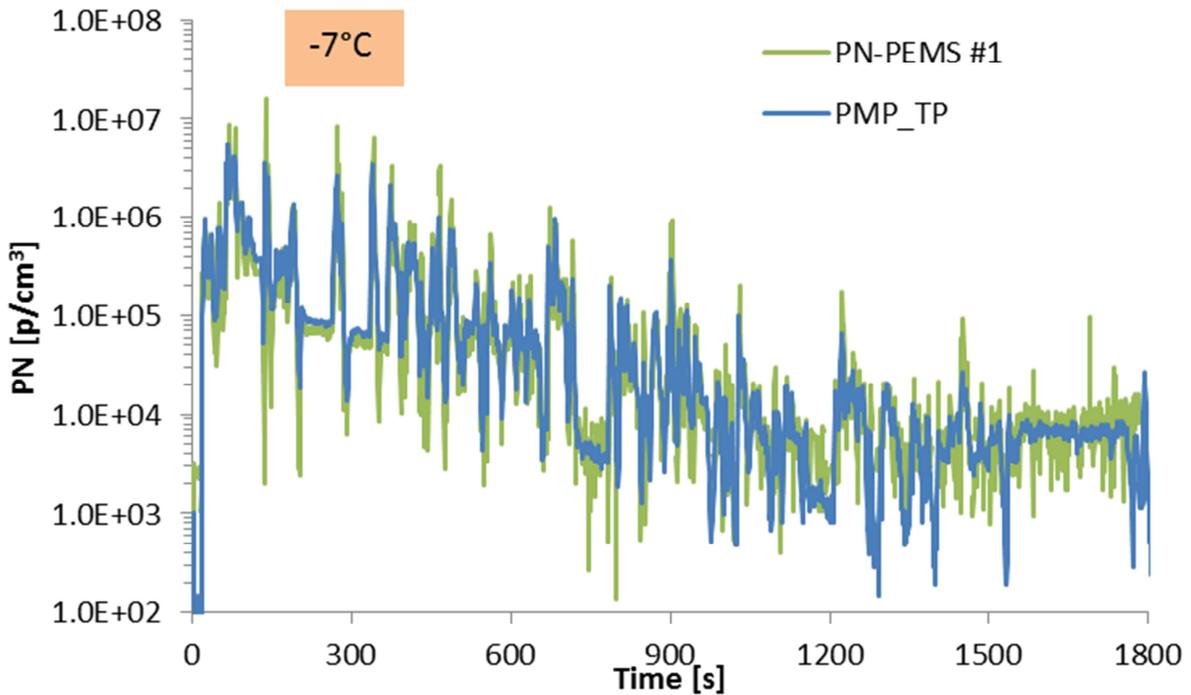


Figure 38: Real time comparison of PN-PEMS #1 with PMP\_TP over a cold start WHVC (vehicle V3) (20160415\_01\_WHVC cold\_-7°C)

## **4.5 Conclusions**

The conclusions for PN-PEMS #1 in the main evaluation phase are:

Only for high concentration levels (e.g. during cold start) the correlation of PN-PEMS to PMP\_TP is good (within 30%).

Very high differences were observed very often at low emission levels. One reason could be the sensitivity to particles smaller than 23 nm, although highly unlikely. The main reason though was high spikes which probably originated from pressure fluctuations and/or droplets entering the system.

It seems that the ambient temperature doesn't have any direct effect at the device. Indirectly it can affect the emissions by droplets and condensation upstream of the system that can create spikes.

No indication in the data file of errors or warnings. However this is not the case for the complete PEMS unit, which is logging all warnings and errors.

## 5 Main evaluation phase: PN-PEMS #2: HORIBA (mod NPET)

### 5.1 General

PN-PEMS #2 was available with vehicles V1 (unit PN-PEMS #2a and #2b), V3 (PN PEMS #2c), V5 (PN PEMS #2c) and V6 (PN-PEMS #2c).

### 5.2 Robustness

During the evaluation phase three units were tested. One of them was the light-duty unit (PN-PEMS #2a) and was available only for a limited time.

PN-PEMS #2b (solid diamonds in Figure 39) had a good agreement with the reference system at the tailpipe (within 25%) (vehicle V1). However, after the tests at low ambient temperature the difference drifted to -20% to -30% and remained at those levels for all tests (even at 20°C). During those low ambient temperature tests the instrument showed some errors. The on-road tests were done without any errors from the device. This unit failed at the first test with vehicle V2 and was sent back for repair.

PN-PEMS #2c (open squares) was within 20% of the PMP\_TP and remained at this level for all laboratory before and after on-road tests (including a few low temperature tests before the on-road tests). With vehicle V3 the differences remained within 20% (open triangles). However during the low ambient temperature tests some errors appeared. With the next vehicle V6 (open circles) the differences were up to -40%. After a few tests the system stopped working.

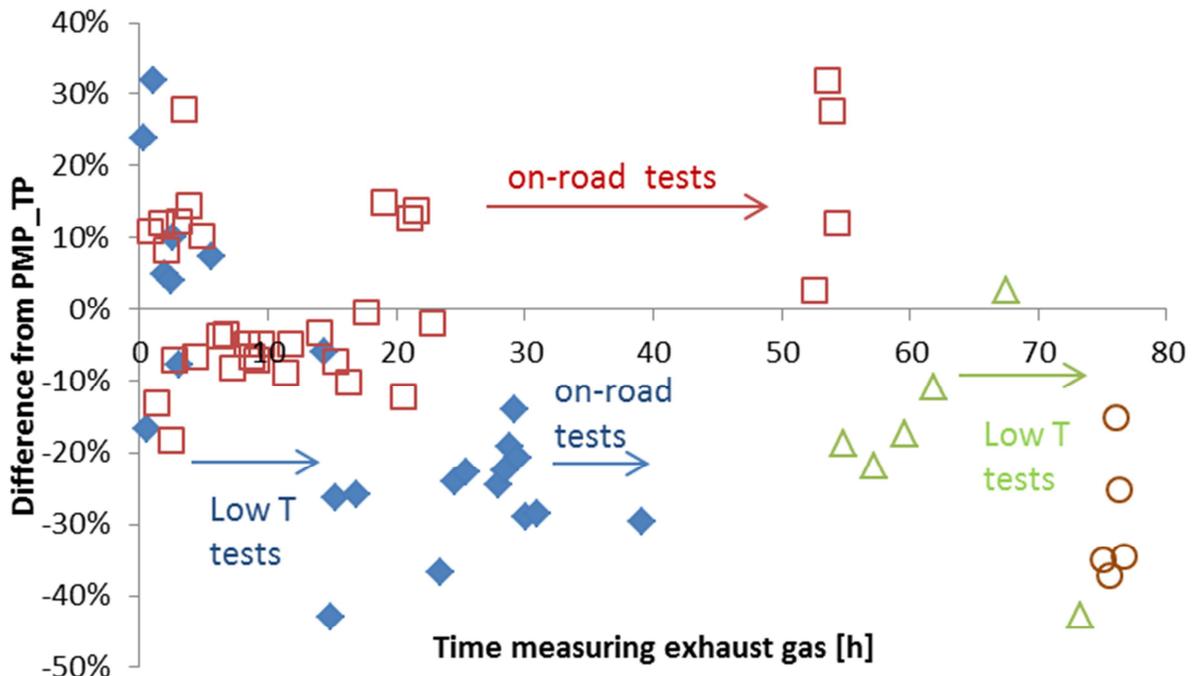


Figure 39: Evaluation over measuring time of PN-PEMS #2. Solid diamonds are unit PN-PEMS #2b with vehicle V1. Open symbols are unit PN-PEMS #2c with vehicle V3 (open squares), V5 (open triangles) and V6 (open circles).

The main conclusion is that the system is not very robust at low ambient temperatures. It needs to be mentioned that HORIBA's modified NPET, which is prototype, was a concept study to prove the feasibility of the system design with respect to accuracy and robustness in mobile applications. Further improvements regarding robustness against low ambient temperatures were introduced in the final product, namely the OBS-ONE-PN (On-Board System for Particle Number measurements). Some of these improvements will be discussed in this report in the real time measurements section.

### 5.3 Tilting

The CPC of the PN-PEMS #2c was evaluated regarding the stability of its counting efficiency on tilting the instrument and shaking. Only this system was checked as it was the only PEMS CPC-based system available at that time. No DC-based system was checked as there were no concerns regarding tilting for this technology.

The setup was the typical calibration set up: A soot generator (APG from AVL) produced thermally stable particles which were classified in a Differential Mobility Analyzer 3080L from TSI. The monodisperse aerosol was sent to a reference CPC (3025A from TSI), a PMP CPC (3790 from TSI) (but not any of those used in the current measurement campaign) and the isopropanol CPC of the PEMS. For these tests the dilution and thermal pre-treatment system of the PN-PEMS was bypassed, thus the monodisperse aerosol was connected directly to the inlet of the CPC. For this reason the results of the PN-PEMS were divided with the PCRF. The PMP CPC was kept at a fixed position without any tilting or shaking, as control unit.

The results are shown in Figure 40. The PMP CPC has low counting efficiency at 23 nm (30%) and reaches approximately 95% at 100 nm. The PEMS CPC has 65% counting efficiency at 23 nm and 90% at 100 nm. The absolute levels of the counting efficiencies should be considered with care as they were estimated by the PEMS result divided with the (estimated) PCRF of the unit. In addition, it's not known how the experimental setup (opened device and connecting directly to the PEMS CPC) has affected the instrument.

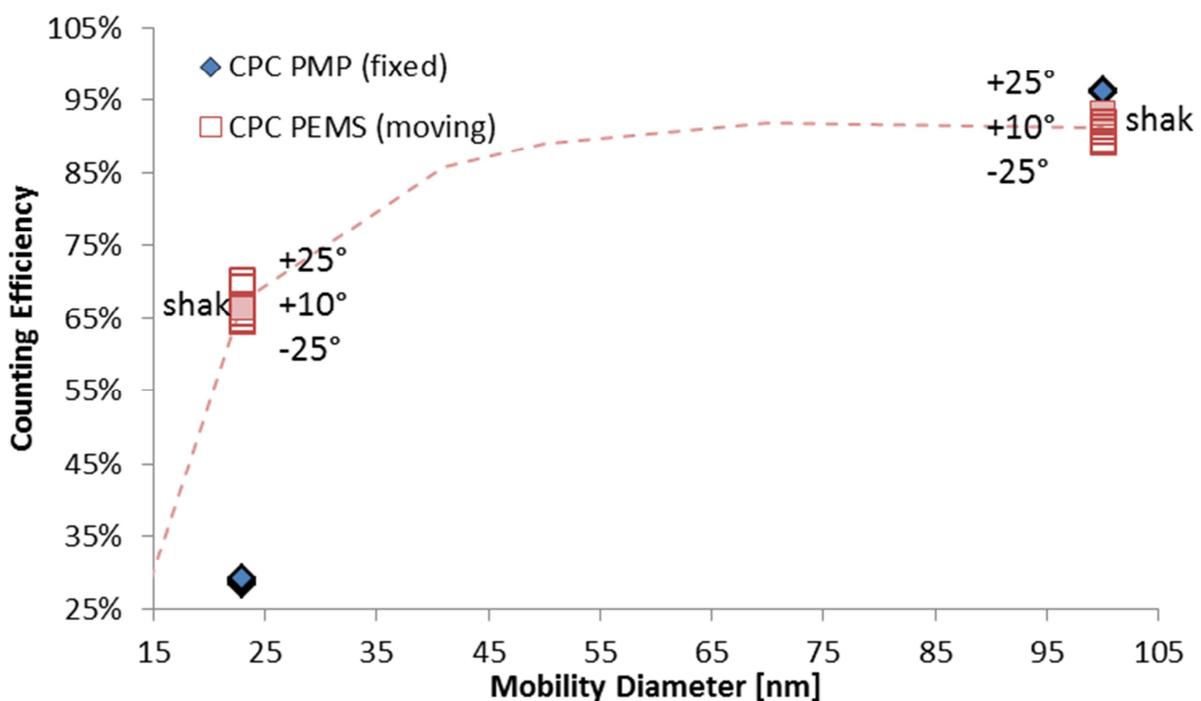
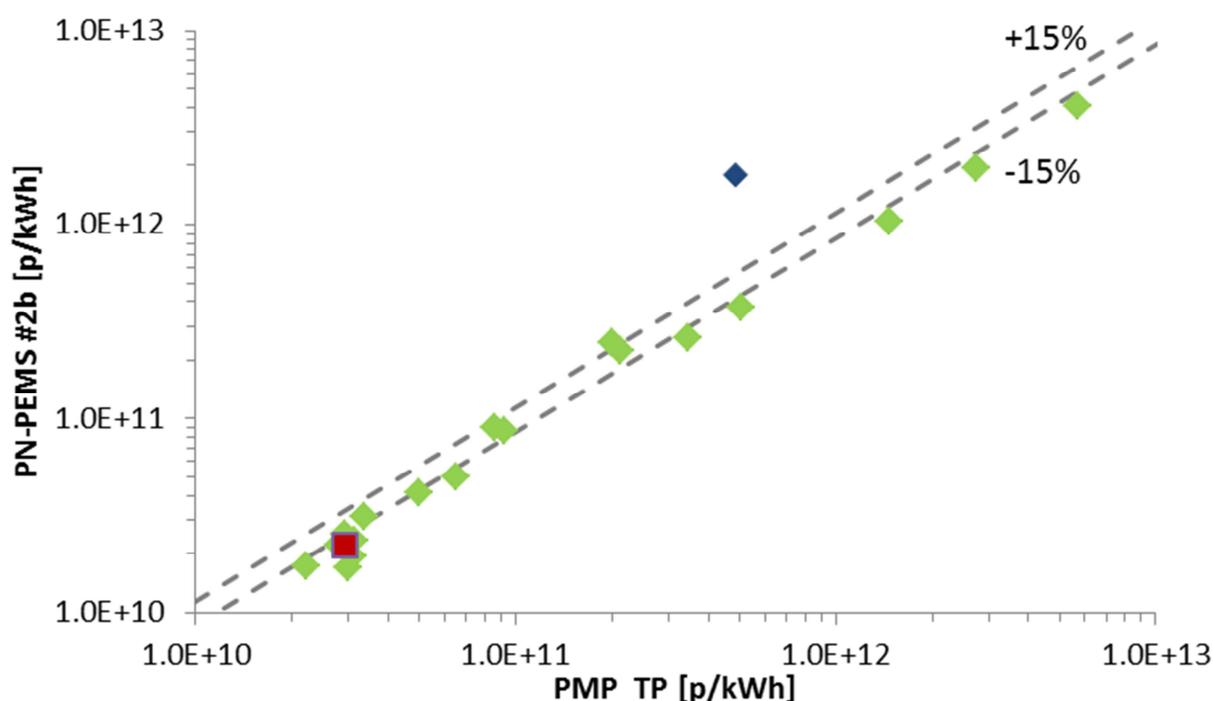


Figure 40: Stability of the CPC of PN-PEMS #2 at vibration and tilting at different angles.

Tilting the instrument for around 2 min had a small effect on the counting efficiencies; they were slightly higher or lower at the 23 nm size. The effect on the counting efficiencies was in the range of 5% at 23nm during extreme tilting (+25° slope, which is above the specification of the manufacturer)) and it was a little bit smaller at 100 nm. The efficiencies during strong shaking of the instrument were also within the experimental uncertainty. This information in addition to the vibration testing of the instrument manufacturer indicate that the instrument can be considered robust enough for the on-road tests.

## 5.4 Accuracy

The comparison of PN-PEMS #2b with the PMP\_TP for vehicle V1 can be seen in Figure 41. All green points (i.e. at temperatures between around 20°C) are within  $\pm 25\%$ .



**Figure 41: Comparison of PN-PEMS #2b with PMP\_TP for vehicle V1. Green points are tests at ambient temperature of 20°C. At different temperatures the system had errors. Only for illustrative purposes a test at -7°C is shown (blue point) and one at +35°C (red point). Dotted lines show the  $\pm 15\%$  differences from the 1:1 line.**

The comparisons of PN-PEMS #2c with PMP\_TP for vehicles V3 and V5 are shown in Figure 42 and Figure 43 respectively. The differences are within 15%. With vehicle V3 only a limited number of tests at extended ambient conditions were conducted. These tests were still within the 15% differences that was observed at the 20°C tests.

Different ambient temperatures were examined with vehicle V5. The tests at -7°C and 0°C with high emissions were again within 15% from the PMP\_TP. The tests with lower concentrations had big (relatively) differences. As it will be shown in the real time graphs, there were spikes that artificially increased the concentration. The +35°C tests were lower than the PMP\_TP system. It is not clear though if this has to do with the temperature or because these tests were after the low temperature tests and there was a small drift (see discussion in robustness).

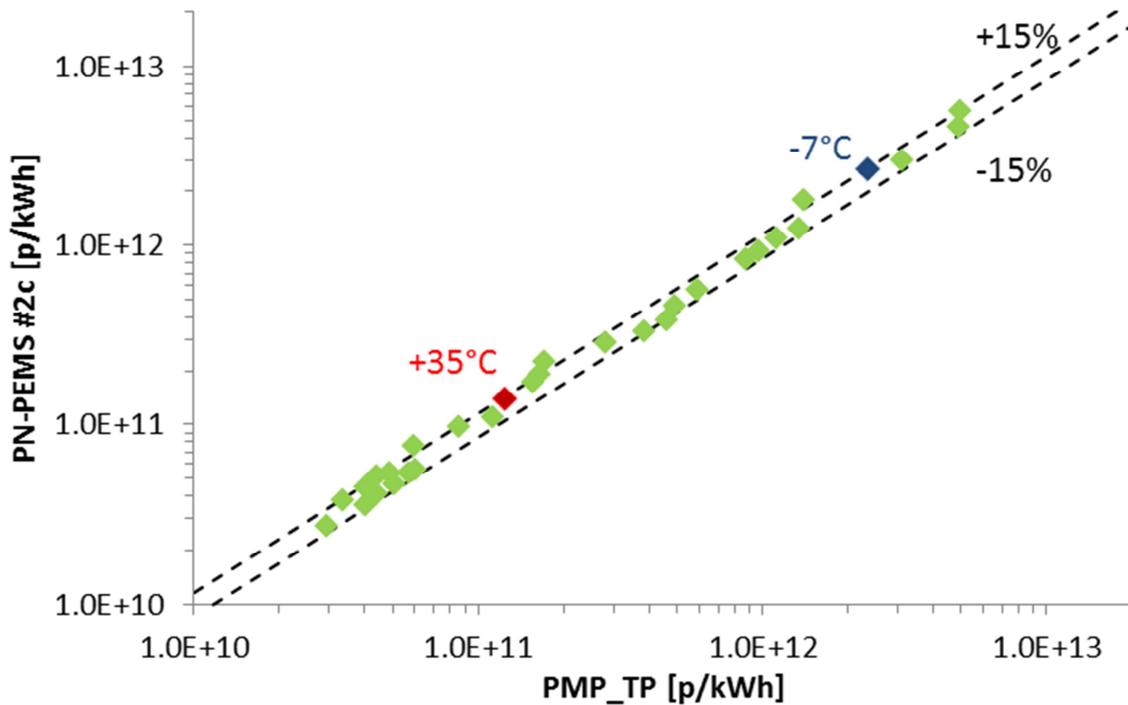


Figure 42: Comparison of PN-PEMS #2c with PMP\_TP for vehicle V3. Green points are tests at ambient temperature of 20°C. A test at -7°C is shown (blue point) and one at +35°C (red point); no more tests were conducted at extended ambient temperatures. Dotted lines show the ±15% differences from the 1:1 line.

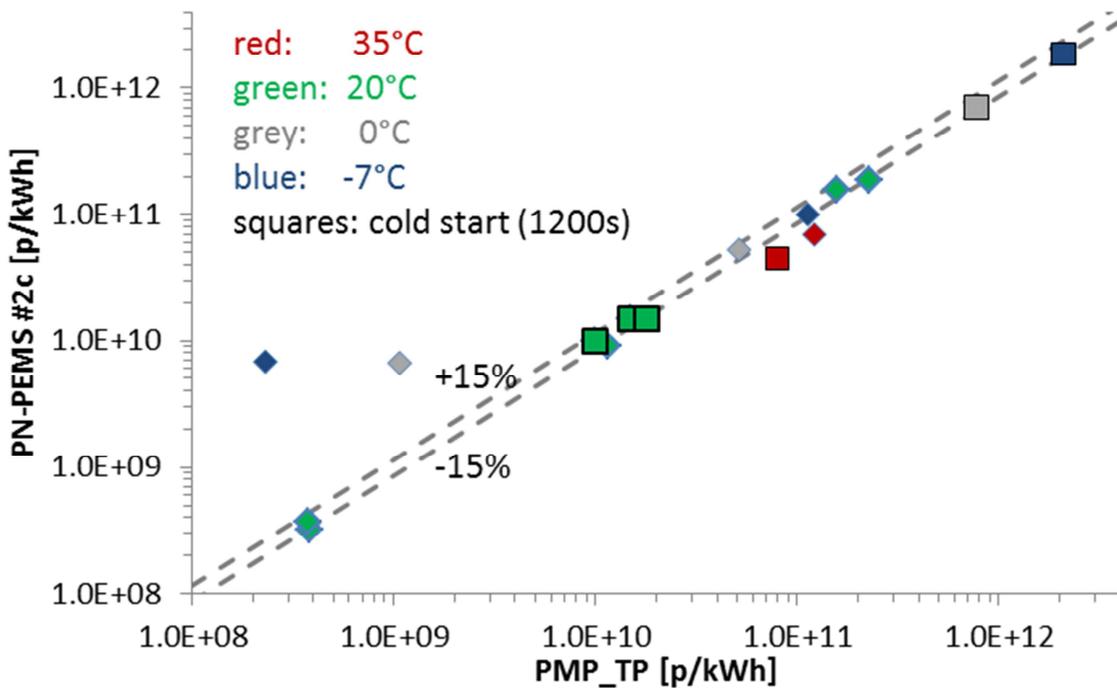


Figure 43: Comparison of PN-PEMS #2c with PMP\_TP for vehicle V5. Dotted lines show the ±15% differences from the 1:1 line.

## 5.5 Real time measurements

Some real time comparisons with the PMP\_TP and PMP\_CVS systems are shown in Figure 44 and Figure 45 where an excellent agreement is shown. This agreement holds true even for cold start (Figure 46).

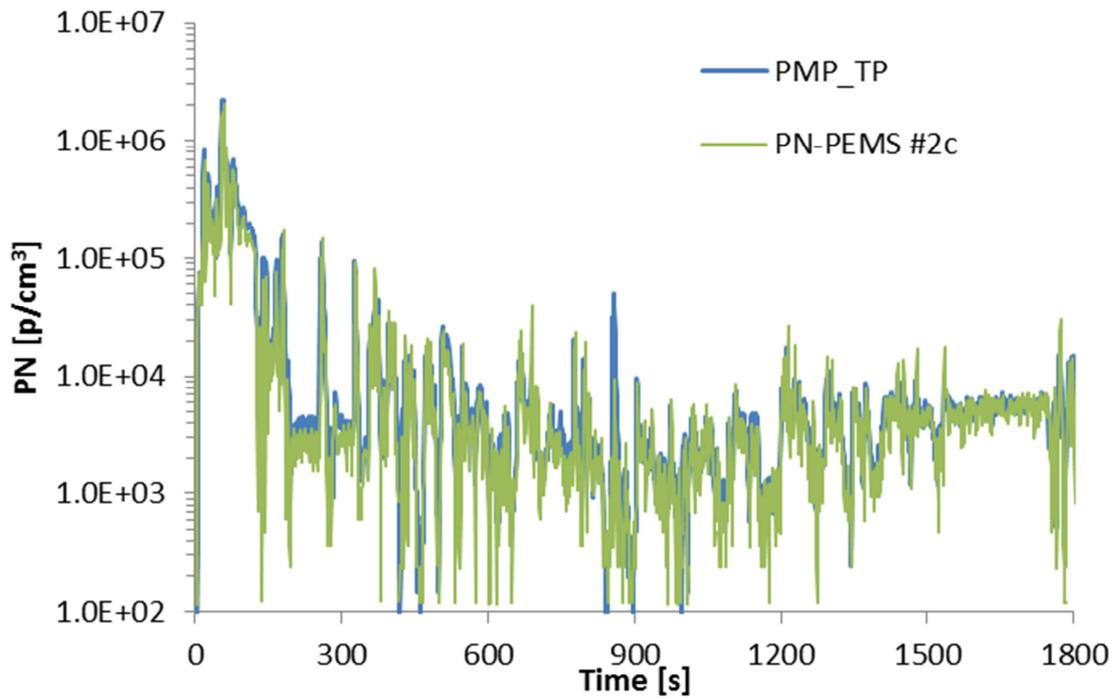


Figure 44: Real time comparison of PN-PEMS #2c with PMP\_TP over a cold WHVC (vehicle V3) (20160411\_1\_WHVC cold).

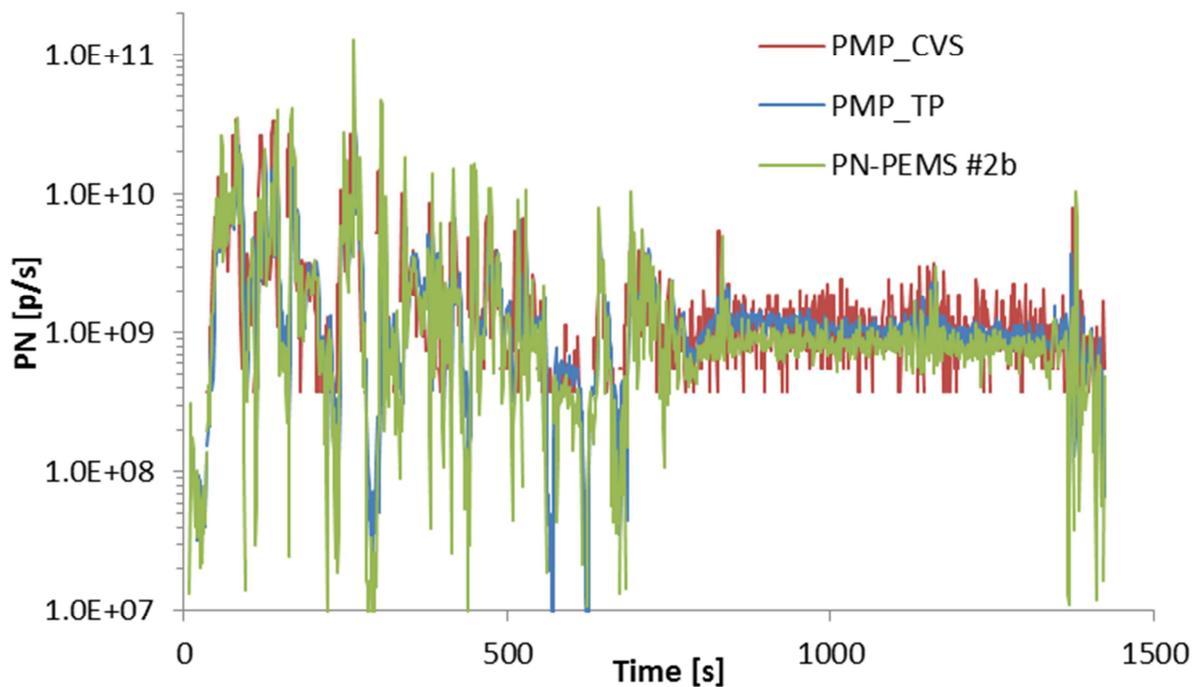
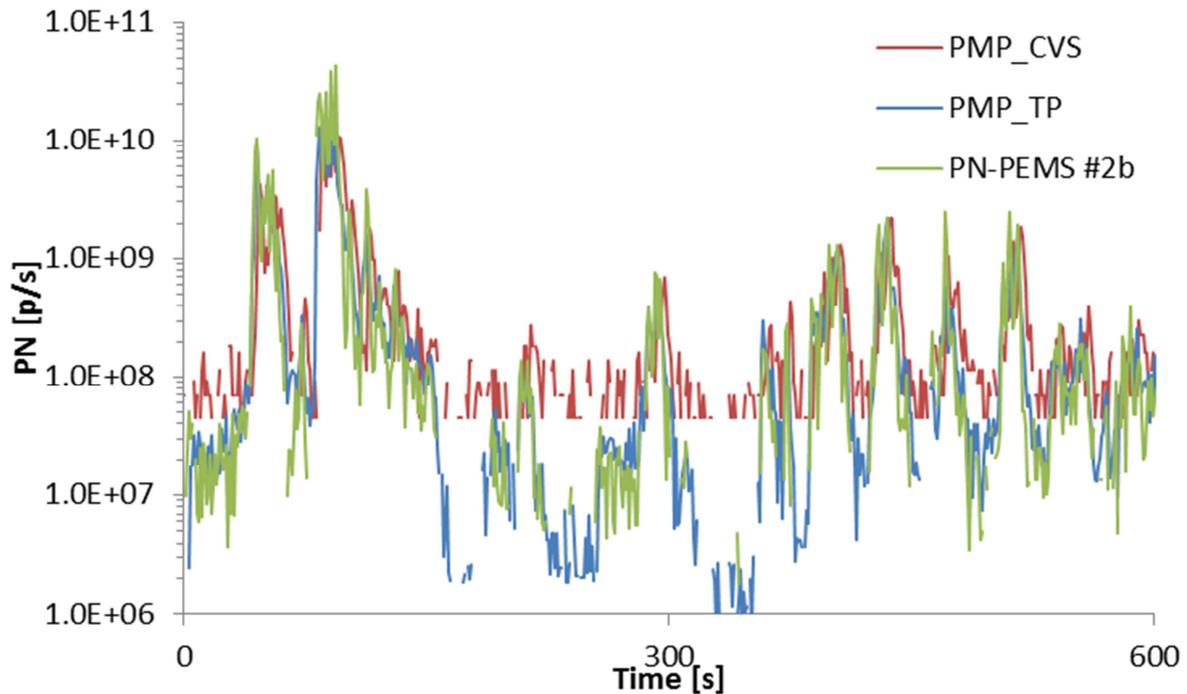


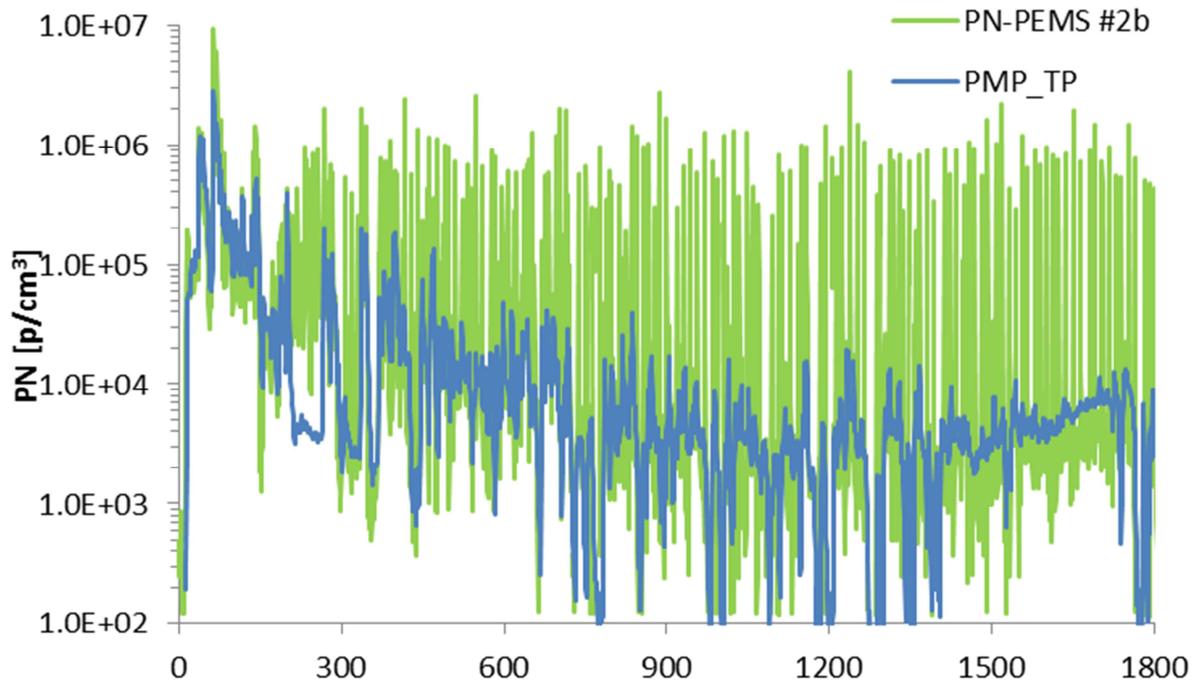
Figure 45: Real time measurements with vehicle V1 (20160204\_3\_cycle-steady).



**Figure 46: Real time comparisons at cold start with vehicle V1 (20160205\_1\_WHVC cold).**

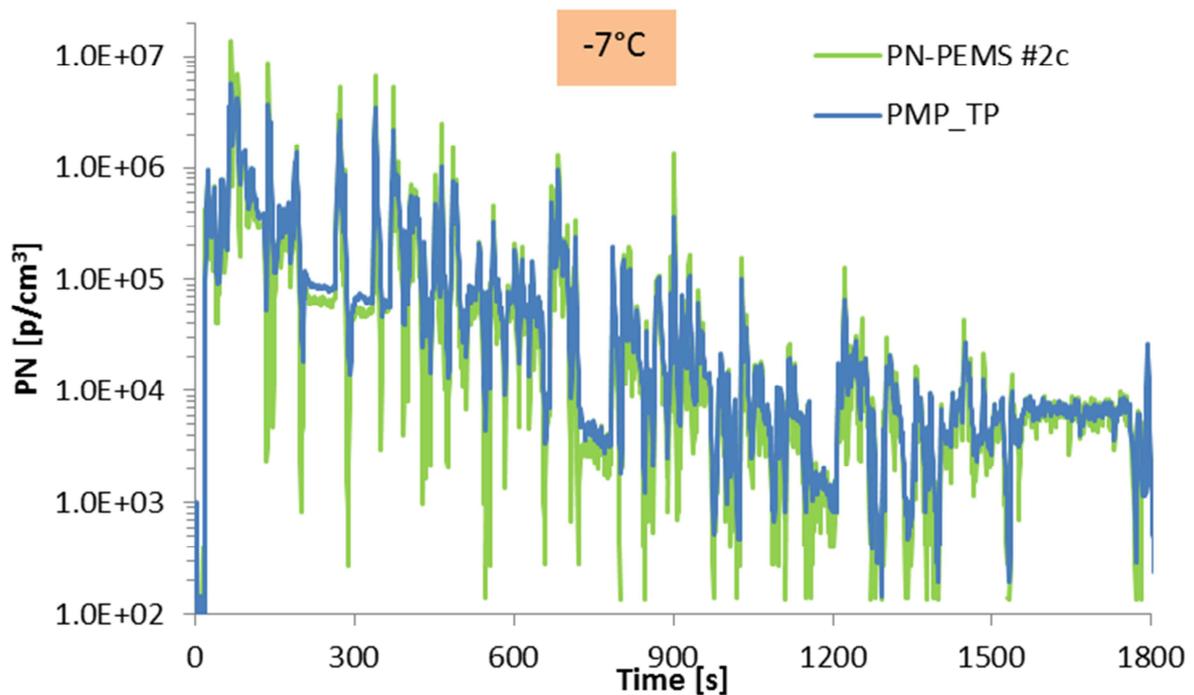
In 10 tests at extended temperature conditions with vehicle 1, e.g. at low ( $\leq 0^{\circ}\text{C}$ ) or high ambient temperatures ( $35^{\circ}\text{C}$ ), the PN-PEMS #2b had several errors such as CPC flow error, CPC bypass flow error, optics temperature error or dilution ratio error. These tests are not shown in (Figure 41). One of these tests is shown only for illustrative purposes (Figure 47). There are many spikes of high concentration that would result in emissions  $>6 \times 10^{11}$  p/km. The root cause of these spikes is unclear but according to the instrument manufacturer there are several possible explanations:

- (1) Electrical noise due to ice formation on the CPC detector board: PN-PEMS #2 was not actively controlling the cabinet temperature. The OBS-ONE-PN production version contains an active control of the cabinet temperature by means of shutting down the cooling fans at a certain ambient temperature to avoid cabinet temperatures below  $0^{\circ}\text{C}$ .
- (2) Water condensation in the sample line due to either an exceedance of the water storage capacity of the dryer for the dilution air or cold spots somewhere in the main cabinet. The OBS-ONE-PN keeps the cabinet temperature above  $0^{\circ}\text{C}$  under all conditions as described above. Furthermore a humidity sensor was implemented in the dilution air line to give an indication about the remaining water storage capacity of the desiccant dryer. The mod. NPET did not had these functions.
- (3) Formation of isopropyl alcohol particles in the CPC optics block. The mod. NPET controls the optics temperature so that the temperature is kept a few degrees above the condenser temperature in order to avoid condensation of isopropyl alcohol in the optics block. Nevertheless the upper temperature limit is not controlled (this function has been implemented in the OBS-ONE-PN production version) which might lead to nucleation of isopropyl alcohol particles.

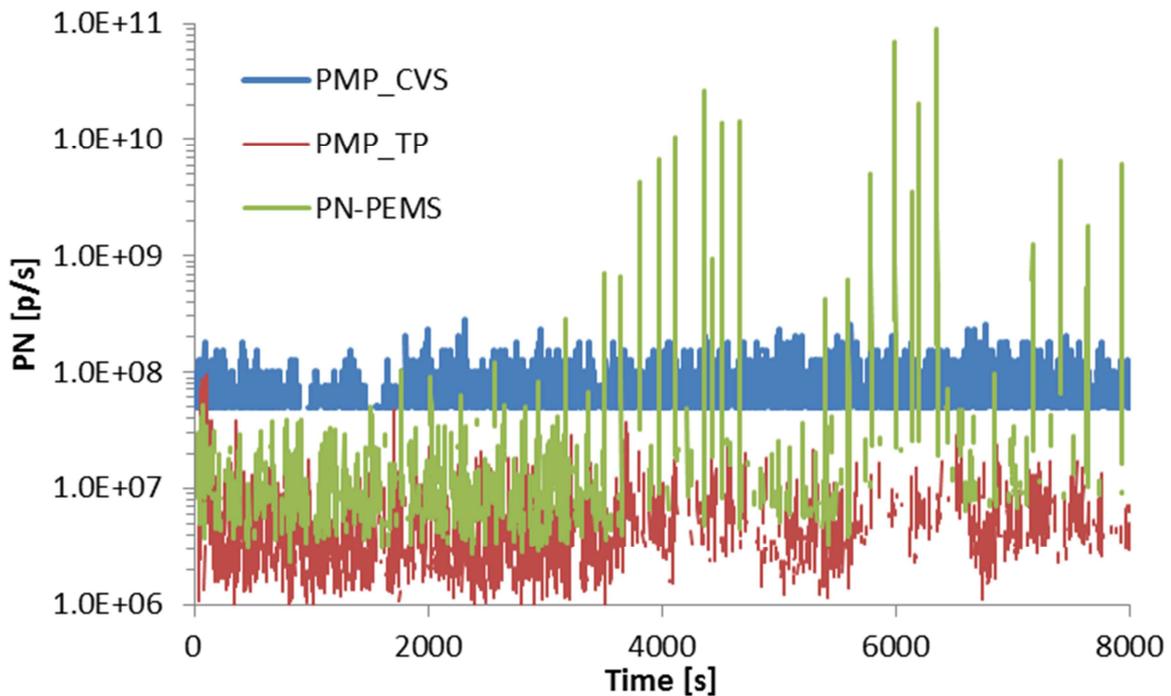


**Figure 47: Real time measurements over a WHVC at ambient temperature of 0°C (20160225\_1\_WHVC cold 0°C). Vehicle V1.**

The PN-PEMS #2c could measure one WHVC cold start test at -7°C without any issues (Figure 48). However, during an ISC cycle at -7°C spikes appeared probably due to one of the reasons discussed above. The first spike appeared approximately after 6h of operation at -7°C (Figure 49). Note that approximately after 4h the wick was exchanged by another fully charged wick (PN-PEMS #2 does not have a reservoir of liquid working fluid, but a charged CPC wick only. This wick needs to be recharged in isopropyl alcohol after approximately 4 hours).



**Figure 48: Real time measurements over a WHVC at ambient temperature of -7°C with vehicle V3 (20160415\_01\_WHVC cold at -7°C).**



**Figure 49: Real time measurements over an ISC cycle at ambient temperature of -7°C with vehicle V5 (20160520\_2\_ISC -7°C).**

In this case the effect on absolute emissions was small. The 'true' emissions as measured by the PMP\_TP were  $1.7 \times 10^8$  p/kWh, the emissions measured by the PMP\_CVS system were  $3.2 \times 10^9$  p/kWh due to the CVS background and the PN-PEMS #2c measured  $5.0 \times 10^9$  p/kWh due to the spikes. The spikes in this case were up to  $5 \times 10^5$  p/cm<sup>3</sup> and not  $2 \times 10^6$  p/cm<sup>3</sup> like in Figure 47.

## 5.6 Regeneration

All vehicles tested (except V2 which was a CNG one) had DPFs and they regenerated passively. Only in a few tests where high loads and exhaust gas temperatures were experienced (SICO tests) the instruments were really challenged regarding high temperatures. For one test it was possible to actively regenerate the DPF with the help of the OEM. The results of this test can be seen in Figure 50. The regeneration starts at approximately time 3000 s and lasts until time 7500 s. The first 3000 s the engine was off or idling ("missing" data of the PN-PEMS #2b in the first 3000s are related to zero emissions which cannot be plotted in log scale). The emissions at the tailpipe are approximately  $10^5$  p/cm<sup>3</sup>. The PN-PEMS #2b measures as the PMP\_TP without any indication of malfunctioning. Note that the PN-PEMS was connected at the tailpipe and it was installed inside the vehicle (immediately after the on-road tests). Thus it was experiencing very high exhaust gas temperatures (425°C). The PMP\_TP was connected just before the CVS mixing point thus the temperatures were much lower. The final result of the PN-PEMS was -30% compared to the PMP\_TP in agreement with previous tests that had differences of around -25%. The conclusion is that the PN-PEMS can measure during regeneration events without any wear issues.

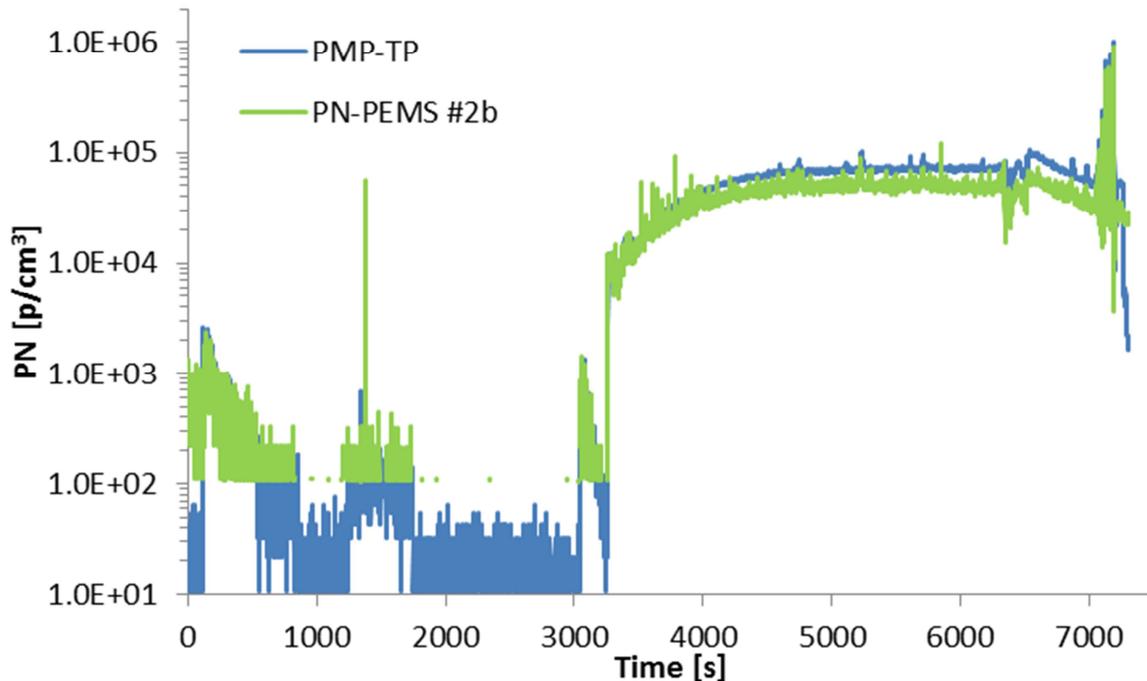


Figure 50: Active regeneration test (20160314\_regeneration).

## 5.7 Comparison of Horiba units

For a short period two units were available. Unit PN-PEMS #2a is the light-duty inter-laboratory correlation exercise unit. Unit PN-PEMS #2b was the unit for the heavy-duty vehicles evaluation program. Both units were measuring in parallel. The differences of the two units were within 10-25%; the light-duty unit probably was overestimating as it was also measuring higher than the PMP systems both at the tailpipe and the CVS. There was no particular tendency or trend at these tests to explain the differences; i.e. the differences couldn't be explained by emission levels, test type or duration of the test.

## 5.8 Conclusions

The main conclusions for the PN-PEMS #2 from Horiba (modified NPET) are:

- Very good correlation with the PMP\_TP: Differences within 15% (or 25% with the first unit) at 0-20°C.
- No issues with engine cold start and regeneration events.
- Robust device for mobile applications (no issues with inclination and/ or shaking)
- Tendency of drift after tests at low ambient temperature. The low ambient temperature tests had errors of the optics. They also showed high artificial spikes. These issues shouldn't appear in the production version units OBS-ONE-PN which have implemented some functionalities to address this topic.
- File with no real time errors (only one error for the whole test) as the mod. NPET was operated by a very basic software. A real time error file is implemented in the OBS-ONE-PN control software.
- No results are available with vehicle V2 (CNG).

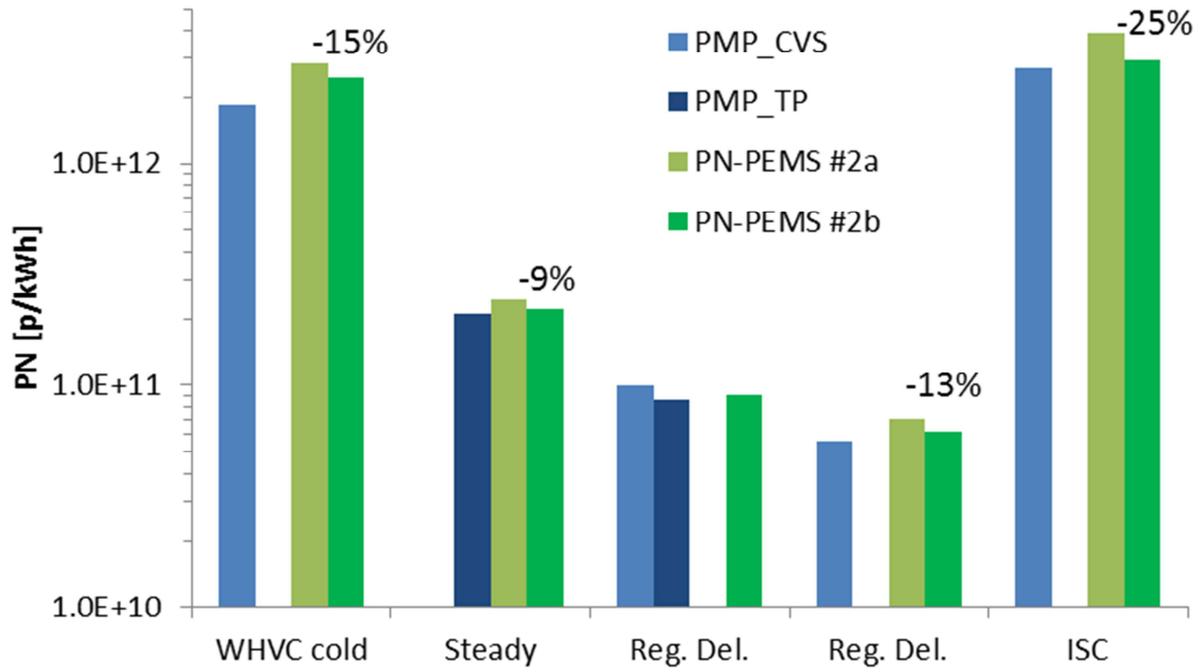


Figure 51: Comparison of two PN-PEMS units with the reference systems.

## 6 Main evaluation phase: PN-PEMS #3: TESTO (NanoMet 3)

### 6.1 General

PN-PEMS #3 was available with V1 (unit PN-PEMS #3a), V2 (unit PN-PEMS #3b) and V3 (unit PN-PEMS #3b).

### 6.2 Robustness

During the evaluation phase two units were tested. Both of them had issues and failed. The first one was the light-duty unit (PN-PEMS #3a). It had already some issues from the inter-laboratory exercise ('offsets too high or unstable', ' $I_{diff}$  out of range'). At the tests at +35°C the error 'temp. stage out of range' also appeared. The second unit was used with the CNG vehicle V2. A warning appeared at the +35°C tests ('corona voltage out of range') but there was no indication of malfunctioning even at the low ambient temperature tests.

The same warning insisted with vehicle V3. At the -7°C test the error 'low meas. gas pump' appeared and then the unit was not functioning as the pump was not sampling (the unit was left overnight at -7°C). When the unit was sent back to the manufacturer it was found that this problem was due to a kinked tubing upstream of the impactor module.

The conclusion of these tests is that the unit was robust enough at the temperatures specified by the manufacturer (5-30°C).

### 6.3 Accuracy

The comparison of PN-PEMS #3a with the PMP\_TP for vehicle V1 can be seen in Figure 52. Although many points are missing due to errors and warnings (that existed from the beginning of the measurement campaign), the points that are shown have a relatively good agreement with the PMP\_TP.

The comparison of the PN-PEMS #3b with the PMP\_TP for vehicle V2 is shown in Figure 53 and for vehicle V3 in Figure 54. The results are within 30% for emission levels  $>1 \times 10^{11}$  p/kWh. Higher (relative) differences can be seen at lower levels where the detection limit of the PN-PEMS is approached.

The results also show, that as long as there are no errors, the values that are measured at low or high ambient temperatures are accurate enough, i.e. the differences to the PMP\_TP are similar to the differences observed at 20°C.

A point that needs attention is the cold start. Depending on the size of the particles there might an effect (i.e. PN-PEMS and PMP\_TP measuring differently) (Figure 53) or there could be no effect (Figure 54). This will be shown better in the real time measurements section.

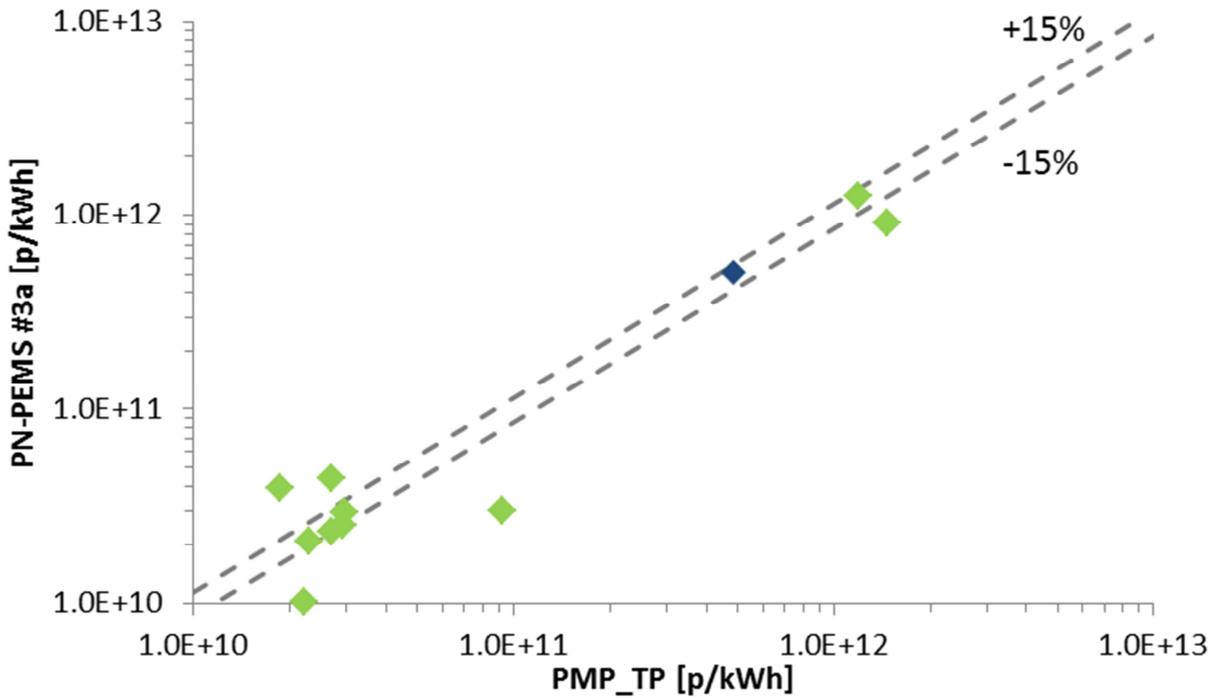


Figure 52: Comparison of PN-PEMS #3a with PMP\_TP for vehicle V1. Green points are tests at ambient temperature of 20°C. The blue point is a test at -7°C. Many tests with low concentrations are not shown. Dotted lines show the  $\pm 15\%$  differences from the 1:1 line.

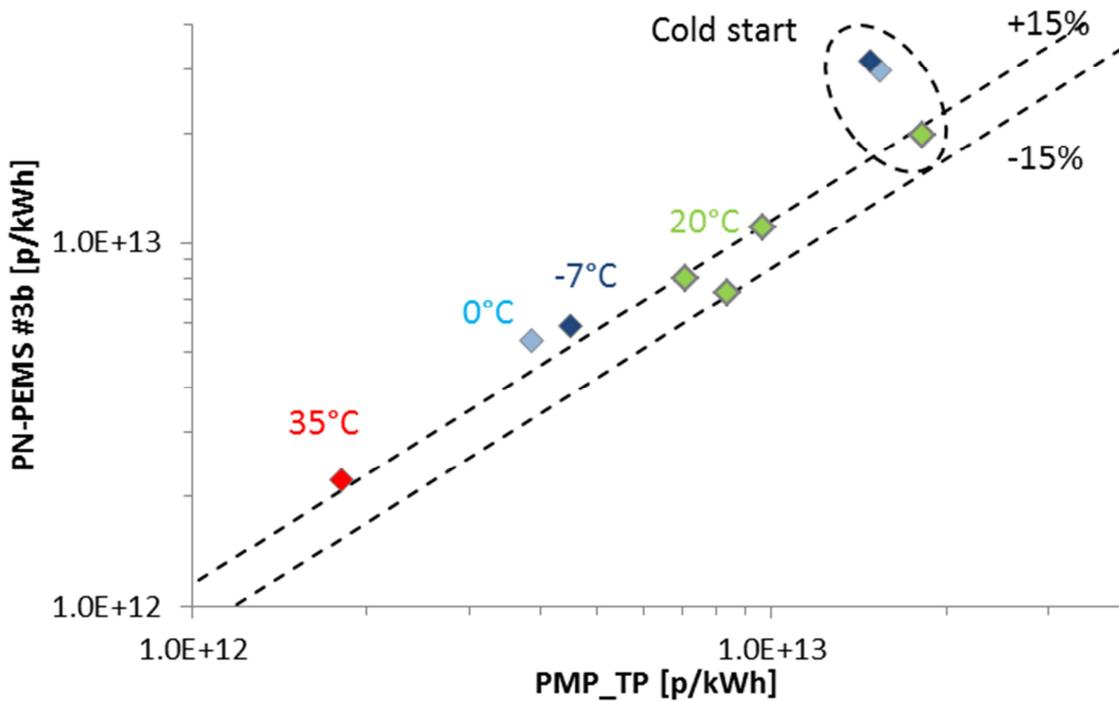


Figure 53: Comparison of PN-PEMS #3b with PMP\_TP for vehicle V2. Dotted lines show the  $\pm 15\%$  differences from the 1:1 line.

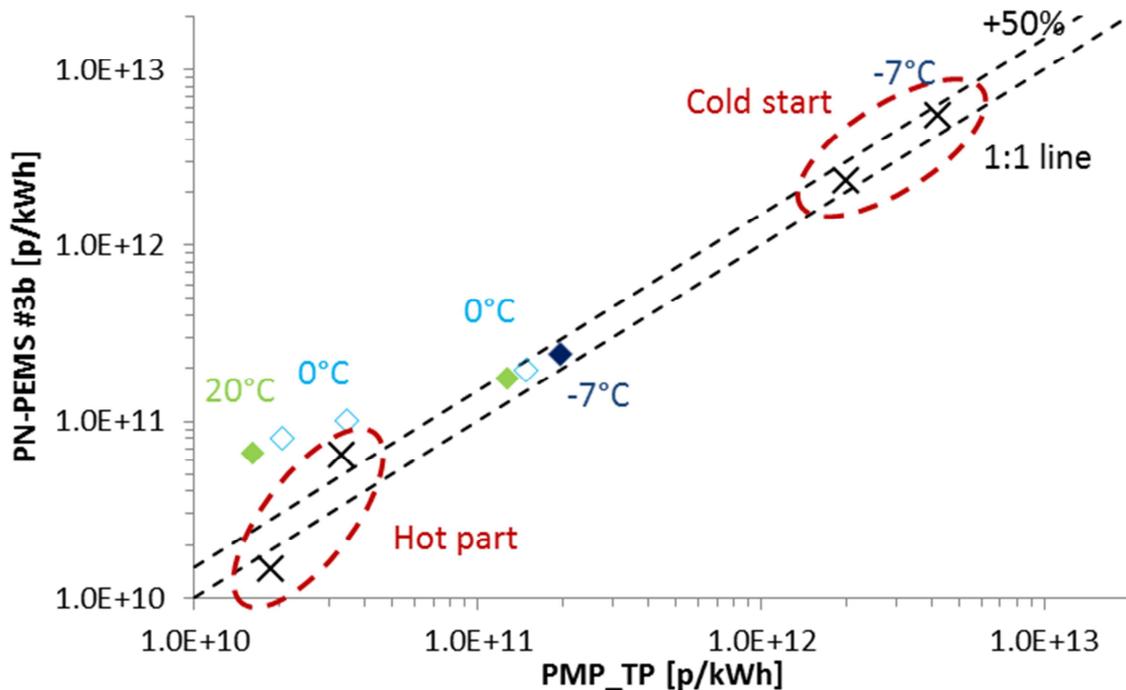


Figure 54: Comparison of PN-PEMS #3b with PMP\_TP for vehicle V3. Dotted lines show the 0-50% differences from the 1:1 line.

## 6.4 Real time measurements

Some real time comparisons of PN-PEMS #3a with the PMP\_TP can be seen in the following Figures. Figure 55 and Figure 56 show the PN emissions of P-PEMS #3a with warnings or errors (offsets too high or unstable,  $I_{diff}$  out of range). The real time agreement with the PMP\_TP is not satisfactory. For both low ( $2.5 \times 10^{10}$  p/kWh) and high ( $2.5 \times 10^{12}$  p/kWh) levels. The average result though agrees relatively well with the PMP\_TP.

The real time comparability of PN-PEMS #3b (without any warnings or errors) with the PMP\_TP was very good for cold start or hot parts of the cycle at different emission levels with vehicle V2 (Figure 57 and Figure 58) or vehicle V3 (Figure 61).

However there can be case where the agreement is not so good. This is the case for a cold start of vehicle V2 where high concentration of small particles were emitted (15-40 nm according to the mean size estimated by the PN-PEMS #3b) or the relatively big difference between the 23 nm and 10 nm CPCs (Figure 59). Note however that these tests at 0°C and -7°C were outside the specified temperature range of the instrument. The hot part had good agreement though (Figure 60). Correcting the second by second PN concentrations of the PN-PEMS with the efficiency of a PMP system for the size estimated by the PN-PEMS improves the correlation (Figure 59). In other words mathematically forcing a PMP efficiency at the PN-PEMS could improve the results. This assumption though has to be further evaluated. This function will be implemented in the future PN-PEMS units according to the manufacturer.

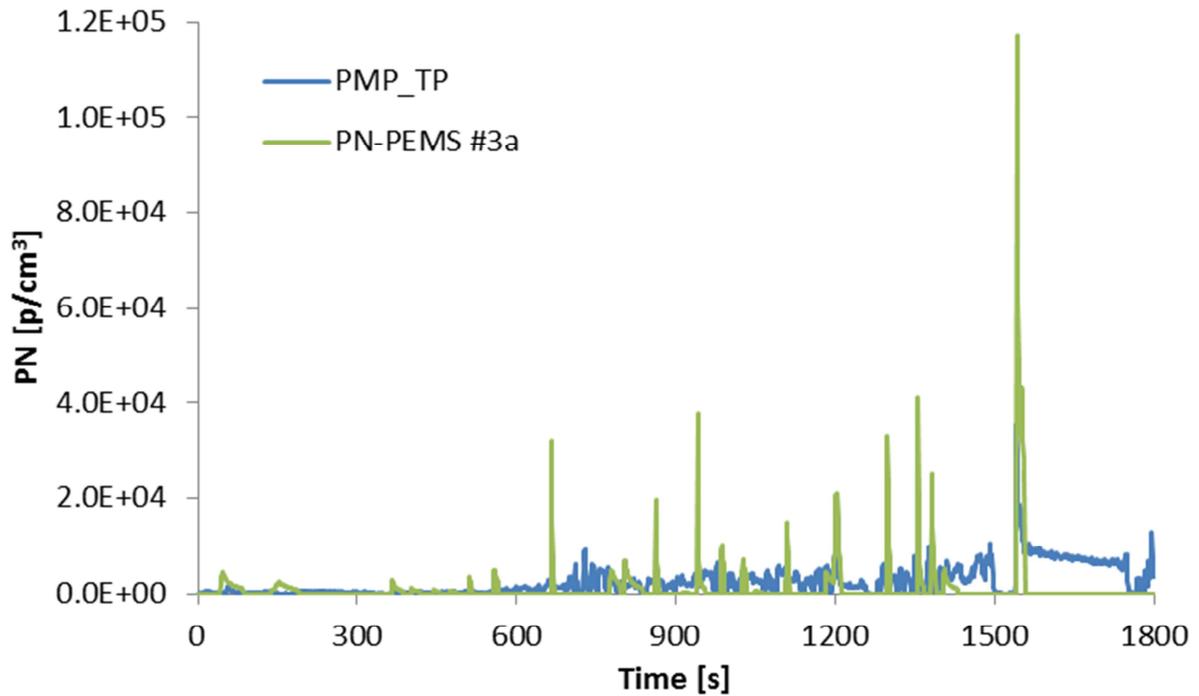


Figure 55: Real time comparison of PN-PEMS #3a with PMP\_TP for vehicle V1. PN-PEMS had an error ' $I_{diff}$  out of range'. Emission levels of  $2.5 \times 10^{10}$  p/kWh (20160224\_1\_WHVC cold).

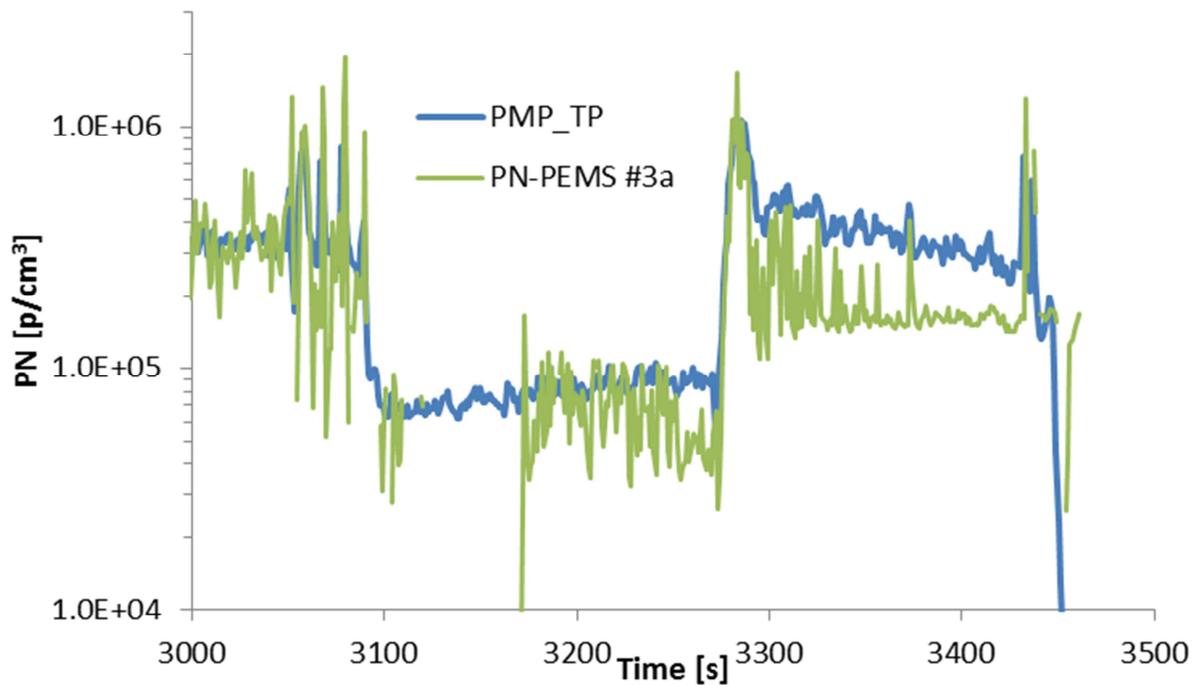


Figure 56: Real time comparison of PN-PEMS #3a with PMP\_TP for vehicle V1. PN-PEMS had a warning 'offset too high or unstable' and an error ' $I_{diff}$  out of range'. Emission levels of  $2.5 \times 10^{12}$  p/kWh (20160224\_3\_SICO).

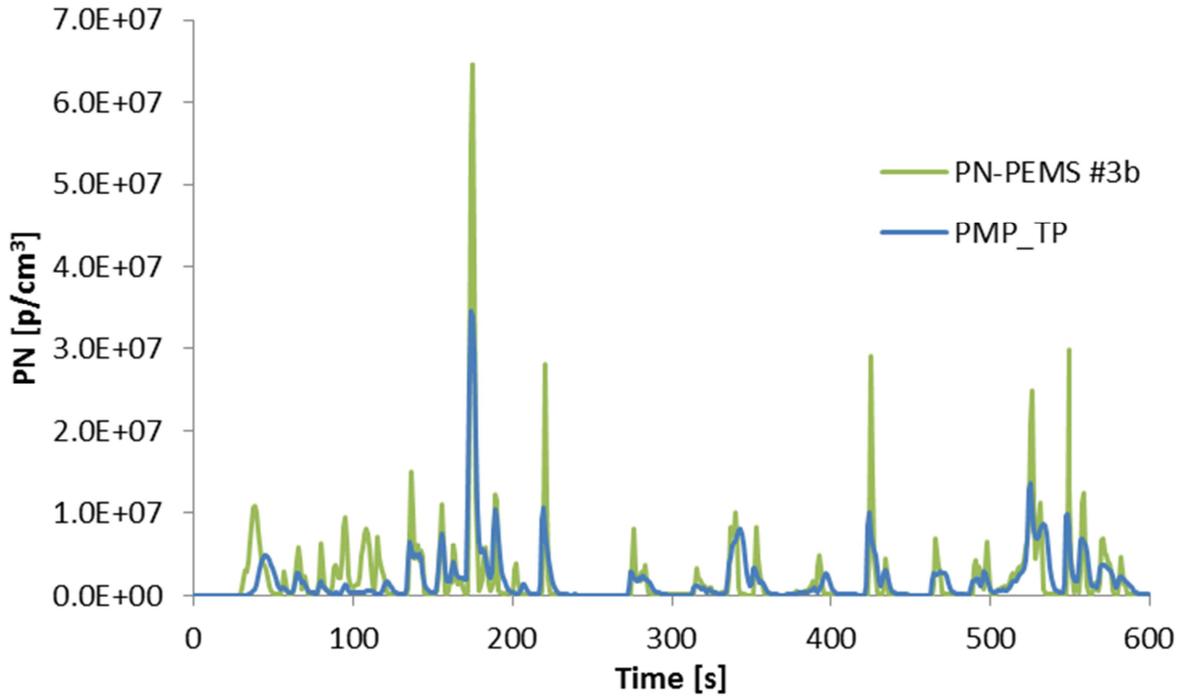


Figure 57: Real time comparison of PN-PEMS #3b with PMP\_TP for vehicle V2. Cold start (20160321\_1\_ISC\_cold\_10°C).

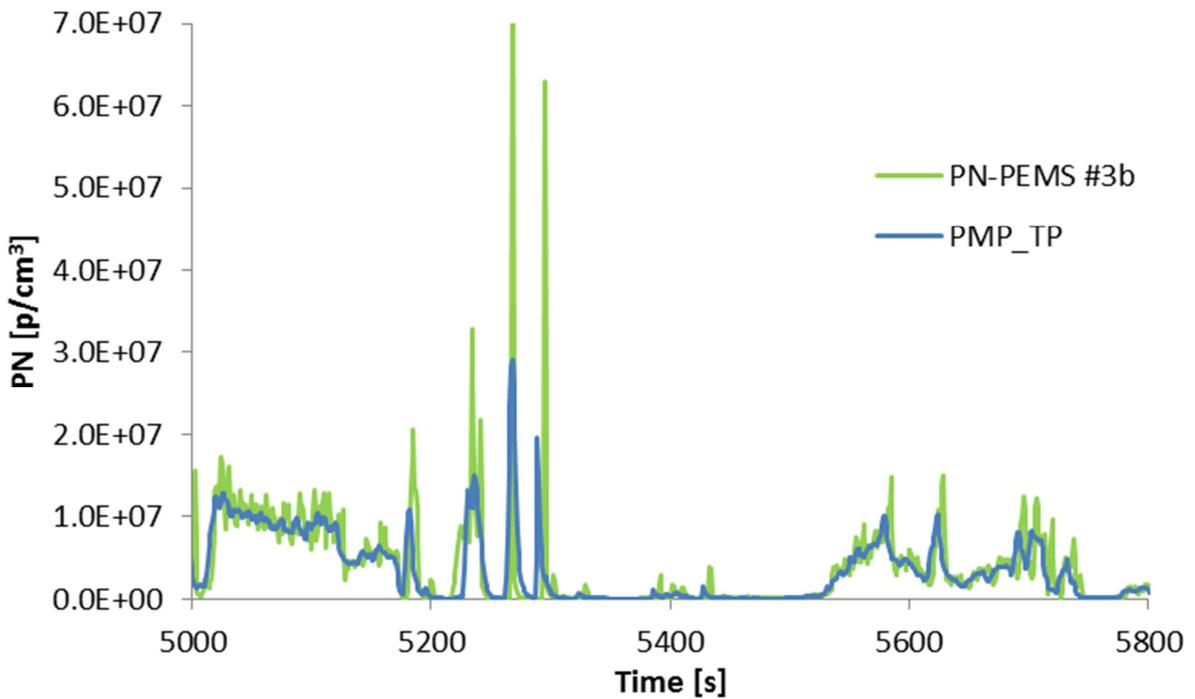


Figure 58: Real time comparison of PN-PEMS #3b with PMP\_TP for vehicle V2. Hot part of a long test (20160321\_1\_ISC\_cold\_10°C).

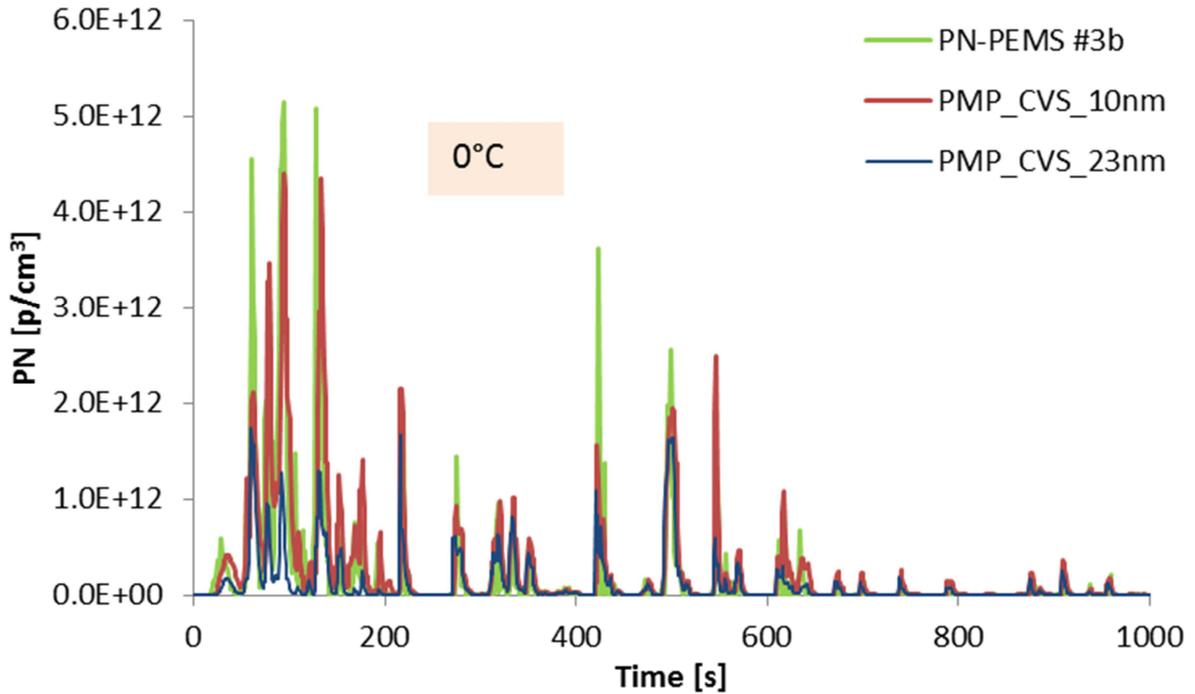


Figure 59: Real time comparison of PN-PEMS #3b with PMP\_TP for vehicle V2. Cold start at 0°C (20160323\_1\_ISC\_cold\_0°C). 'Corr' means signal corrected with a typical PMP penetration efficiency based on the estimated size of the PN-PEMS #3.

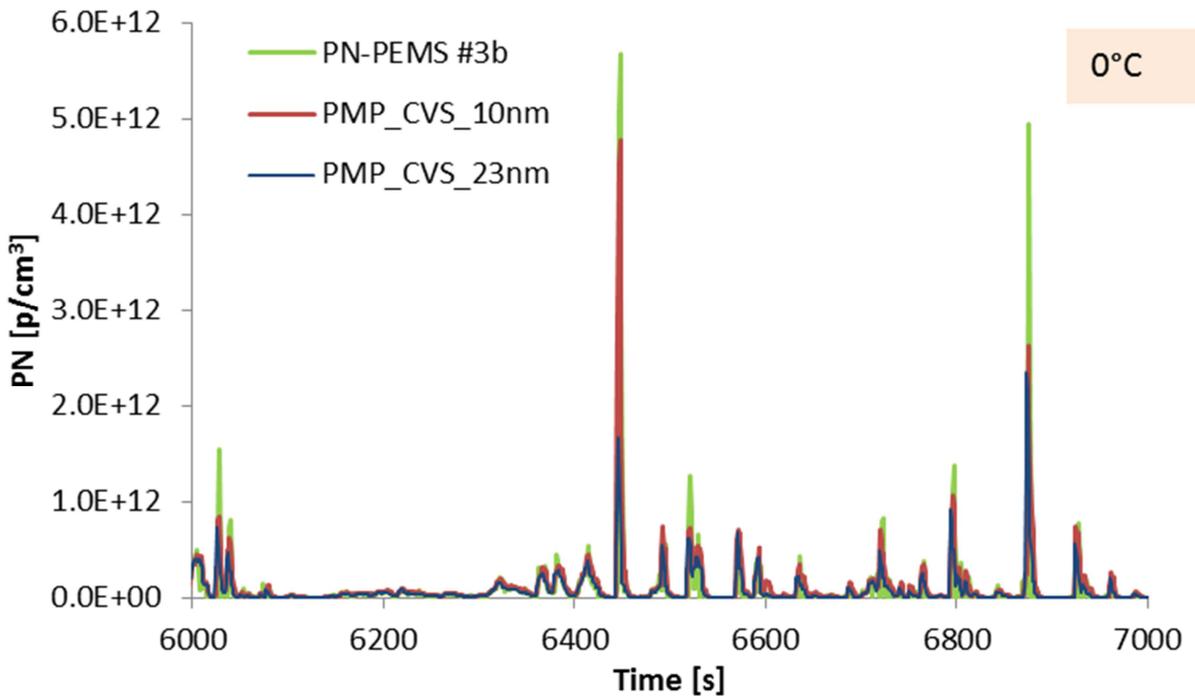


Figure 60: Real time comparison of PN-PEMS #3b with PMP\_TP for vehicle V2. Hot part of a long test (20160323\_1\_ISC\_cold\_0°C).

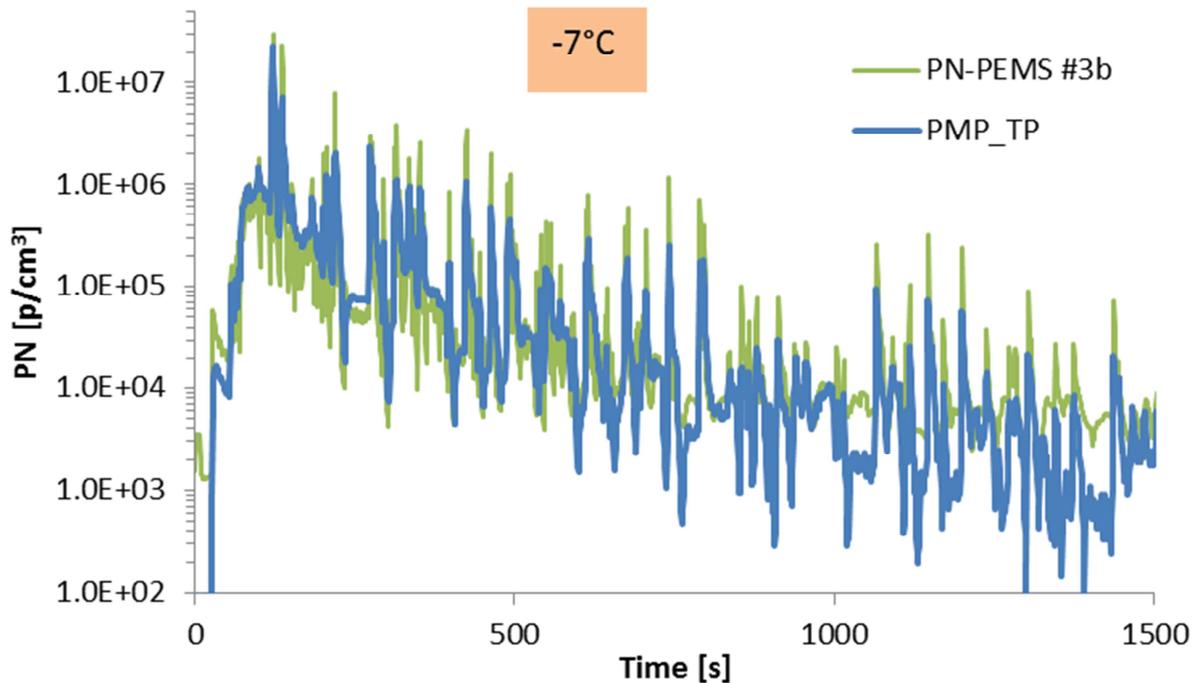


Figure 61: Real time comparison of PN-PEMS #3b with PMP\_TP for vehicle V3. Cold start at -7°C (20160331\_01\_ISC cold\_-7°C).

### 6.5 Conclusions for PN-PEMS #3

The main conclusion for PN-PEMS #3 from Testo (NanoMet 3) were:

- The agreement with the PMP\_TP was good (around 30%) for emission levels  $>1 \times 10^{11}$  p/kWh. Higher relative differences were observed for lower levels as the unit was approaching its detection limit.
- The real time signals were in good agreement with the PMP\_TP
- The unit when operated outside its specified temperature range (around 5-30°C) had warnings and errors that resulted in failure of the device. Typically observed warnings and errors were: 'offsets too high or unstable' and ' $I_{diff}$  out of range'. In these cases the real time agreement with the PMP\_TP was not good.

## 7 Main evaluation phase: PN-PEMS #6: SHIMADZU

### 7.1 General

PN-PEMS #6 (prototype) was available with vehicle V2, V3 and V5. The commercial unit was available during the second evaluation phase with vehicle V8.

### 7.2 Robustness

There are no warnings and errors in the exported file, thus it is not clear whether there were any issues during the campaign.

### 7.3 Accuracy

The comparison of PN-PEMS #6 with the PMP\_TP for vehicle V2 can be seen in Figure 62. This was the high emitting CNG vehicle. The 20°C tests were relatively close to the PMP\_TP. The rest of the tests at sub 0°C, which were conducted afterwards, were 40% lower. Comparing the +35°C and the -7°C it seems that the temperature doesn't have an effect on the operation of the unit. However why the absolute levels are 40% lower it's not clear; maybe condensates blocked orifices in the device.

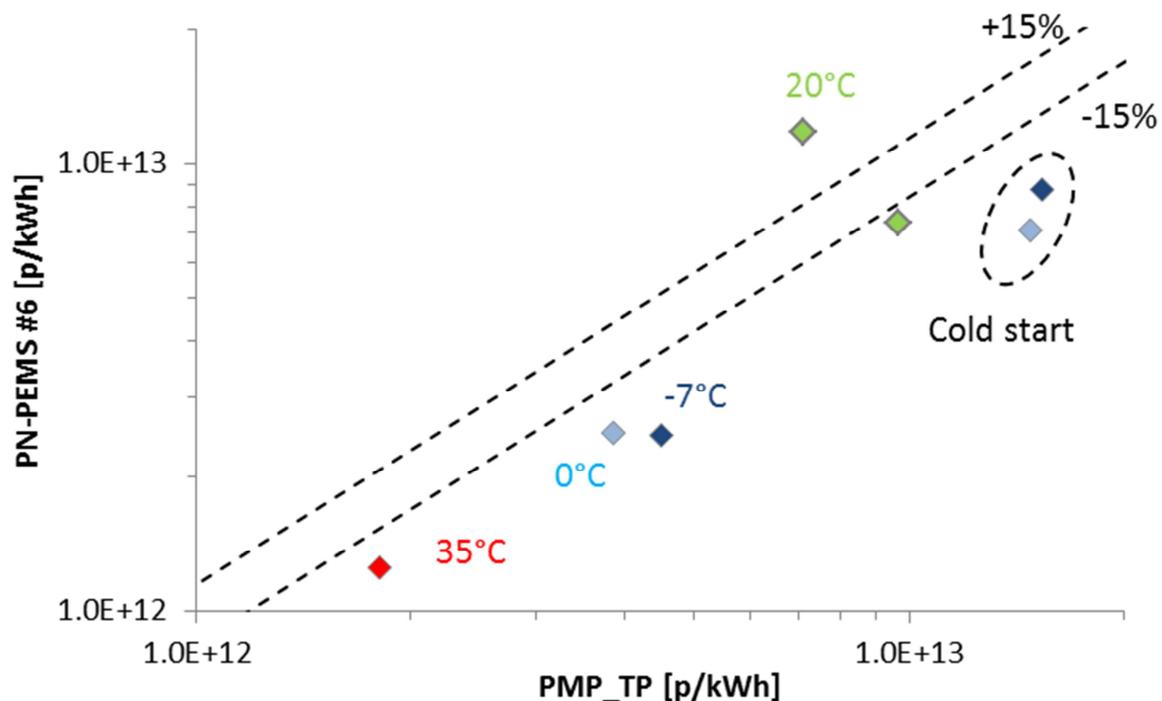


Figure 62: Comparison of PN-PEMS #6 with PMP\_TP for vehicle V2.

The results with the low emitting vehicle V3 can be seen in Figure 63. The scatter of the results is high. Figure 64 shows the results for vehicle V5 (all PN\_PEMS #6 results in this figure were multiplied by 100 to have better agreement with the PMP\_TP).

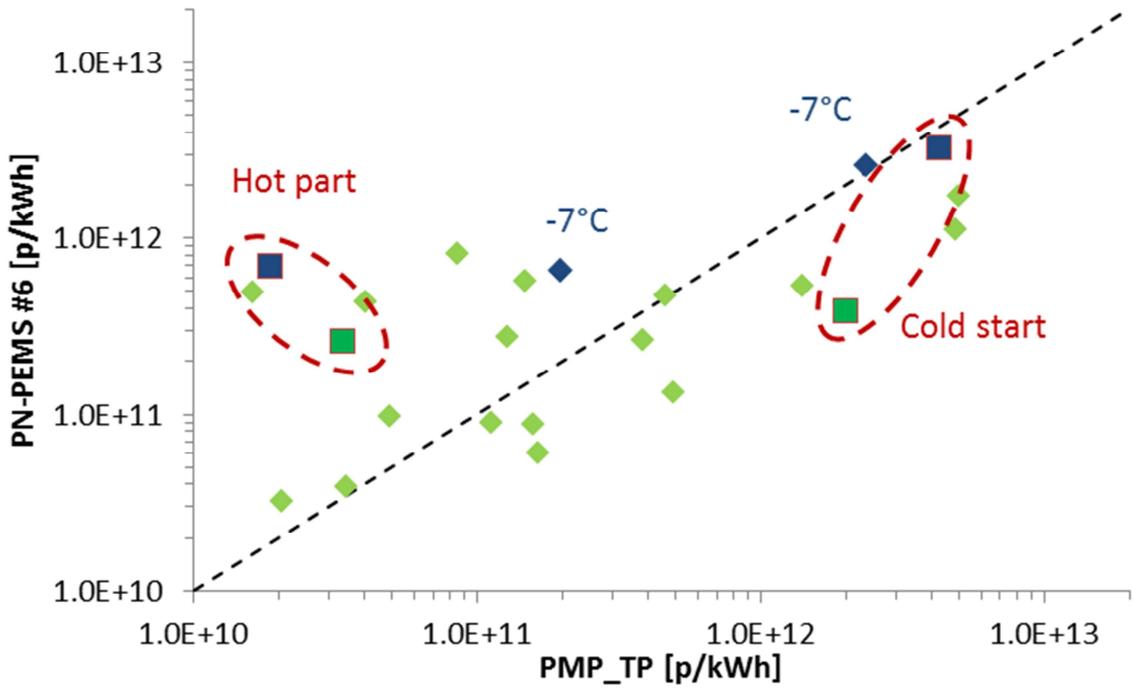


Figure 63: Comparison of PN-PEMS #6 with PMP\_TP for vehicle V3.

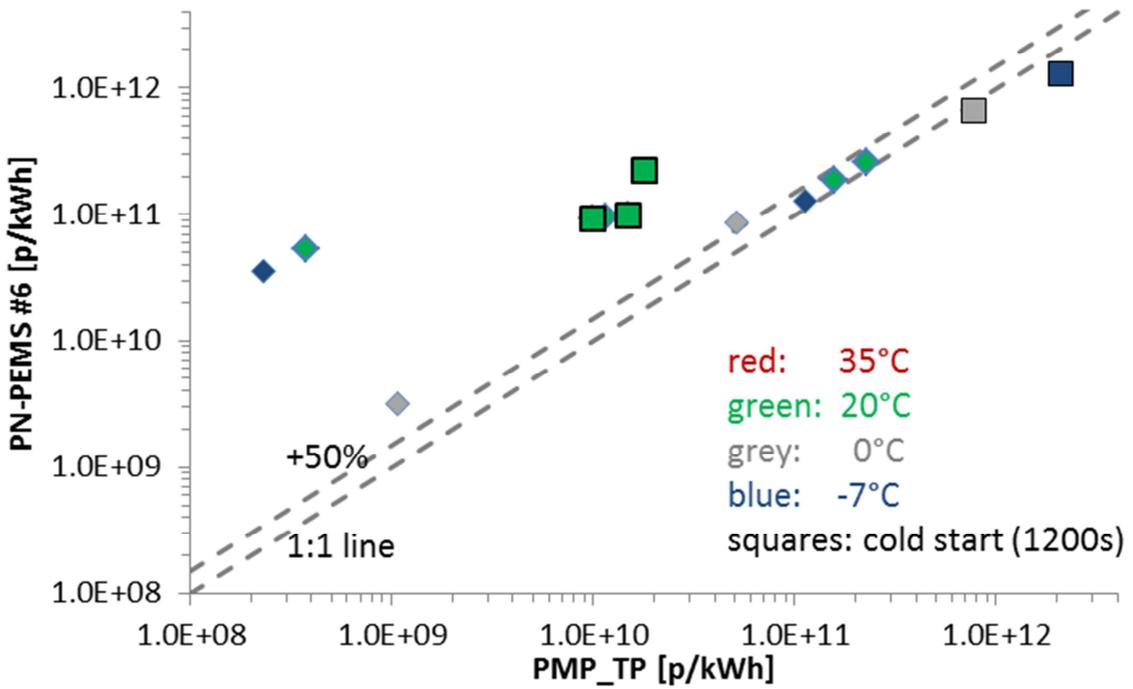


Figure 64: Comparison of PN-PEMS #6 with PMP\_TP for vehicle V5. PN-PEMS #6 results were multiplied by 100 for this figure.

### 7.4 Real time measurements

An example of a real time measurement of PN-PEMS #6 versus the PMP\_TP for vehicle V2 can be seen in Figure 65 (+35°C) and Figure 66 (-7°C). The agreement is good (after correcting with a factor of 2 for better visualization).

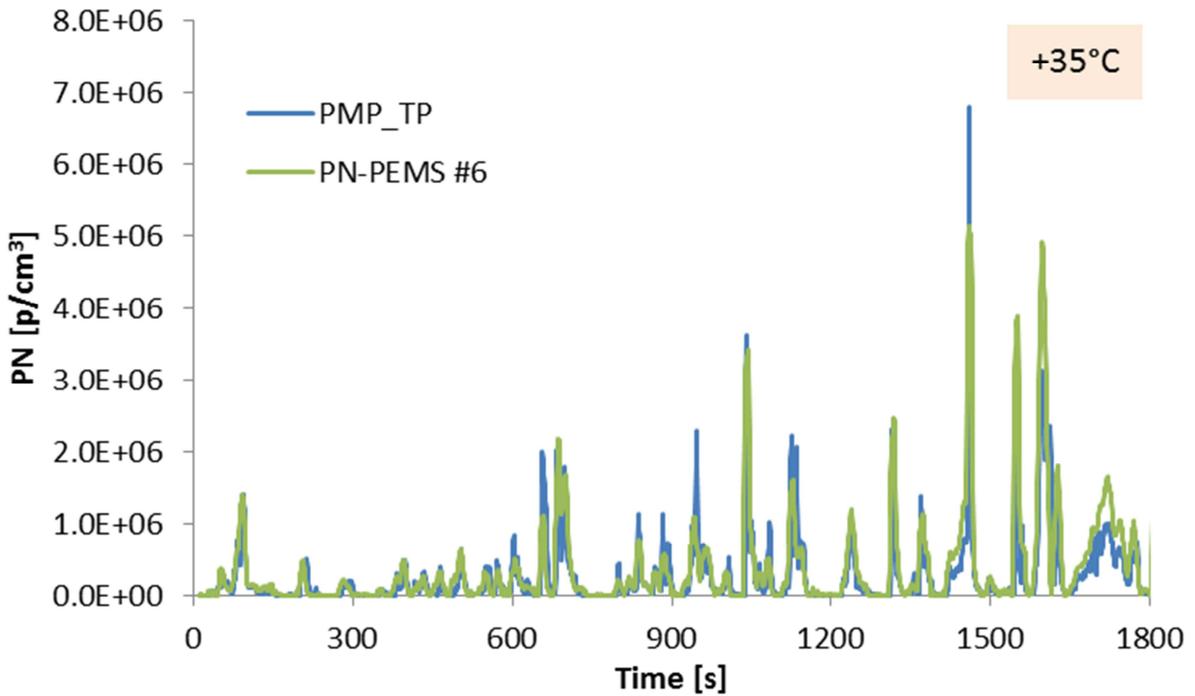


Figure 65: Real time comparison of PN-PEMS #6 with PMP\_TP over a WHVC (vehicle V2) (20160321\_02\_WHVC\_+35°C). PN-PEMS #6 concentration was multiplied by 2 for better visualization.

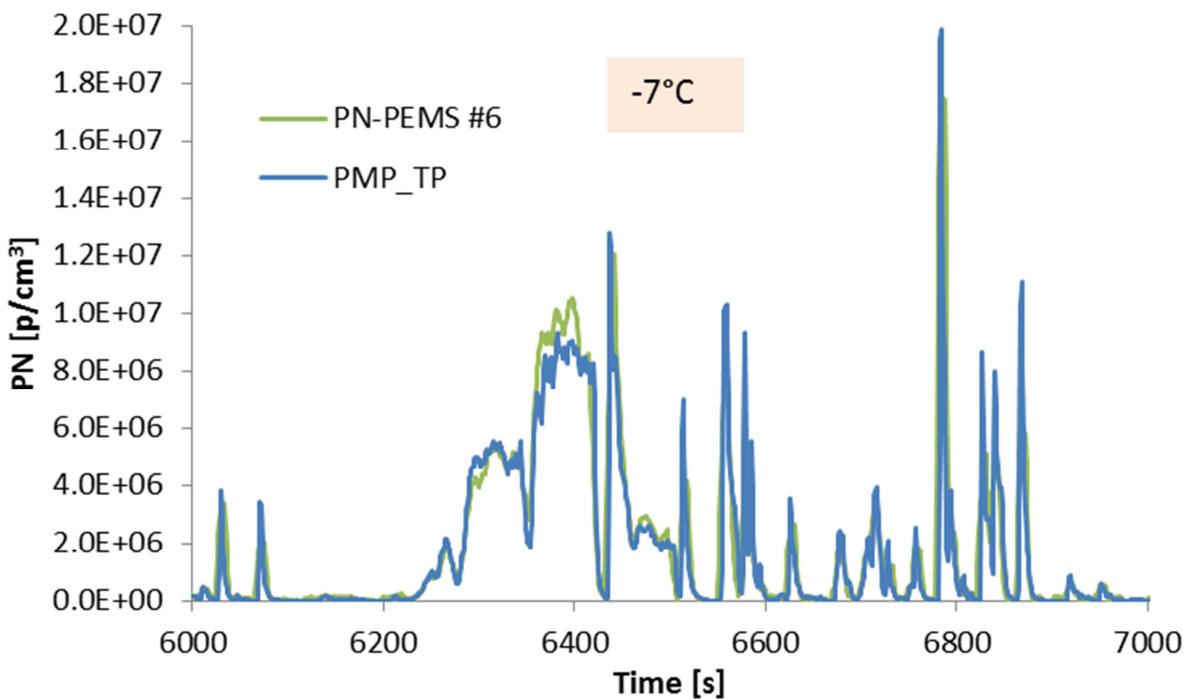


Figure 66: Real time comparison of PN-PEMS #6 with PMP\_TP over a WHVC (vehicle V2) (20160322\_01\_WHVC\_-7°C). PN-PEMS #6 concentration was multiplied by 2 for better visualization.

Real time examples with the low emitting vehicle V3 can be seen in the following figures. For vehicle V5, Figure 70 shows that the agreement is not very good. There is an offset and the cold start peaks do not match.

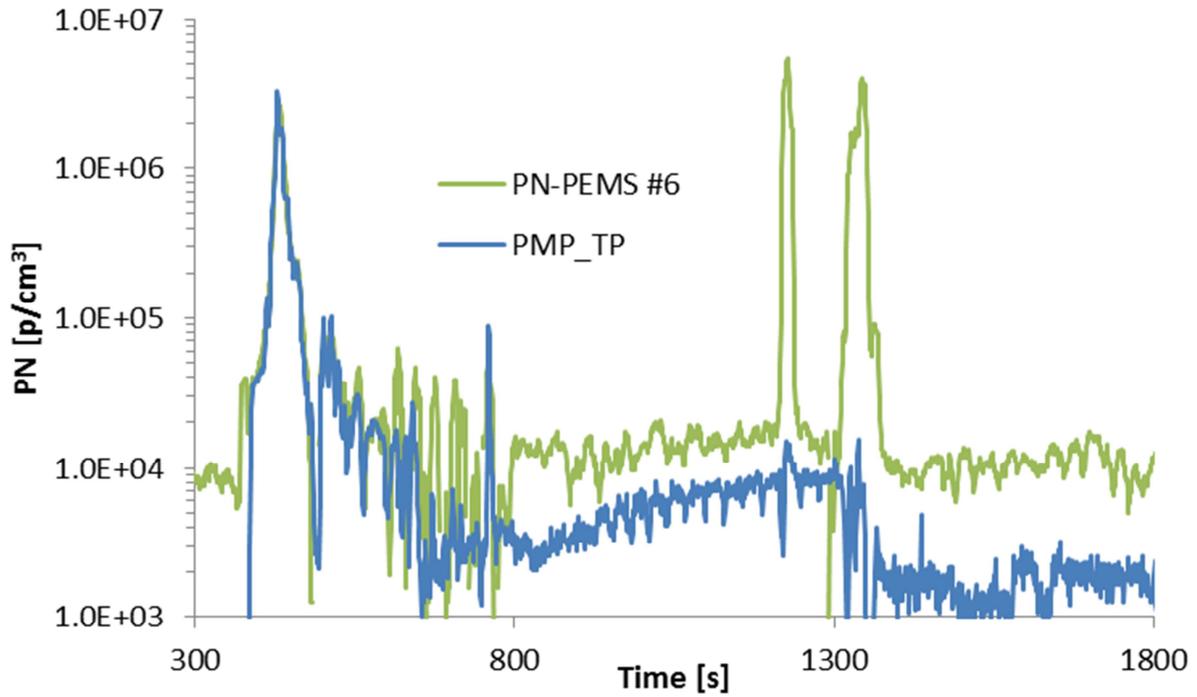


Figure 67: Real time comparison of PN-PEMS #6 with PMP\_TP over a warmup test (vehicle V3) (20160330\_01\_WHVC\_2°C).

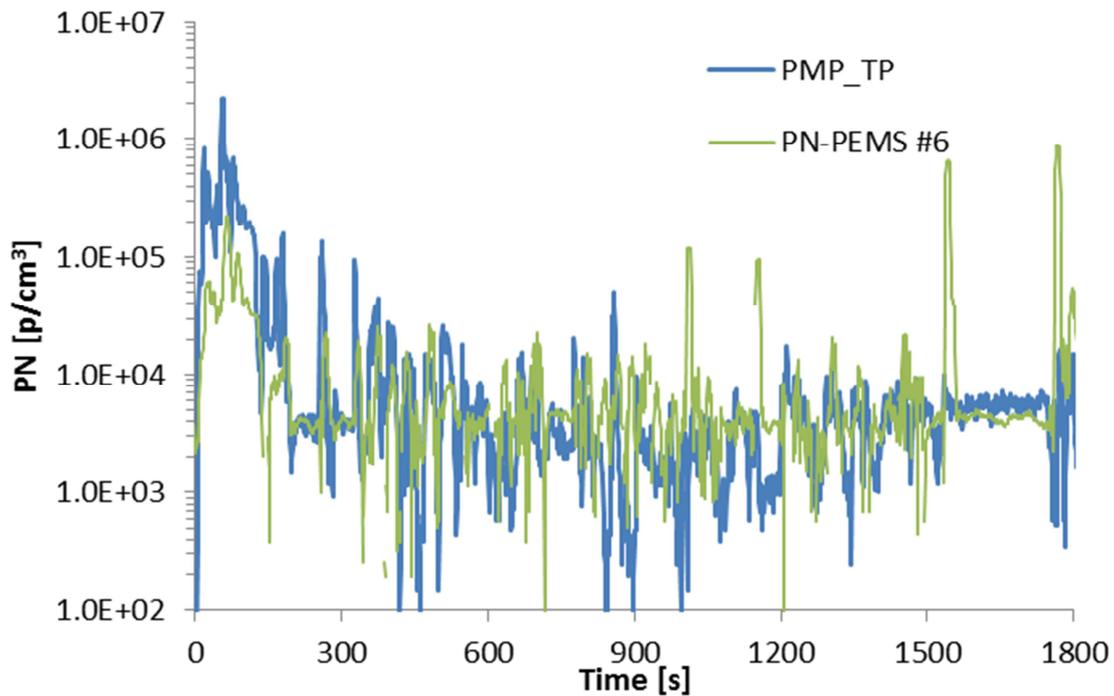


Figure 68: Real time comparison of PN-PEMS #6 with PMP\_TP (20160411\_01\_WHVC cold) (vehicle V3).

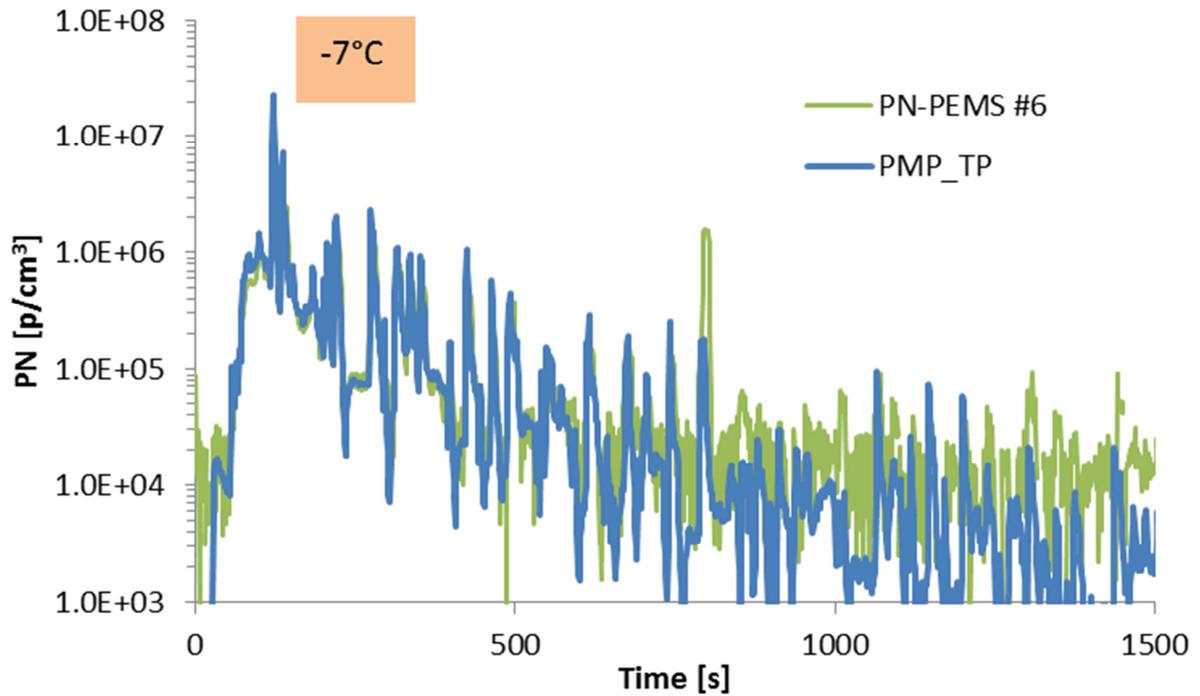


Figure 69: Real time comparison of PN-PEMS #6 with PMP\_TP (20160331\_01\_ISC\_-7°C) (vehicle V3).

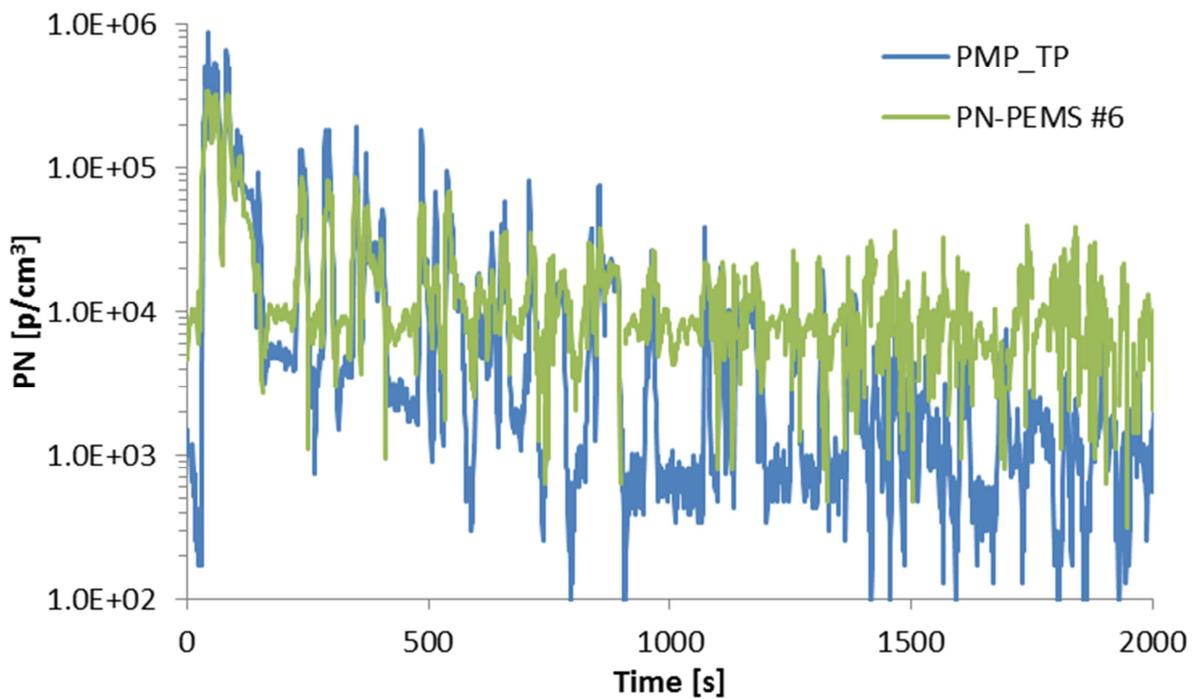


Figure 70: Real time comparison of PN-PEMS #6 with PMP\_TP (vehicle V5). (20160525\_01\_ISC cold\_0°C). PN-PEMS #6 was multiplied by 100.

## 8 On-road tests

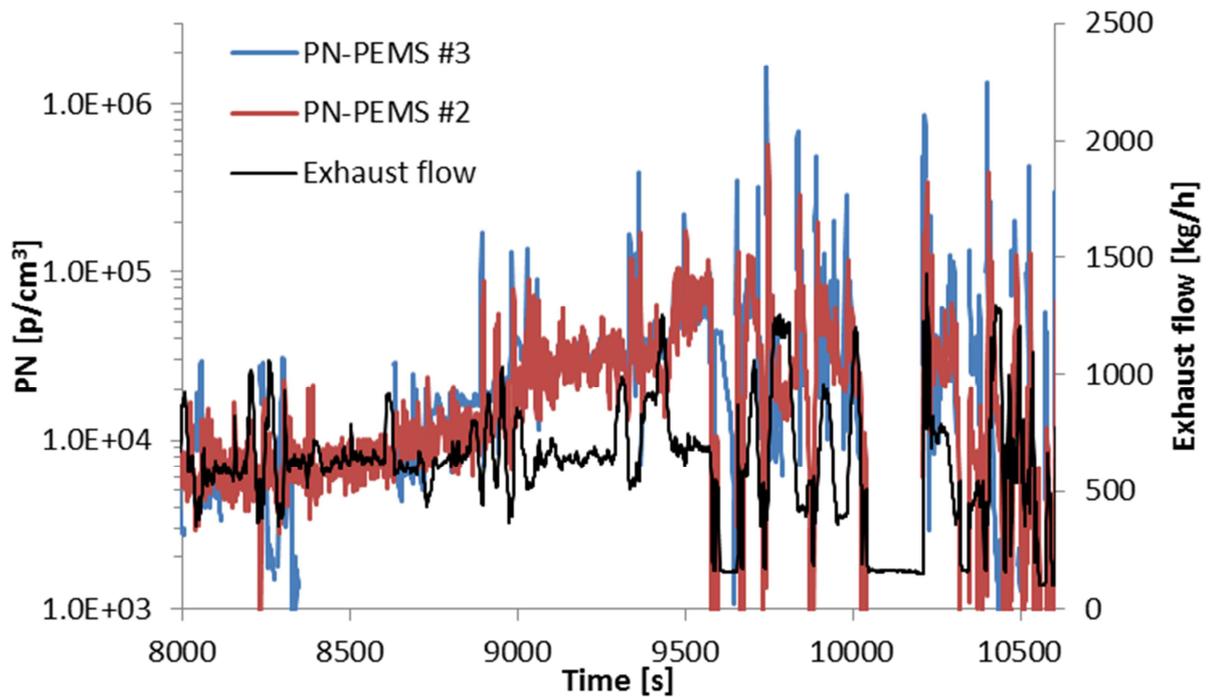


Figure 71: Real time signal of PN-PEMS during an on-road test with vehicle V1 (20160309\_01\_Road). Emissions  $8.0 \times 10^{10}$  (PN-PEMS #2) and  $7.4 \times 10^{10}$  (PN-PEMS #3) p/kWh.

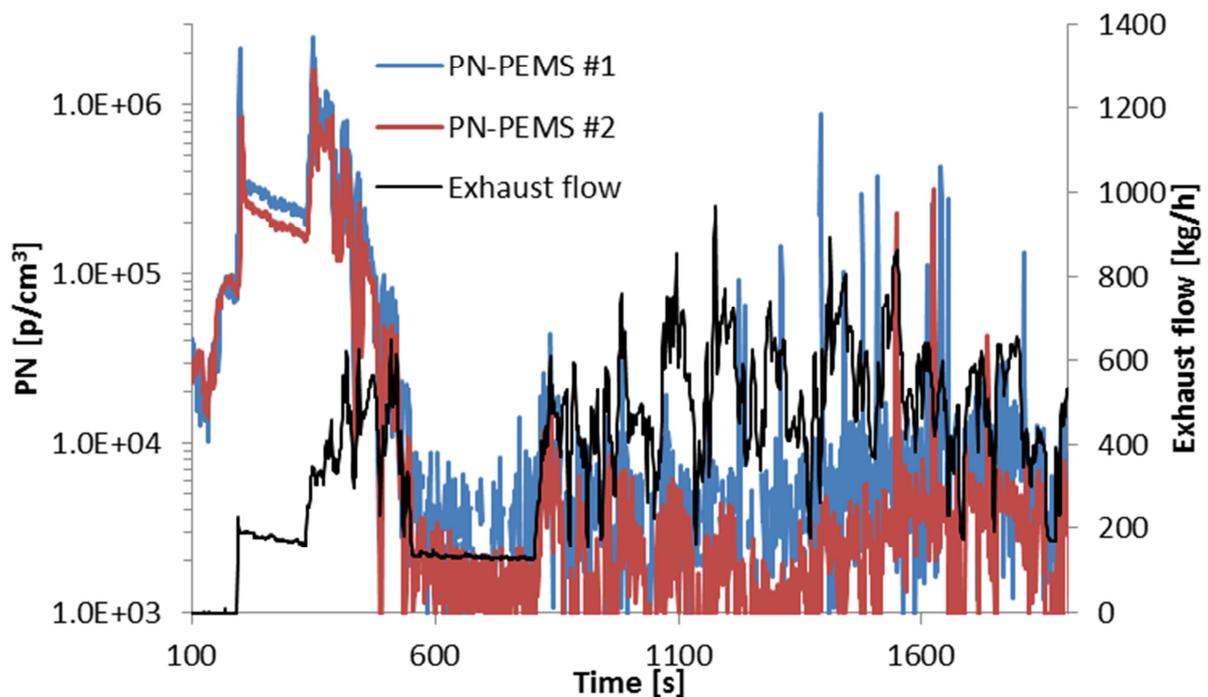


Figure 72: Real time signal of PN-PEMS during an on-road test with vehicle V3 (20160427\_01\_Road). Emissions  $7.5 \times 10^{10}$  (PN-PEMS #2) and  $1.5 \times 10^{11}$  (PN-PEMS #1) p/kWh.

For the on-road tests there was no reference system installed on-board. However, in most cases two PN-PEMS were installed and were measuring simultaneously.

The comparison of the real time signals can be seen in Figure 71 for PN-PEMS #2 and #3 and Figure 72 for PN-PEMS #2 and #1. The comparability of the two signals is acceptable and in line with the lab tests: PN-PEMS #2 and #3 were within 10% and this reflects the good comparability they had with the reference PMP system in the laboratory. PN-PEMS #1 was 50% higher than PN-PEMS #2 and this is also similar to the overestimation that the PN-PEMS showed in the laboratory.

The emission levels that were measured during the on-road tests were close to the ISC cycles in the laboratory (Figure 9 and Figure 11) and also on the expected range (Giechaskiel et al. 2015b). Thus the on-road tests didn't indicate any special issues with the PN-PEMS, or at least in addition to those identified in the laboratory.

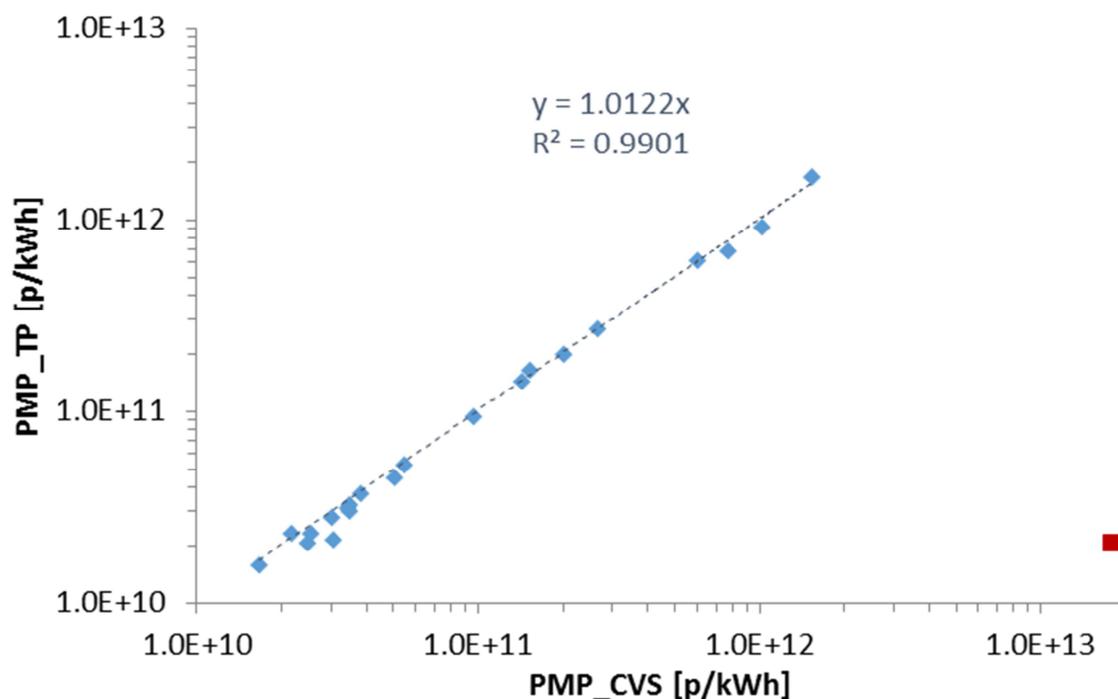
For a few laboratory tests with vehicle V1 the PN-PEMS #2 and #3 were installed on the vehicle, exactly as on the road. The difference to the reference system remained the same indicating that having the system inside the vehicle didn't affect their performance.

## 10 Second evaluation phase

The second evaluation phase was conducted in order to check the improvements of the instruments. In this phase commercially available instruments were tested. Representative of the OEM that provided the vehicle V8 was present, participated in the setup and tests, had access to all data, and did the calculations. Thus this phase can be considered as an OEM pre-validation phase. The final check of the results and the reporting was still done by JRC. No CNG vehicle was available for this phase.

### 10.1 PMP\_CVS vs. PMP\_TP

The correlation of the PMP\_TP to the PMP\_CVS can be seen in Figure 73. The agreement is excellent with a slope of 1.01 and  $R^2=0.99$ . The differences, with one exception, are within 15% and there is no dependency of the ambient temperature in the climatic room, as it should, because the PMP\_TP was installed in a room with controlled temperature of 20°C. As mentioned in the main evaluation phase the position of the tailpipe system close to the dilution tunnel probably masked any effects due to pressure pulsations, thermophoresis, diffusion and agglomeration.



**Figure 73: Correlation of PMP\_TP to PMP\_CVS for vehicle V8. The red point was not considered in the correlation.**

The real time signals of the outlier of Figure 73 are shown in Figure 74. The high difference is due to two high spikes of the system at the dilution tunnel (PMP\_CVS). For this test an EEPs (Engine Exhaust Particle Sizer) was also connected to the full dilution tunnel to measure total particles (i.e. without any thermal pre-treatment). It is evident that the high spike of the PMP\_CVS coincides with the increase of the exhaust gas temperature and the increase of total particle concentration. Thus it can be assumed that the high spike of the PMP\_CVS system is re-nucleation downstream of the evaporation tube of the system due to the high concentration of nucleation mode mass

in the dilution tunnel (estimated  $>0.5 \text{ mg/m}^3$ ). The PMP\_TP system didn't have this artefact because this nucleation mode probably doesn't form in the first place: at the tailpipe the exhaust gas is sampled at high temperature before any nucleation mode formation. A key message from this figure is that systems should be capable of handling masses of  $>0.5 \text{ mg/m}^3$ . Thus the requirement in technical specifications of volatile removal efficiency of  $>1 \text{ mg/m}^3$  is the right order of magnitude (alkanes or emery oil).

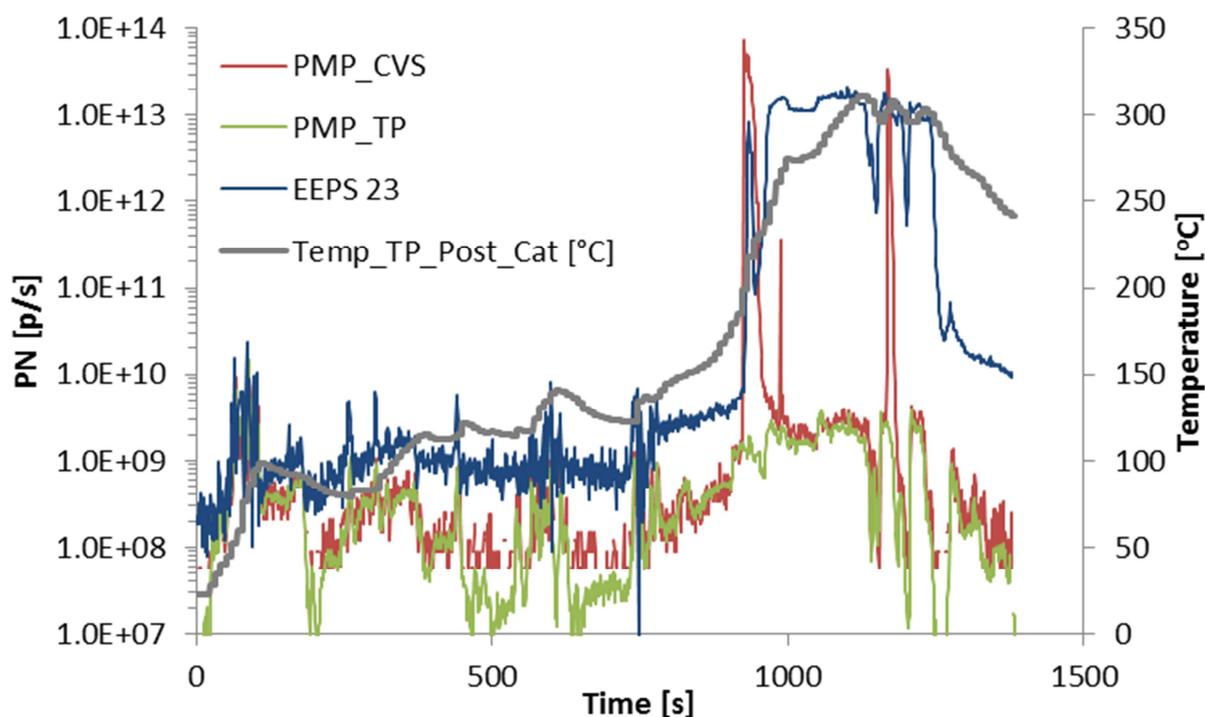


Figure 74: Real time comparison of PMP\_TP and PMP\_CVS (20160914-02\_Steady).

## 10.2 Sub-23 nm fraction

The sub-23 nm fraction was estimated by comparing the concentrations of a 10 nm CPC and the 23 nm CPC measuring in parallel downstream of the VRP of the PMP\_CVS (3772 from TSI) and PMP\_TP (Airmodus A20-10nm). No correction was applied to the 10 nm CPC for the particle losses in the PMP system, thus the fractions might be underestimated.

The sub-23 nm fraction for the DPF and SCR equipped vehicle V8 is low ( $<20\%$ ) at concentrations  $>1 \times 10^{11} \text{ p/kWh}$  (Figure 75). However, quite often it was high at low concentrations ( $<1 \times 10^{11} \text{ p/kWh}$ ) and the main assumption is formation of small urea particles (Amanatidis et al. 2014); their contribution in relative terms increases as the absolute emissions decrease. Lower counting efficiency of the 23 nm CPC of these particles due to their chemistry is also another possibility.

The comparison of the sub-23 nm fractions as measured at the full dilution tunnel by the PMP\_CVS and the tailpipe by the PMP\_TP are shown in Figure 76. The correlation is very good with a 13% difference on average. This difference could originate either from higher losses of sub-23 nm particles in the PMP\_TP system or more efficient removal of the condensed material. This can happen because the system at the tailpipe theoretically never permits condensation of volatile material on the particles as the sample temperature is always held above the dew point. On the other hand the system at the dilution tunnel measures particles that condensation of volatile on them has already happened.

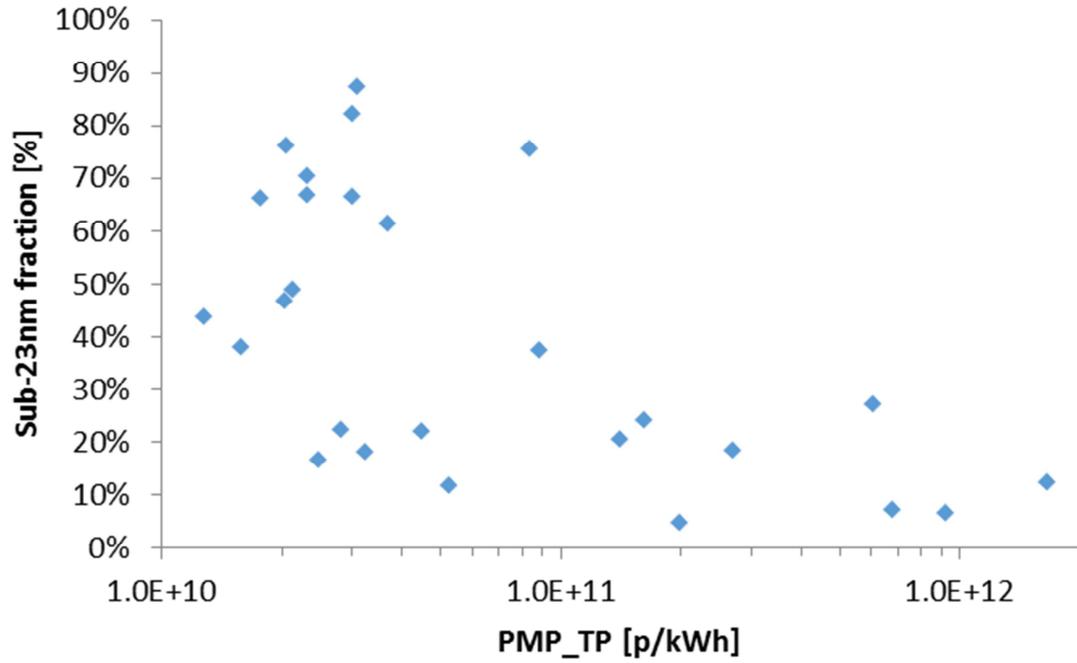


Figure 75: Sub-23 nm fraction of V8.

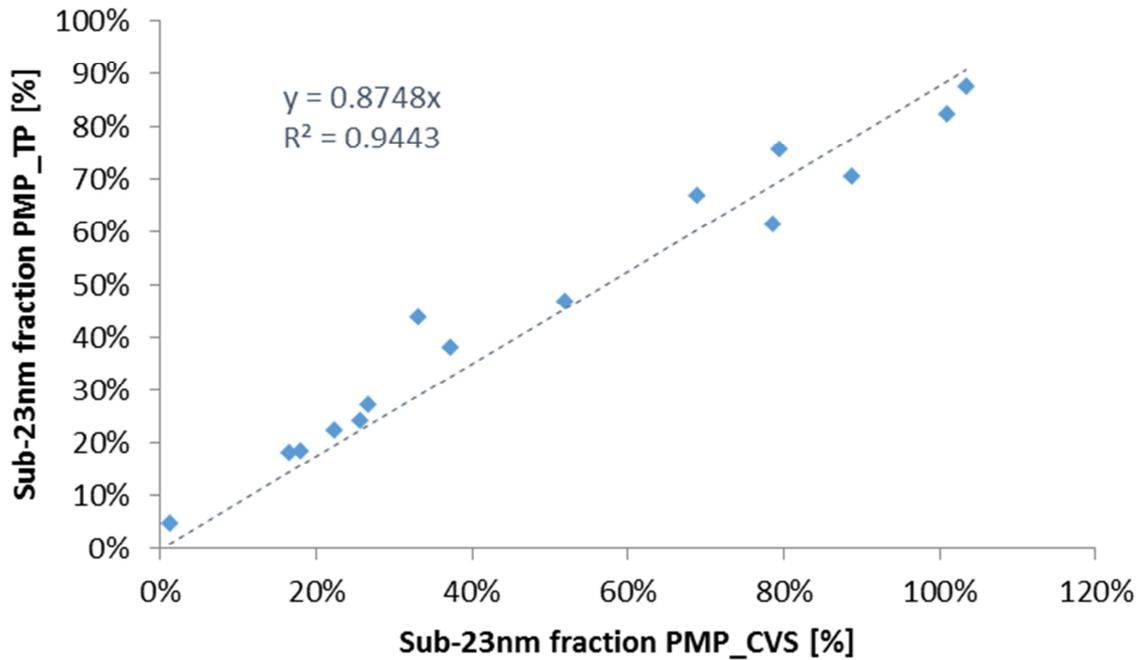


Figure 76: Correlation of sub-23 nm fractions as identified in the system at the full dilution and the tailpipe.

### 10.3 PN-PEMS #1: AVL MOVE

PN-PEMS #1b had the following modifications compared to the main evaluation phase:

- The dilution ratio was reduced to 6:1 in order to a) increase the sample flowrate and reduce the sensitivity of dilution on pressure fluctuations and b) improve the noise levels of the device.
- The operating voltages of the sensor were modified to reduce the counting efficiency at small sizes and thus assess whether the device was indeed detecting sub-23 nm particles. These specific settings were not optimal for the size dependence efficiency of the device, but were rather focusing on investigating the possibility that sub-23 nm particles were actually detected.
- A probe heater was supplied to be installed on the adaptor used to connect the heated line on the sampling probe, as this was considered by the supplier to be the cold spot that could lead to condensation issues.

The results can be seen in Figure 77. There is a slight overestimation of the emissions (17%) but in general the correlation is good ( $R^2 > 0.97$ ) until emission levels of  $1 \times 10^{11}$  p/kWh. The instrument didn't have any issues at low or high ambient temperatures.

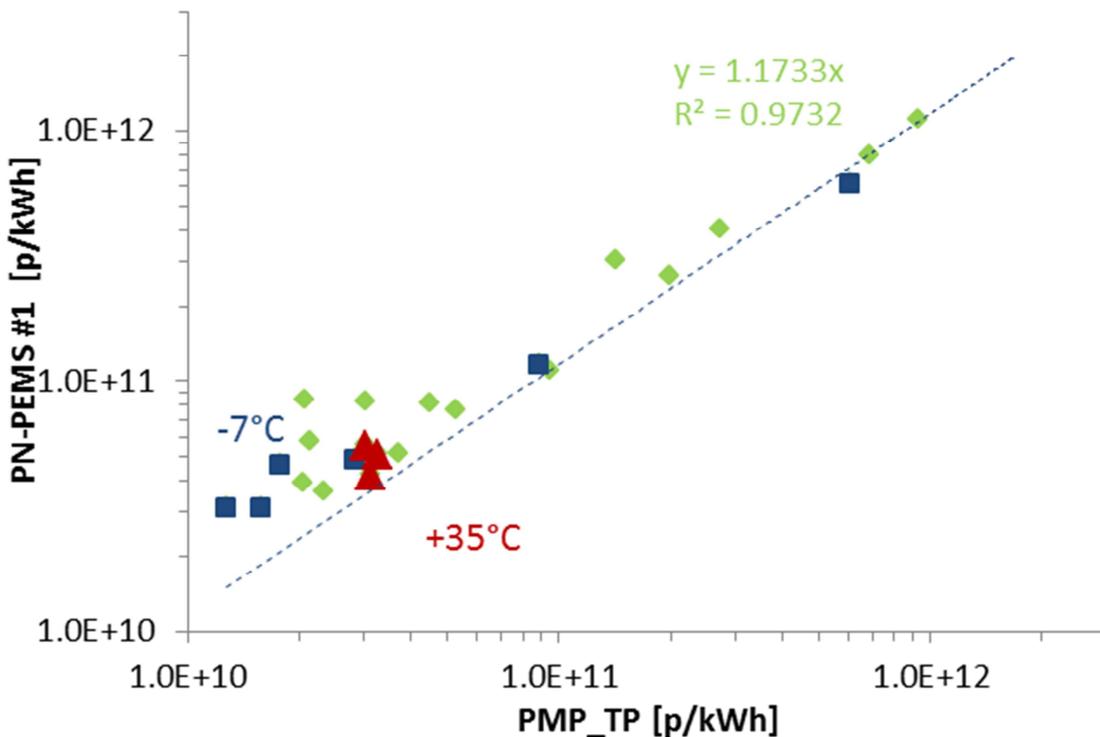
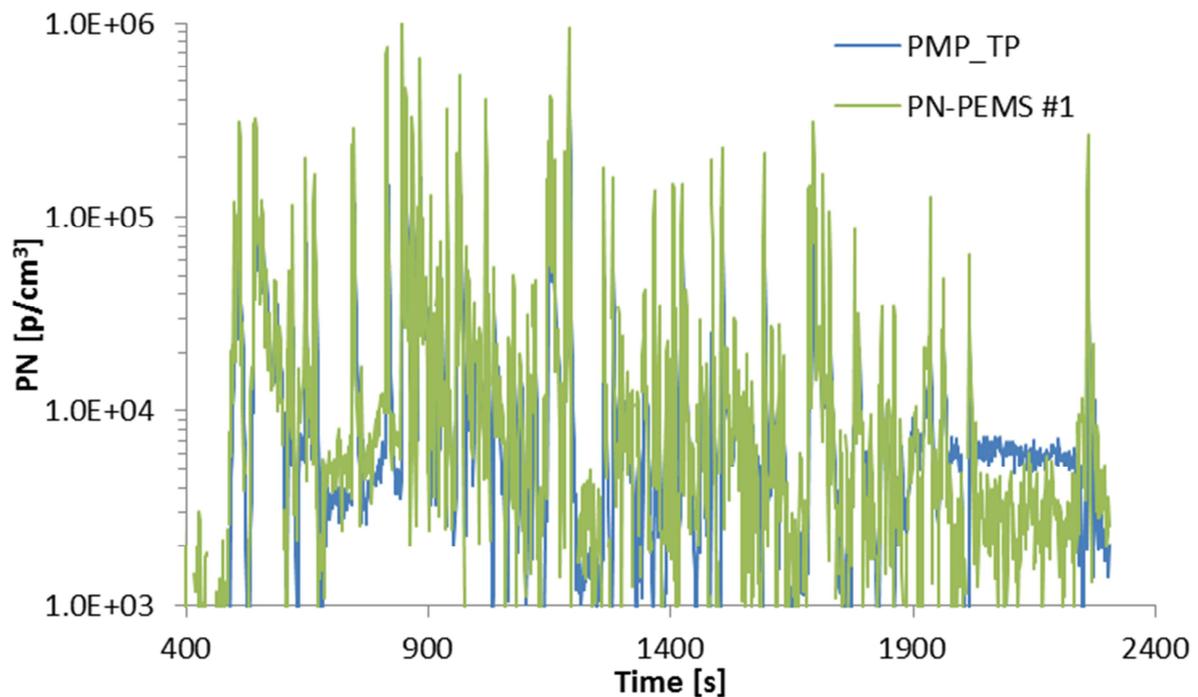


Figure 77: Comparison of PN-PEMS #1 with PMP\_TP for vehicle V8. Green points are tests at ambient temperature of 20°C. Blue points are tests at ambient temperature of -7°C. Red points are tests at ambient temperature of 35°C.

The real time signals agree well with the PMP\_TP and the high spikes that were observed at the main phase disappeared (Figure 78). Thus it is verified that many of these spikes were due to condensates forming on the adaptor used to connect the instrument's heated line to the tailpipe and entering into the system.

Emission can be measured accurately over a wide range of emissions (4 orders of magnitude) (Figure 79). However there can be cases where the absolute levels have differences (e.g. around second 600). In this case the pressure difference was <10 mbar thus the reason probably has to do with the nature and size of the particles. On the basis of the counting efficiencies experimentally determined (see Chapter 12), it seems unlikely that sub-23 nm particles are actually detected by the system.

A small pressure effect (absolute level and variation) might be still present when the changes are >15 mbar (Figure 80). At this test a high nucleation mode was observed at the CVS (see Figure 74), however it's highly unlikely that the emissions observed by PN-PEMS #1 were due to inefficient removal efficiency as the calibration tests showed very high removal efficiency (see Table 8) or the regeneration tests (to be discussed later in Figure 90). This would happen only if the pressure change would affect the residence time in the catalytic stripper of the device, which is unlikely. As discussed in the main evaluation phase it cannot be excluded that the difference could also be due to lower detection efficiency of the specific type of particles for the 23 nm CPC.



**Figure 78: Real time comparison of PN-PEMS #1 with PMP\_TP over a hot start WHVC (vehicle V8) (20160906-05\_WHVC hot). Emission levels  $1.4 \times 10^{11}$  p/km (PN-PEMS #1 +83%).**

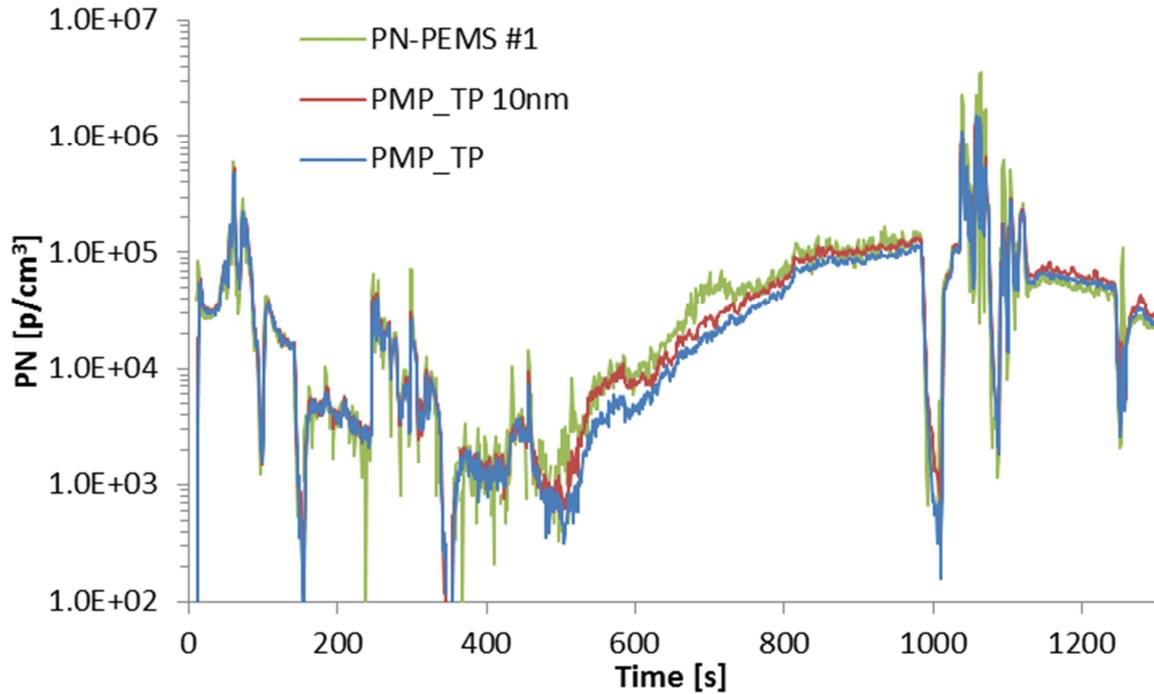


Figure 79: Real time comparison of PN-PEMS #1 with PMP\_TP over steady state points (vehicle V8) (20160906\_04\_Steady). Pressure variation <10 mbar.

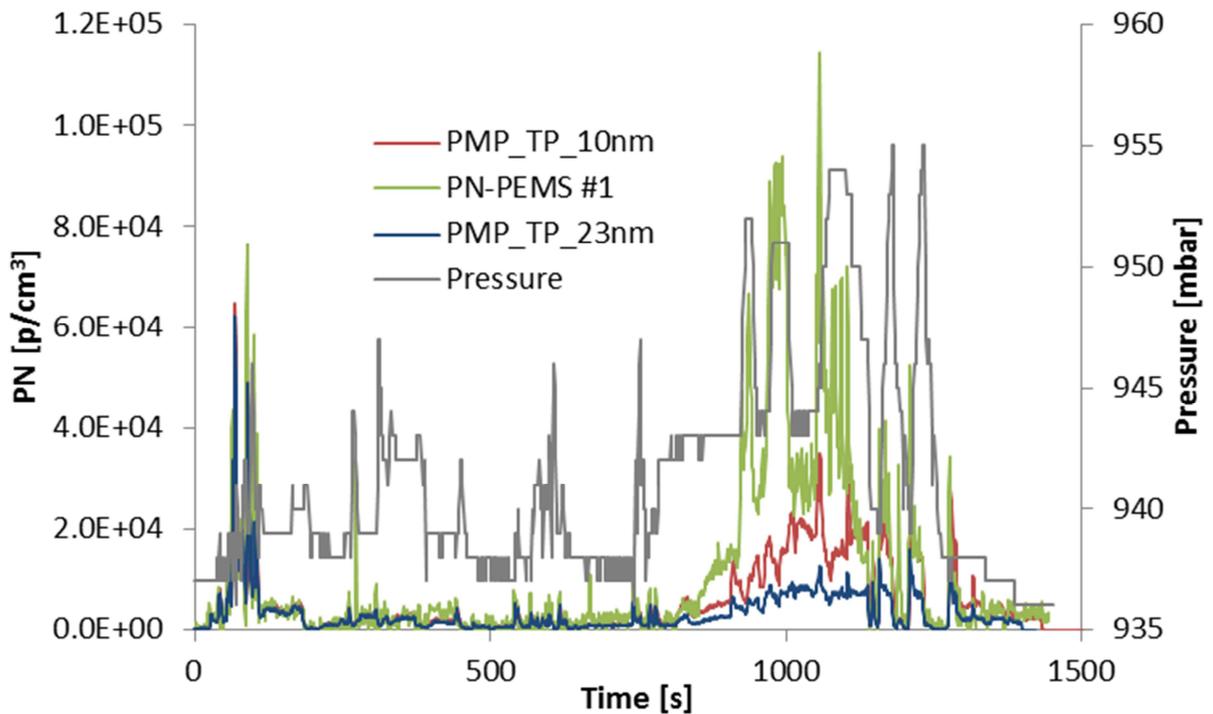
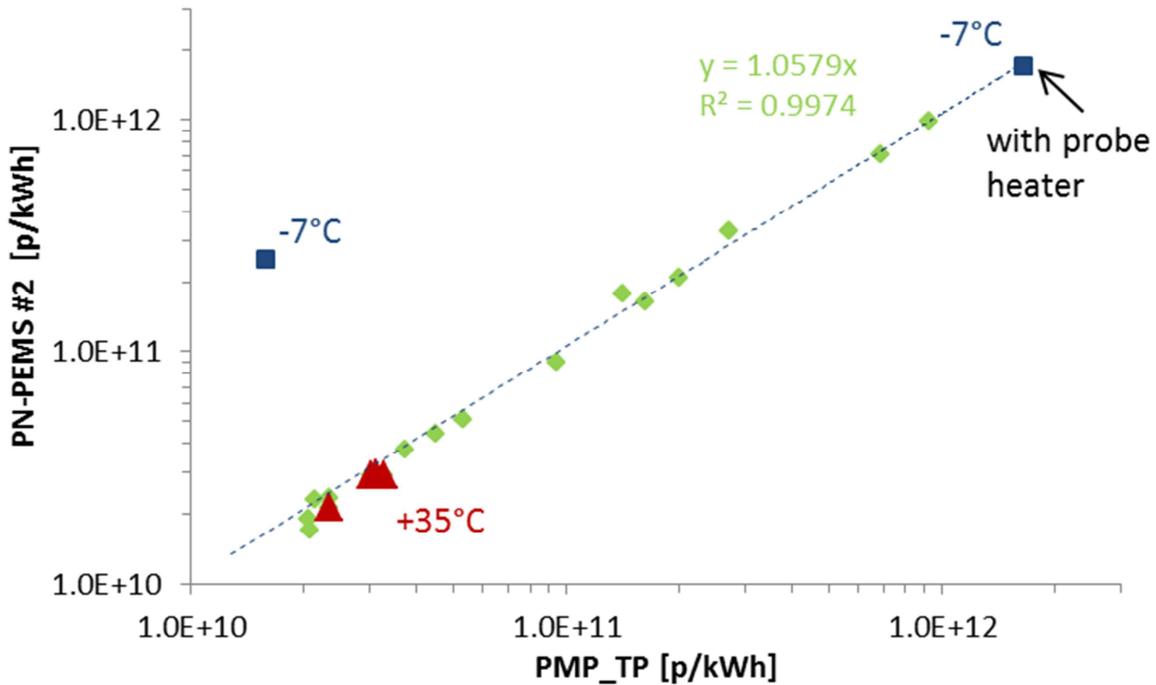


Figure 80: Real time comparison of PN-PEMS #1 with PMP\_TP over steady state points (vehicle V8) (20160914-02\_Steady).

### 10.4 PN-PEMS #2: HORIBA OBS-ONE

For the second evaluation phase the commercial unit OBS-ONE PN was available (PN-PEMS #2d). The correlation was excellent (slope 1.05,  $R^2 > 0.99$ ) and the differences were within  $\pm 15\%$  with the exception of the tests at  $0^\circ\text{C}$  and  $-7^\circ\text{C}$  (Figure 81).



**Figure 81: Comparison of PN-PEMS #2d with PMP\_TP for vehicle V8. Green points are tests at ambient temperature of  $20^\circ\text{C}$ . Red points are tests at ambient temperature of  $35^\circ\text{C}$ . All tests at sub- $0^\circ\text{C}$  had errors and only one (blue square) is shown for illustrative reasons. One test with a probe heater had no errors (blue square).**

The low ambient temperature tests had spikes, like in the main campaign. These spikes resulted in emission levels around  $2 \times 10^{11}$  p/km. It seems that the insulation of the tube was not enough to avoid condensation in the tube between the tailpipe and the instrument, which was longer than it would be in real applications due to lack of the appropriate parts to connect it directly (Figure 5). These condensates could result in many small particles when heated inside the device. When a heater was used at the sample probe these spikes didn't appear even during a 3 h test (Figure 82).

For tests at  $20^\circ\text{C}$  the agreement with the reference system at tailpipe was excellent, even when high concentration of sub-23 nm particles existed (Figure 83).

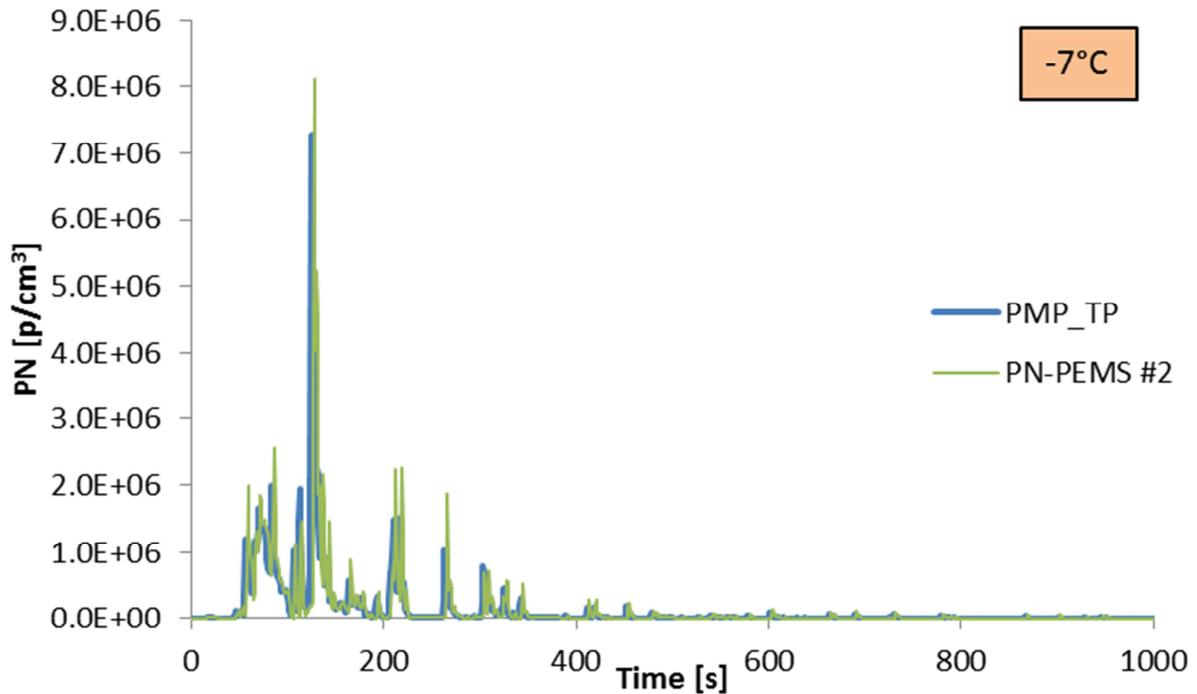


Figure 82: Real time comparison of PN-PEMS #2d with PMP\_TP over an ISC cycle at -7°C (vehicle V8) (20160913-01\_ISC\_-7°C). With probe heater.

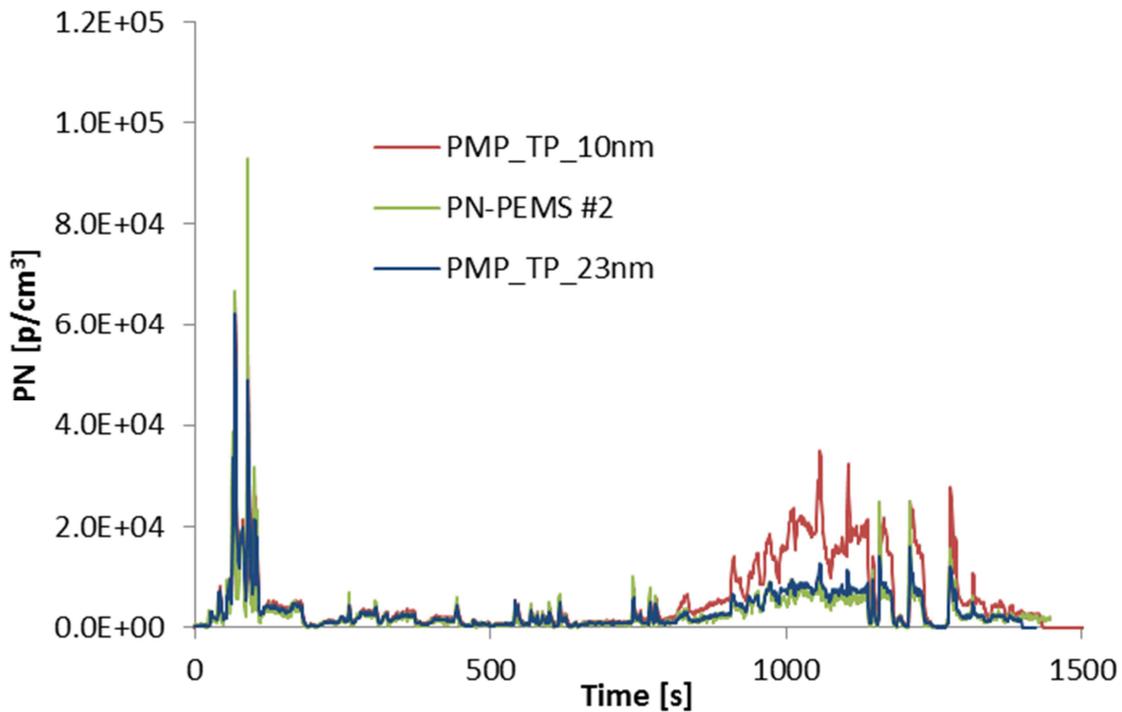


Figure 83: Real time comparison of PN-PEMS #2d with PMP\_TP over steady state modes (vehicle V8) (20160914-02-Steady).

### 10.5 PN-PEMS #3: TESTO NANOMET 3

PN-PEMS #3c is basically the same unit since 2013 with only minor modifications. The results can be seen in Figure 84. The agreement with the PMP\_TP is excellent for emission levels above the emission limit  $6 \times 10^{11}$  p/kWh. From  $1 \times 10^{11}$  p/kWh to

$3 \times 10^{11}$  p/kWh the differences are from 0% up to 150% (still the result below  $6 \times 10^{11}$  p/kWh). The reason is that a dilution (PCRF) of 30 was used (instead of 10) and thus the uncertainty which is typically 50% increased 3 times. This can be seen on Figure 85 where the signal of PN-PEMS is higher than the PMP\_TP. It can also be seen that the signal matches better with the 10 nm CPC.

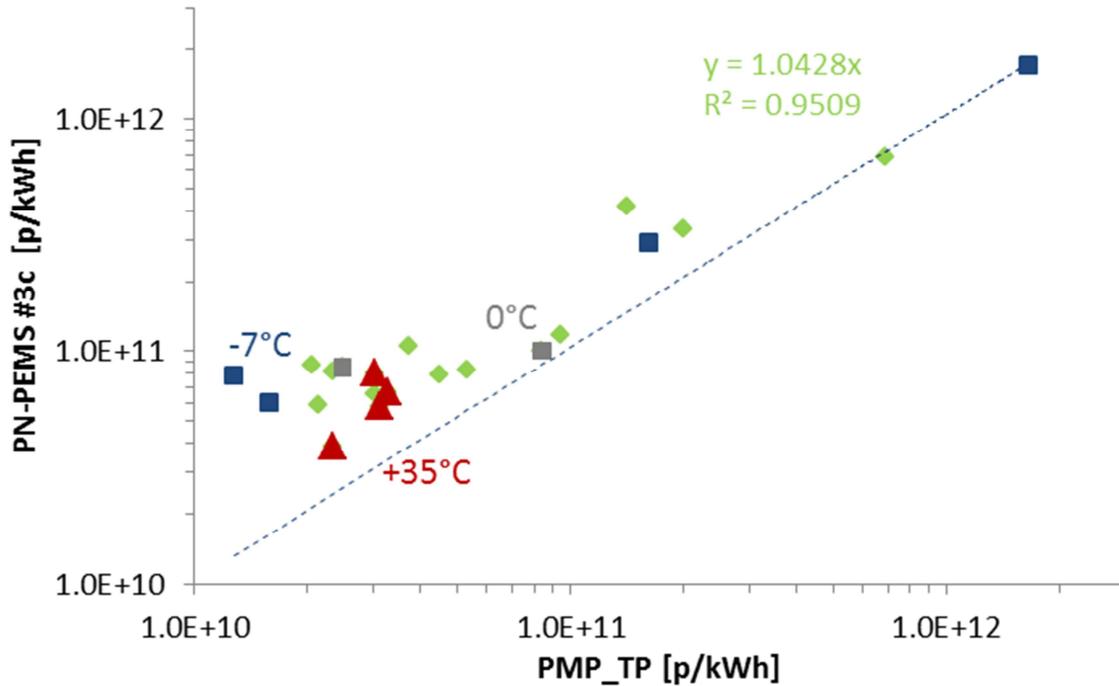


Figure 84: Comparison of PN-PEMS #3c with PMP\_TP for vehicle V8. Green points are tests at ambient temperature of 20°C. Blue points are tests at ambient temperature of -7°C. Red points are tests at ambient temperature of 35°C.

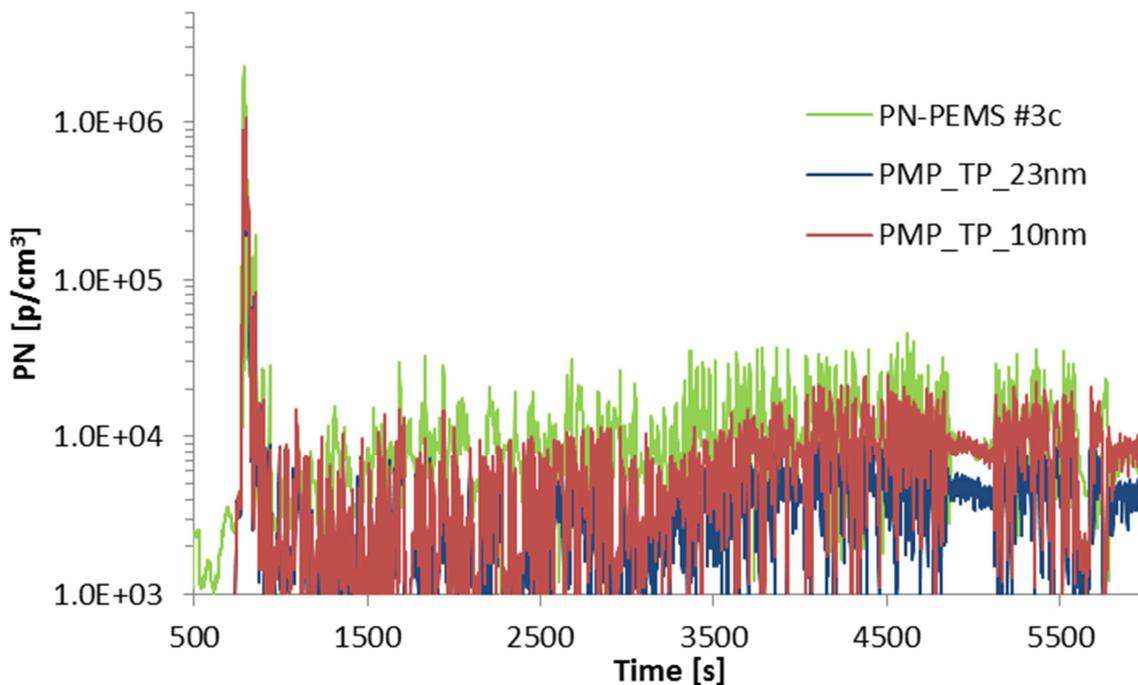


Figure 85: Real time comparison of PN-PEMS #3c with PMP\_TP over an ISC cycle at 22°C (vehicle V8) (20160912-01\_ISC\_22°C).

### 10.6 PN-PEMS #6: SHIMADZU NanoPEM-10

The correlation of PN-PEMS #6b with the PMP\_TP was not satisfactory (Figure 86). The reasons are not clear. However applying a correction factor tests with high emissions could match the reference system PMP\_TP (Figure 87).

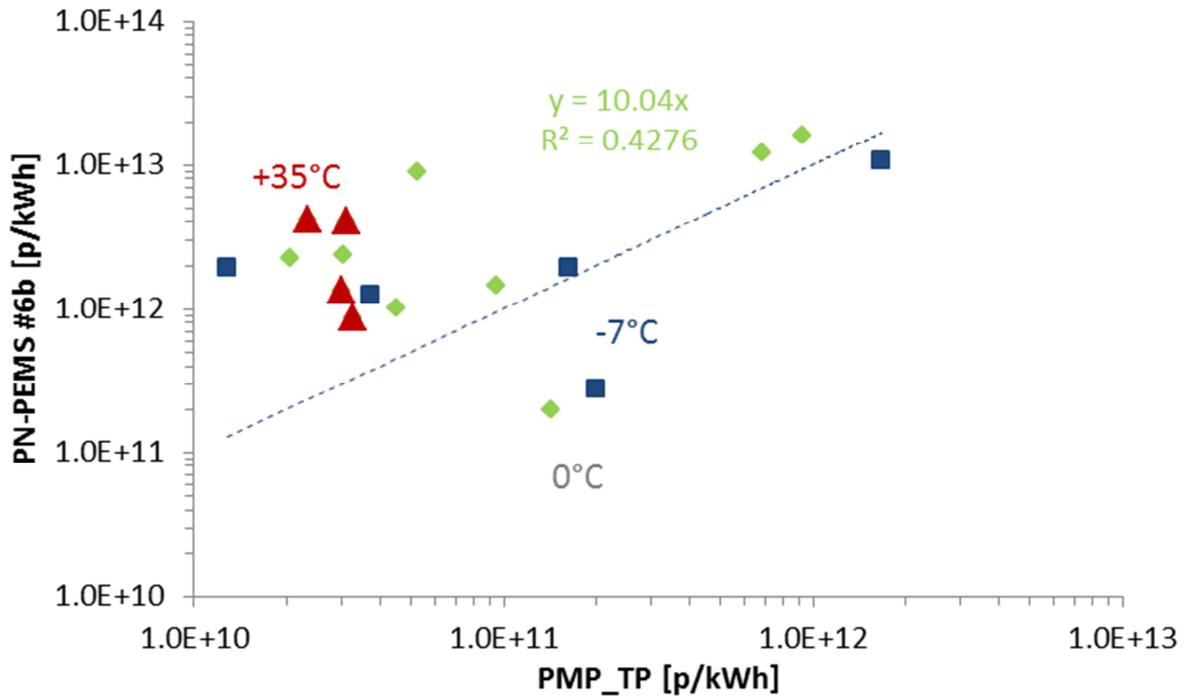


Figure 86: Comparison of PN-PEMS #6b with PMP\_TP for vehicle V8. Green points are tests at ambient temperature of 20°C. Blue points are tests at ambient temperature of -7°C. Red points are tests at ambient temperature of 35°C.

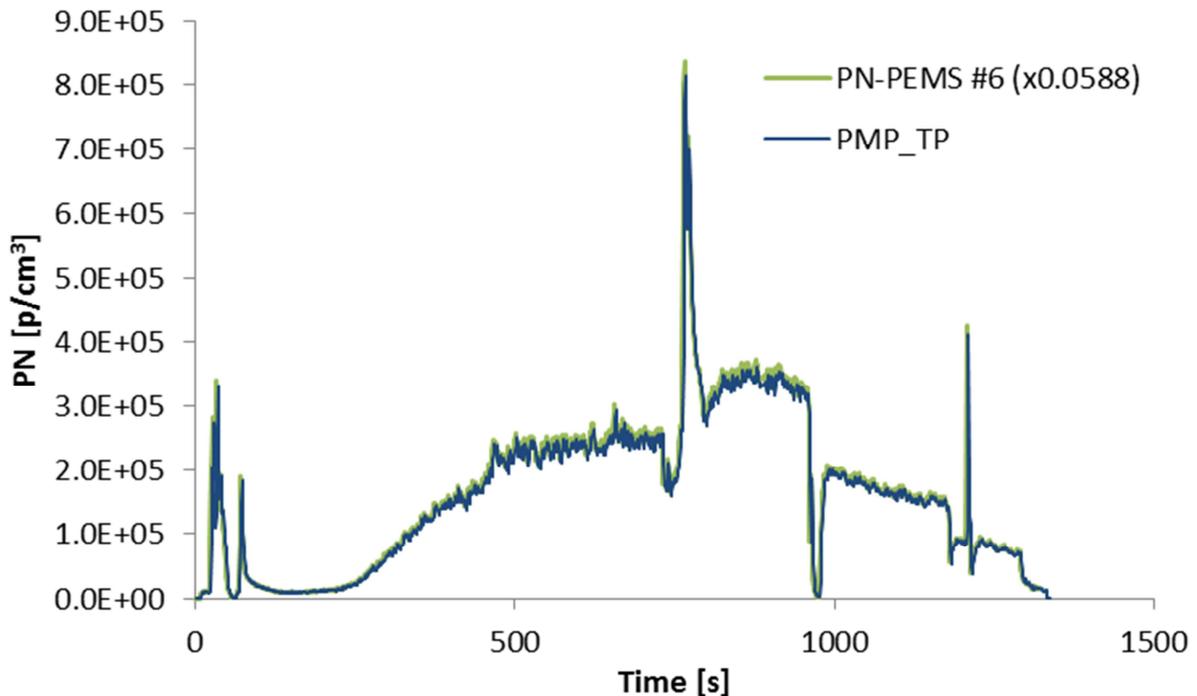


Figure 87: Real time comparison of PN-PEMS #6b with PMP\_TP over steady state points (vehicle V8) (20160906-03\_Steady)

### 10.7 PN-PEMS #7: MAHA

PN-PEMS #7 was tested only in the second evaluation phase. The summary results can be seen in Figure 88. The agreement is in general very good ( $R^2$  almost 0.99) with an offset (slope 0.67). The device didn't show any issues at low or high ambient temperatures. The real time signal matched perfectly with the PMP\_TP (having an offset as previously mentioned) (Figure 89).

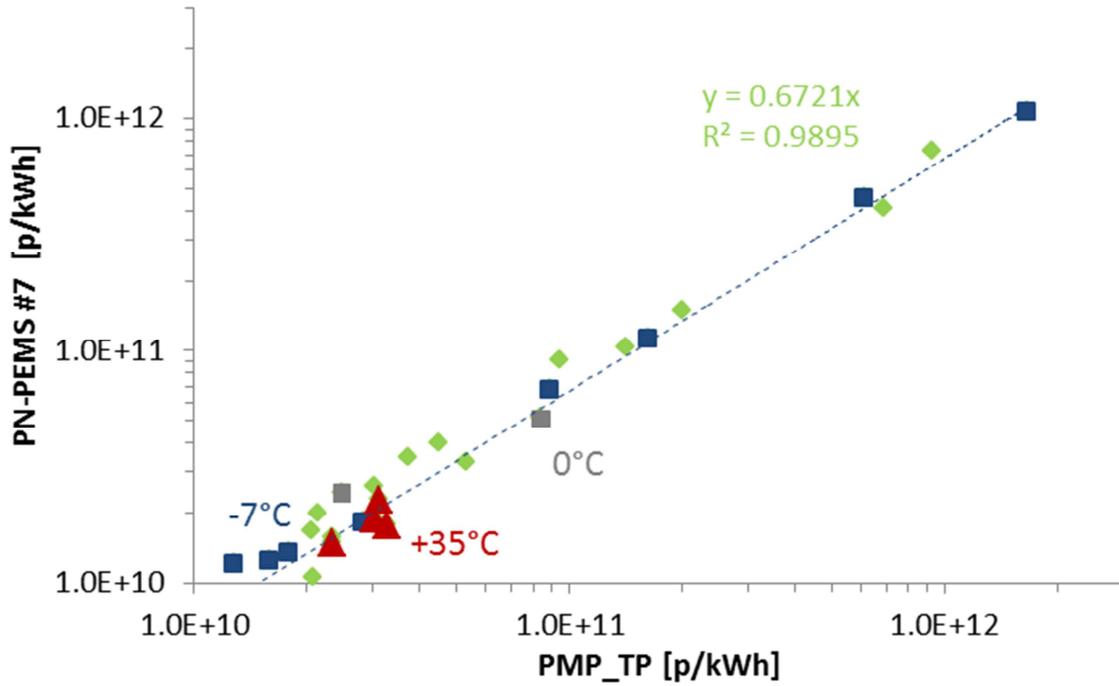


Figure 88: Comparison of PN-PEMS #7 with PMP\_TP for vehicle V8. Green points are tests at ambient temperature of 20°C. Blue points are tests at ambient temperature of -7°C. Red points are tests at ambient temperature of 35°C.

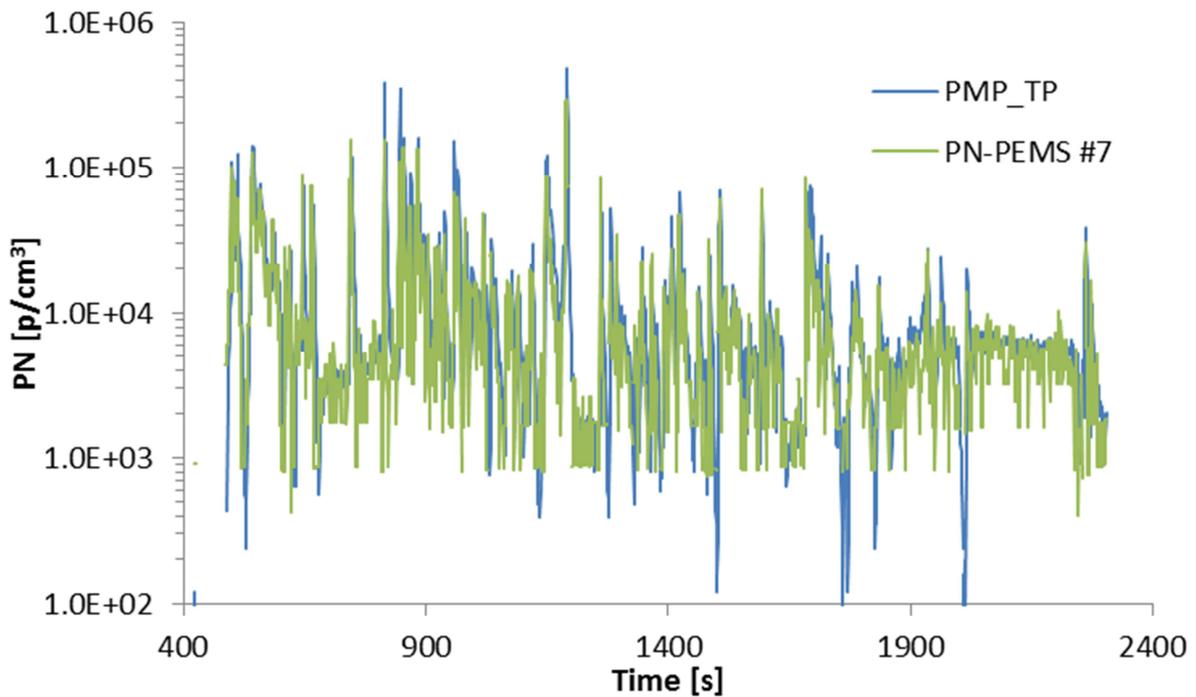


Figure 89: Real time comparison of PN-PEMS #7 with PMP\_TP over a WHVC (vehicle V8) (20160906-05\_WHVC hot).

## 10.8 Regeneration

During the second evaluation phase a regeneration test at 80 km/h was possible. The results of the instruments that were connected during that test can be seen in Figure 90. All instruments measured similarly with the PMP\_TP (PN-PEMS #6 and #7 with the offsets that were discussed in the respective paragraphs). After the test no issues were observed with any of the instruments confirming the findings of the main evaluation phase, that the PN-PEMS are robust enough during regenerations and in addition they measure accurately.

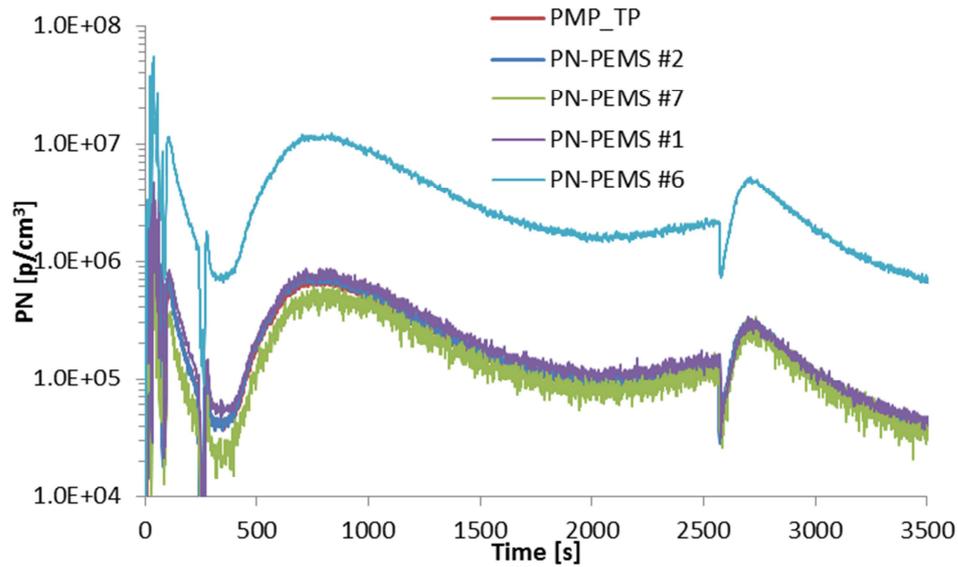


Figure 90: Regeneration test at 80 km/h.

## 11 Comparison with the CVS

In this chapter the best performing systems will be compared with the reference PMP system at the dilution tunnel for all examined vehicles. The differences give an indication of the expected uncertainty of the current PN-PEMS procedure.

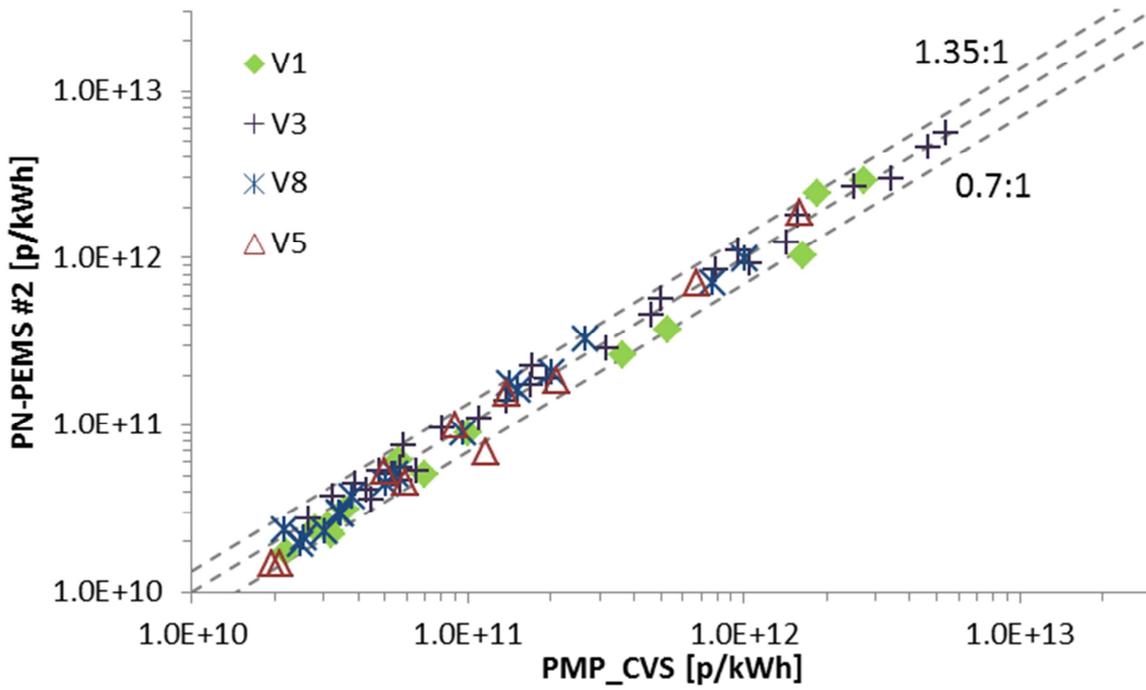


Figure 91: Comparison of PN-PEMS #2 with the PMP\_CVS. Each point is a test and each symbol is a different vehicle. Tests with errors (most at sub-0°C) have been excluded. Lines indicate the 1.35:1, 1:1 and 0.7:1 lines.

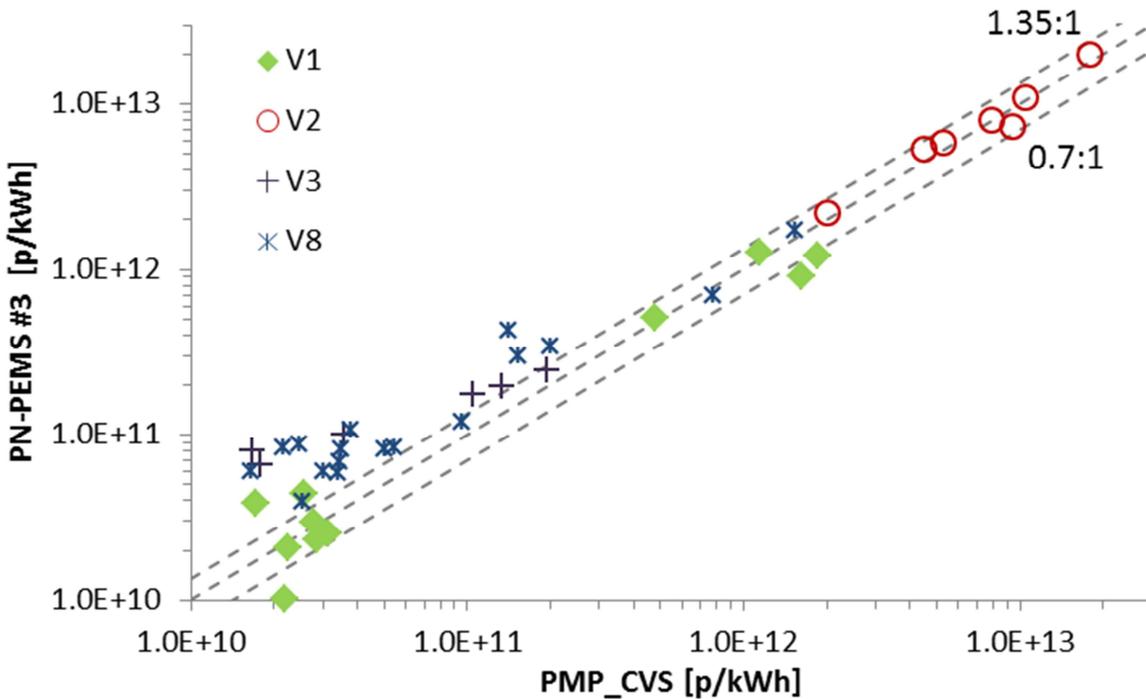


Figure 92: Comparison of PN-PEMS #3 with the PMP\_CVS. Each point is a test and each symbol is a different vehicle. Tests with errors (most at sub-0°C) have been excluded. Lines indicate the 1.35:1, 1:1 and 0.7:1 lines.

Figure 91 and Figure 92 present the results for PN-PEMS #2 (V1, V3, V5, V8) and #3 (V1, V2, V3, V8) respectively. The major conclusions are:

- Both systems are within 35%. Only a few exceptions for the CPC-based system (#2) and some for the DC-based (#3) as the emissions reach  $1 \times 10^{11}$  p/kWh approximately which is close to the detection limit.
- The uncertainty of PN-PEMS measurement procedure is better than the 50% that was found in the light-duty study for levels  $> 1 \times 10^{11}$  p/km.

The most probable explanation is the small effect of particle dynamics in the tube between the vehicle and the dilution tunnel due to the low particle emission levels.

## 12 Calibration of PN-PEMS

During the second evaluation phase the only instrument with a calibration certificate was PN-PEMS #3. Some checks that are required by the draft light-duty on-road regulation were conducted at JRC.

### 12.1 Leak check

This is obligatory. PN-PEMS #1 and PN-PEMS #6 have available an automated underpressure leak check, while PN-PEMS #3 a manual one. CPC based PN-PEMS have the HEPA filter zero check as leak check (but with lower than 5000 p/cm<sup>3</sup> limit) (see below).

### 12.2 Zero check

The zero check of CPC-based systems (PN-PEMS #2 and #7) was almost 0 p/cm<sup>3</sup>. The zero check of DC-based systems (PN-PEMS #1 and #3) was around 500 p/cm<sup>3</sup>. PN-PEMS #3 though didn't pass the limit of 5000 p/cm<sup>3</sup> the first time. PN-PEMS #6 (DC-based) did not pass the zero check.

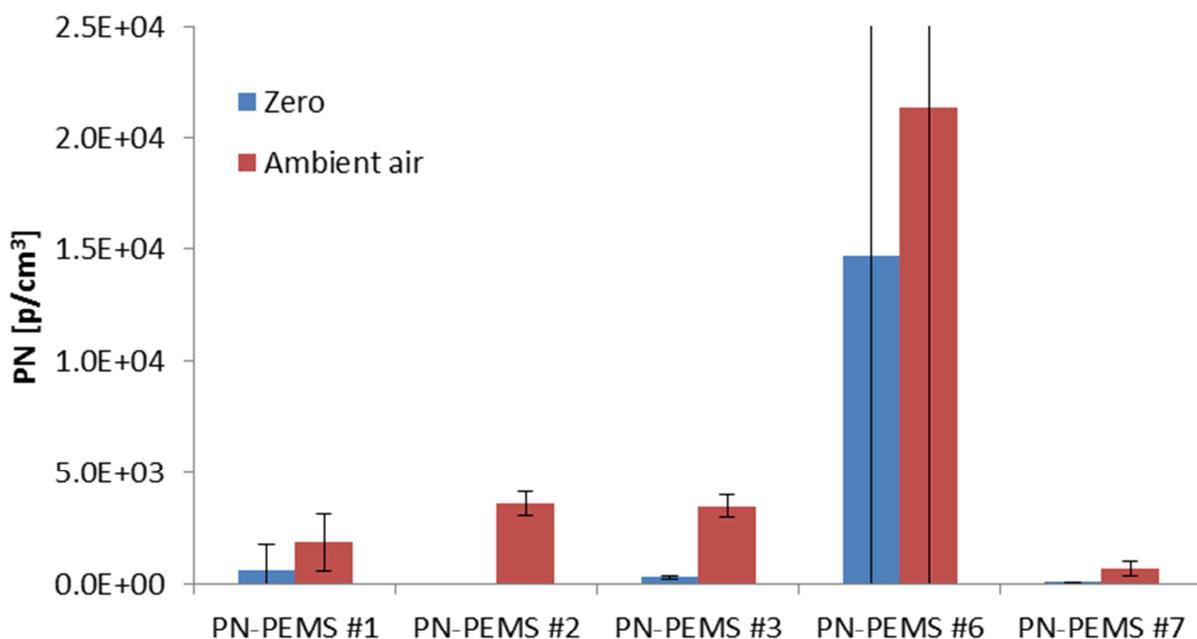


Figure 93: Zero and ambient air checks.

The ambient air check is not required by the PN-PEMS legislation. All systems though measured higher than the zero check. Of course ambient air concentrations can differ from place to place and over time; for this reason it is not required check to evaluate proper operation of the sensors; nonetheless it's a good quality check of the proper operation of the system.

## 12.3 Penetration efficiency requirements

The results of the penetration efficiency checks conducted at JRC can be seen in Table 7. Note that no correction for multiply charged particles was applied that would slightly affect the DC-based instruments results (10%). PN-PEMS #2 and #3 passed the technical specifications. PN-PEMS #1 and PN-PEMS #7 could pass by multiplying by a factor (but outside the permitted 0.9-1.1 range). This factor was in the right direction in explaining some of the differences observed in the second evaluation phase. PN-PEMS #6 had a response as normal diffusion charger and was outside the technical specifications.

**Table 7: Penetration efficiencies. In red non-compliant values. 'Corr' means adjusted more than 10%.**

$d_p$ [nm]	15*	23	30	50	70	100	200	
<b>Specs</b>	-	<b>0.2-0.6</b>	<b>0.3-1.2</b>	<b>0.6-1.3</b>	<b>0.7-1.3</b>	<b>0.7-1.3</b>	<b>0.5-2.0</b>	
#1	0.01	0.16	0.31	0.68	0.97	1.24	1.71	Corr.
#2	0.19	0.50	0.67	0.94	0.97	0.99	-	Pass
#3**	0.07	0.56	0.56	0.97	1.22	1.10	1.03	Pass
#6	-	0.13	0.75	2.64	-	8.94	-	Fail
#7	-	0.40		0.68	0.81	1.00	0.80	Corr.

\* silver particles and high uncertainty

\*\* DF=30

## 12.4 Volatile Removal Efficiency

The volatile removal efficiency results can be seen in Table 8 of the systems evaluated.

**Table 8: Volatile Removal Efficiency results. In red non-compliant results.**

Number	GMD	mass	PMP23	PMP10	#1	#2	#3*	size	Comments
$\mu\text{g}/\text{cm}^3$	nm	$\text{mg}/\text{m}^3$	[%]	[%]	[%]	[%]	[%]	nm	
8.6E6	45	1.1	100	100	100	100	100	-	required
1.3E7	56	11.5	100	99.9	100	100	96.3	10	extreme

\* DF=30

### 13 Theoretical evaluation of the measurement uncertainty

Figure 94 presents the expected measurement uncertainty based on estimations of the uncertainty of the parts that are needed for the calculation of the emissions:

$$PN = \frac{\sum PN, i}{Work}$$

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

where:

- $PN, i$  is the particle number flux [particles/s]
- $c_{PN, i}$  is the measured particle number concentration [ $\#/m^3$ ] normalized at 0°C (time aligned to the exhaust flow)
- $q_{mew, i}$  is the measured exhaust mass flow rate [kg/s]
- $\rho_e$  is the density of the exhaust gas [ $kg/m^3$ ] at 0°C

The estimated uncertainty of the parts are based on the technical specifications of the on-road procedure. The critical parts are:

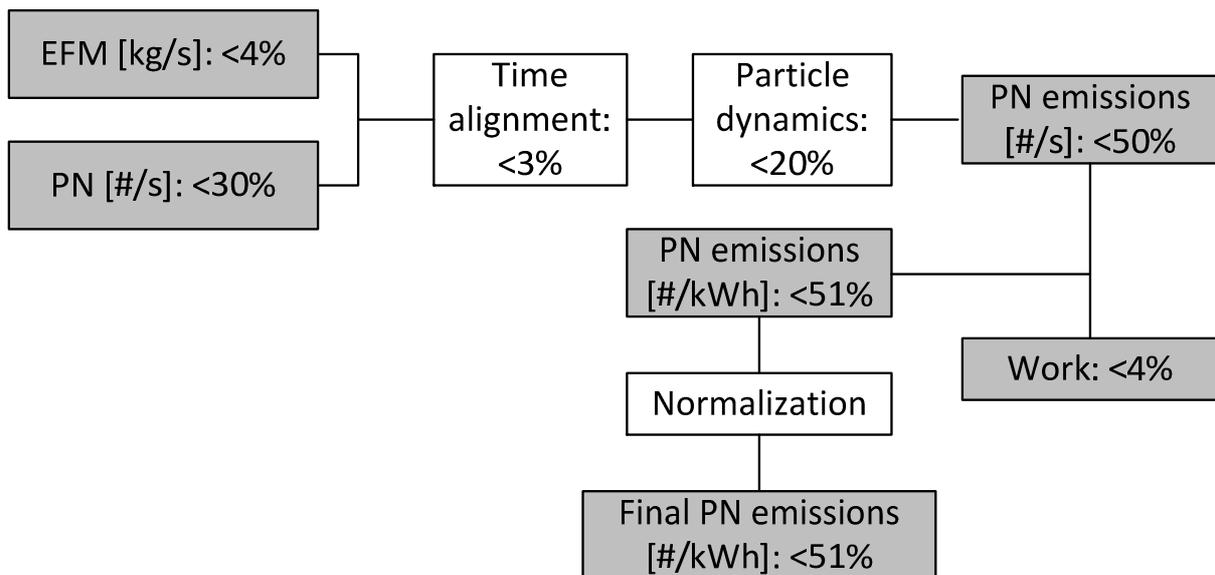


Figure 94: Theoretical estimation of PN-PEMS measurement uncertainty.

The 30% uncertainty of the PN analyser (instrument uncertainty) due to the relatively wider permitted efficiencies compared to the reference PN instrument at the full dilution tunnel (PMP). This uncertainty refers to emission levels close to the limit ( $6 \times 10^{11}$  p/kWh) but remains similar until the detection limit of the instruments (around  $1 \times 10^{11}$  p/kWh for DC-based PN-PEMS and more than one order of magnitude lower for CPC-based).

The 20% uncertainty due to the particle dynamics from the vehicle until the sampling location at the full dilution tunnel where the Euro emission limits are set. This uncertainty includes particle transformations due to e.g. agglomeration and particle losses due to diffusion and thermophoresis. The uncertainty is expected high (i.e. close

to 20%) at cold start but lower during hot operation (i.e. when everything has stabilized).

The theoretical estimation (50%) is a little bit higher than the experimental data (35%), probably due to the smaller effect of the particle dynamics at the HDV emission levels ( $<1 \times 10^{11}$  p/km).

## 14 Suggested technical specifications of PN-PEMS

Based on the light duty technical specifications and the existing PEMS regulation 582/2011, the following modifications are recommended.

Regulation 582/2011 is available at:

<http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02011R0582-20140703&qid=1475580169409&from=EN>

### **Appendix 1**

#### **1. INTRODUCTION**

Replace: 'The gaseous emissions to ...' with:

The pollutants to be measured from the exhaust of the engine include the following components: carbon monoxide, total hydrocarbons, nitrogen oxides and particle number for diesel engines with the addition of methane for gas engines.

**2.1.1** shall change to 2.1.1a

**2.1.1b** Particle analyser to measure the concentration of particle number in the exhaust gas

**2.2** Add at the table a line:

PN concentration (4) cm<sup>3</sup> (5)                      Particle analyser

(4) measured on a wet basis

(5) at 0°C and 101.3 kPa

**2.4.6. Installation of PN analyser** (normally to be added after 2.4.1)

The installation and operation of the PEMS shall be leak-tight. To avoid the generation of particles, connectors shall be thermally stable at the exhaust gas temperatures expected during the test. It is recommended not to use elastomer connectors to connect the vehicle exhaust outlet and the connecting tube. Elastomer connectors, if used, shall have no contact with the exhaust gas to avoid artefacts at high engine load.

**2.4.7 Sampling of PN emissions**

If particles are measured, the exhaust shall be sampled from the centre of the exhaust stream. If several probes are used for emissions sampling, the particle sampling probe should be placed upstream of the other sampling probes. The particle sampling probe should not interfere with the sampling of gaseous pollutants. The type and specifications of the probe and its mounting shall be documented in detail.

If particles are sampled and not diluted at the tailpipe, the sampling line from the raw exhaust sample point to the point of dilution or particle detector shall be heated to a minimum of 373 K (100 °C). The residence time of the sample in the particle sampling line shall be less than 3 s until reaching first dilution or the particle detector.

All parts of the sampling system from the exhaust pipe up to the particle detector, which are in contact with raw or diluted exhaust gas, shall be designed to minimize deposition

of particles. All parts shall be made from antistatic material to prevent electrostatic effects.

### **2.5.5 Checking the PN analyser**

The PEMS shall function free of errors and critical warnings.

The zero level of the analyser shall be recorded by sampling HEPA filtered ambient air at an appropriate sampling point, usually at the inlet of the sampling line. The signal shall be recorded at a constant frequency of at least 1.0 Hz averaged over a period of 2 minutes; the final concentration shall be within the manufacturer's specifications, but shall not exceed 5000 particles per cubic-centimetre.

### **2.7.6 Checking the PN analyser**

The zero level of the analyser shall be checked and recorded according to point 2.5.5

#### **3.1.1** (To be added at the end of the paragraph)

The PN analyser will be time aligned with the rest gaseous pollutants using the transformation time.

### **3.6. Calculation of the instantaneous particle number emissions**

The instantaneous particle number emissions [particles/s] shall be determined by multiplying the instantaneous concentration of the pollutant under consideration [particles/cm<sup>3</sup>] with the instantaneous exhaust mass flow rate [kg/s], both corrected and aligned for the transformation time. If applicable, negative instantaneous emission values shall enter all subsequent data evaluations. All significant digits of intermediate results shall enter the calculation of the instantaneous emissions. The following equation shall apply:

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

where:

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

$c_{PN, i}$  is the measured particle number concentration [# / m<sup>3</sup>] normalized at 0°C

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

$\rho_e$  is the density of the exhaust gas [kg/m<sup>3</sup>] at 0°C (Table 1)

## **Appendix 2**

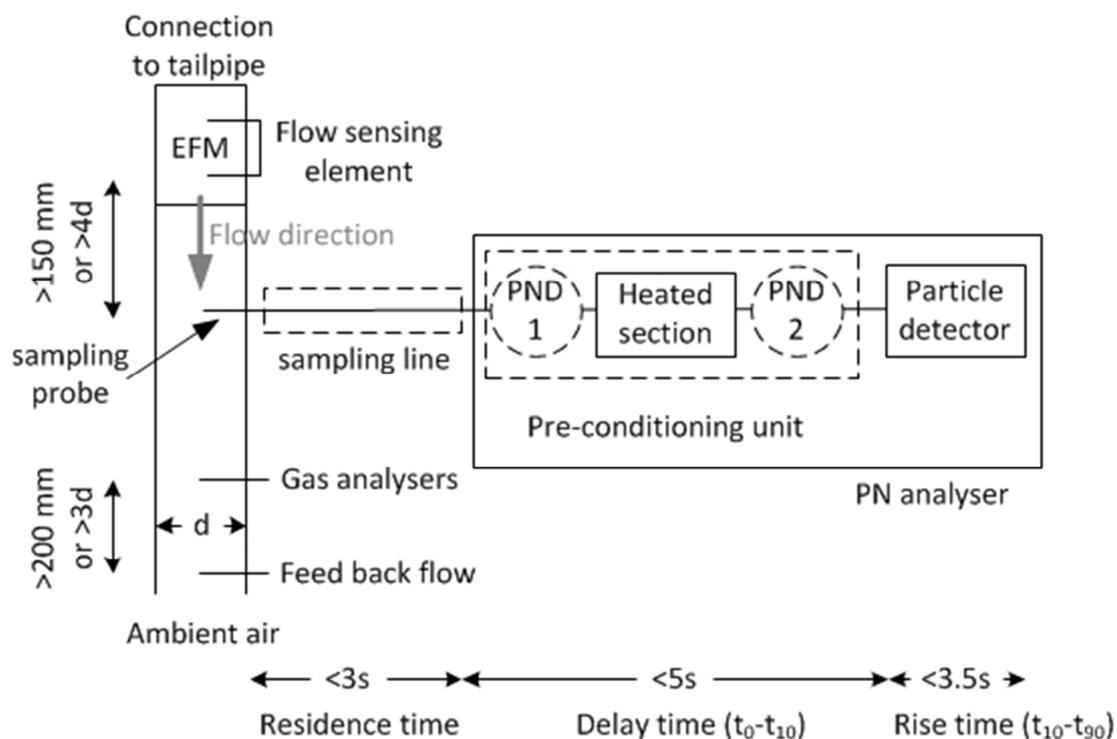
### **2.5 PN analysers**

#### **2.5.1 General**

The PN analyser shall consist of a pre-conditioning unit and a particle detector. It is permissible that the particle detector also pre-conditions the aerosol. The sensitivity of the analysers to shocks, vibration, aging, variability in temperature and air pressure as well as electromagnetic interferences and other impacts related to vehicle and analyser operation shall be limited as far as possible and shall be clearly stated by the equipment

manufacturer in its support material. The PN analyser shall only be used within its manufacturer's declared parameters of operation.

**Figure 14.1:** Example of a PN analyser setup: Dotted lines depict optional parts. EFM = Exhaust mass Flow Meter,  $d$  = inner diameter, PND = Particle Number Diluter.



*Note: Depending on the needs for HDV, the delay time could be possibly increased*

The PN analyser shall be connected to the sampling point via a sampling probe which extracts a sample from the centreline of the tailpipe tube. If particles are not diluted at the tailpipe, the sampling line shall be heated to a minimum temperature of 373 K (100 °C) until the point of first dilution of the PN analyser or the particle detector of the analyser. The residence time in the sampling line shall be less than 3 s.

All parts in contact with the sampled exhaust gas shall be always kept at a temperature that avoids condensation of any compound in the device. This can be achieved, e.g. by heating at a higher temperature and diluting the sample or oxidizing the (semi)volatile species.

The PN analyser shall include a heated section at wall temperature  $\geq 573\text{K}$ . The unit shall control the heated stages to constant nominal operating temperatures, within a tolerance of  $\pm 10\text{K}$  and provide an indication of whether or not heated stages are at their correct operating temperatures. Lower temperatures are acceptable as long as the volatile particle removal efficiency fulfils the specifications of 2.5.4.

Pressure, temperature and other sensors shall monitor the proper operation of the instrument during operation and trigger a warning or message in case of malfunction.

The delay time of the PN analyser shall be  $\leq 5\text{ s}$ .

The PN analyser (and/or particle detector) shall have a rise time of  $\leq 3.5\text{ s}$ .

Particle concentration measurements shall be reported normalised to 273 K and 101.3 kpa. If necessary, the pressure and/or temperature at the inlet of the detector shall be measured and reported for the purposes of normalizing the particle concentration.

PN systems that comply with the calibration requirements of the UNECE Regulations 83 or 49 or GTR 15 automatically comply with the calibration requirements of this Annex.

### 2.5.2 Efficiency requirements

The complete PN analyser system including the sampling line shall fulfil the efficiency requirements of **Table 14.1**:

**Table 14.1:** PN analyser (including sampling line) system efficiency requirements

Dp [nm]	Sub-23	23	30	50	70	100	200
E(dp)	tbd	0.2-0.6	0.3-1.2	0.6-1.3	0.7-1.3	0.7-1.3	0.5-2.0

Efficiency E(dp) is defined as the ratio in the readings of the PN analyser system to a reference Condensation Particle Counter (CPC)'s ( $d_{50}=10\text{nm}$  or lower, checked for linearity and calibrated with an electrometer) or an Electrometer's number concentration measuring in parallel monodisperse aerosol of mobility diameter dp and normalized at the same temperature and pressure conditions. The material should be thermally stable soot-like (e.g. spark discharged graphite or diffusion flame soot with thermal pre-treatment). If the efficiency curve is measured with a different aerosol (e.g. NaCl), the correlation to the soot-like curve must be provided as a chart, which compares the efficiencies obtained using both test aerosols. The differences in the counting efficiencies have to be taken into account by adjusting the measured efficiencies based on the provided chart to give soot-like aerosol efficiencies. Any correction for multiply charged particles should be applied and documented but shall not exceed 10%. These efficiencies refer to the PN analysers with the sampling line. The PN analyser can also be calibrated in parts (i.e. the pre-conditioning unit separately from the particle detector) as long as it is proven that PN analyser and the sampling line together fulfil the requirements of Table 1. The measured signal from the detector shall be >2 times the limit of detection (here defined as the zero level plus 3 standard deviations).

### 2.5.3 Linearity requirements

The linearity requirements shall be verified whenever damage is observed, as required by internal audit procedures or by the instrument manufacturer but no longer than one year before the actual test.

The PN analyser including the sampling line shall fulfil the following linearity requirements (**Table 14.2**).

**Table 14.2:** Linearity requirements of PN analyser (including sampling line)

Measurement parameter /instrument	$ \chi_{\min} \times (a_1 - 1) + a_0 $	Slope $a_1$	Standard error SEE	Coefficient of determination $r^2$
PN analyser	$\leq 5\%$ max	0.85-1.15	$\leq 10\%$ max	$\geq 0.950$

The PN analyser including the sampling line shall fulfil the linearity requirements of **Table 14.2** using monodisperse soot-like particles. The particle size (mobility diameter

or count median diameter) should be larger than 45 nm. The reference instrument shall be an Electrometer or a Condensation Particle Counter (CPC) with  $d_{50}=10$  nm or lower, verified for linearity. Alternatively, a particle number system compliant with UNECE Regulation 49.

In addition the differences of the PN analyser from the reference instrument at all points checked (except the zero point) shall be within 15% of their mean value. At least 5 points equally distributed (plus the zero) shall be checked. The maximum checked concentration shall be the maximum allowed concentration of the PN analyser.

If the PN analyser is calibrated in parts, then the linearity can be checked only for the PN detector, but the efficiencies of the rest parts and the sampling line have to be considered in the slope calculation.

#### **2.5.4 Volatile removal efficiency**

The system shall achieve >99% removal of  $\geq 30$  nm tetracontane ( $\text{CH}_3(\text{CH}_2)_{38}\text{CH}_3$ ) particles with an inlet concentration of  $\geq 10,000$  particles per cubic-centimetre at the minimum dilution.

The system shall also achieve a >99% removal efficiency of polydisperse alkane (decane or higher) or emery oil with count median diameter >50 nm and mass >1 mg/m<sup>3</sup>.

The volatile removal efficiency with tetracontane and/or polydisperse alkane or oil have to be proven only once for the instrument family. The instrument manufacturer though has to provide the maintenance or replacement interval that ensures that the removal efficiency does not drop below the technical requirements. If such information is not provided, the volatile removal efficiency has to be checked yearly for each instrument.

### **Appendix 3**

#### **1.4 PN analyser calibration and verification**

The leakage test shall be conducted in accordance with the requirements set out in paragraph 9.3.4 of Annex 4 to UNECE Regulation 49

The response time check of the PN analyser shall be conducted in accordance with the requirements set out in paragraph 9.3.5 of Annex 4 to UNECE Regulation 49 using particles if gases cannot be used.

#### **1.5 PN validation test**

It is highly recommended to check the proper operation of the PN analyser every 3 months conducting a validation test.

For the validation test, the PN analyser shall be installed and prepared according to the requirements of Appendix 1. The validation test shall be conducted in a test bed, as far as applicable, under type-approval conditions by following the requirements of UN/ECE Regulation No 49.

The total work-specific emissions [# / kWh] measured with laboratory equipment shall be calculated following UN/ECE Regulation No 49. The emissions as measured with the PEMS shall be calculated according to Appendix 1, summed to give the total PN emissions [#] and then divided by the test work [kWh] as obtained from the test bed. The total work-specific PN [# / kWh], as determined by the PEMS and the reference laboratory system, shall be compared and evaluated against the requirements specified in **Table 14.3**.

**Table 14.3:** Permissible tolerances

Parameter [Unit]	Permissible absolute tolerance
PN [# /kWh]	$1 \times 10^{11}$ p/kWh or 50% of the laboratory reference whichever is larger

## 15 Conclusions

JRC evaluated the feasibility of using PN-PEMS systems for HDV applications. The main evaluation phase took place between February and June 2016. One CNG vehicle and three vehicles equipped DPF and SCR were tested. In September commercial PN-PEMS instruments were tested with a DPF and SCR equipped vehicle (no CNG vehicle was available).

Two reference systems were used: One connected to the full dilution tunnel, as prescribed in the legislation (PMP\_CVS), and one was connected to the tailpipe (PMP\_TP). Both were always at constant ambient temperature of 20°C in order to exclude any temperature effect on their results. However, the location of the tailpipe system close to the dilution tunnel probably reduced any effects from pressure pulsations, thermophoresis, diffusion and agglomeration. The differences between the two systems were within  $\pm 15\%$ . However, for other cases calibration or exhaust mass flow uncertainties could further increase this range another 10%.

The fraction of sub-23 nm (solid) particles was determined using a CPC with  $d_{50\%}$  at 10 nm in parallel with the 23 nm CPC of the PMP\_TP. Target was to identify any sensitivity of the PN-PEMS at solid particles  $< 23$  nm. The fraction was relatively high for the CNG vehicle (30-50%) and even higher (double) at cold start with this vehicle. For the DPF and SCR equipped vehicles the fraction was low for emission levels  $> 3 \times 10^{11}$  p/kWh but could reach 100% at lower levels due to the higher contribution of urea formed nanoparticles. It should be mentioned though that there were indications that the 23 nm CPC had lower detection efficiency for these particles.

The volatile particles were determined by using an EEPS connected directly at the CVS, without any thermal pre-treatment. Generally there was no separate nucleation mode with the exception of regeneration events and high load points where the exhaust gas temperature was high. The mass of volatile particles could exceed  $0.5 \text{ mg/m}^3$ .

Comparing the PN-PEMS with the PMP\_TP in order to quantify the measurement uncertainty of the PN-PEMS instruments only the following conclusions could be drawn:

PN-PEMS #2 (HORIBA): It was the best performing instrument (CPC-based) at temperatures  $> 0^\circ\text{C}$ . It had differences typically within 15% to the reference instrument, sometimes up to 25% even for low emission levels close to the background levels of the PMP\_TP system ( $1 \times 10^9$  p/kWh). Similar differences were also observed at the second by second comparisons. It showed no sensitivity to particles smaller than 23 nm, and no issues during regeneration events (active and passive) where the temperatures reached  $425^\circ\text{C}$ . At low ambient temperatures though it degraded fast, showed spikes and then stopped working. This system was not tested with the CNG vehicle. Calibration tests in the laboratory showed that it fully complied with the technical specifications.

PN-PEMS #3 (TESTO): The differences to the reference system were  $< 30\%$  close to the emission limit of  $6 \times 10^{11}$  p/kWh or higher. The differences were on the order of 50% (up to 100% when used with higher dilution ratio) at emission levels close or above its detection limit ( $1 \times 10^{11}$  p/kWh). The real time signals matched quite well the reference systems'. It could measure without errors between 5 and  $35^\circ\text{C}$  (its specifications are 5- $35^\circ\text{C}$ ). At low temperatures though it can degrade fast as the appropriate temperatures cannot be held. However bringing the instrument at  $-7^\circ\text{C}$  half an hour before the test was proven to be possible without any errors and issues. Calibration tests in the laboratory showed that it fully complied with the technical specifications.

PN-PEMS #1 (AVL): This DC-based system had issues in the main campaign mainly from high spikes that originated from pressure changes and condensates entering the system. With a probe heater the results were very good in the second phase. The results were within 20% of the reference instrument for emission levels  $> 1 \times 10^{11}$  p/km. There were no issues for low or high ambient temperatures or regeneration events. Calibration in the

lab confirmed that there was an offset in its penetration efficiency curve. The volatile removal efficiency was extremely high (efficient).

PN-PEMS #6 (SHIMADZU): This DC based system could follow the real time signal of the reference system. However the absolute levels had big differences and the reason is not clear. Calibration in the lab showed that it didn't fulfil the technical specifications.

PN-PEMS #7 (MAHA): This CPC-based system had an offset of 30% (measuring lower) compared to the reference system (bias). The differences from the median though had small variability of 12% (precision, expressed as standard deviation of the differences). The real time signals matched excellent those of the reference system. In the calibration lab similar offset to the reference system was found.

Concluding, PN-PEMS are ready to be used for the purpose of an assessment during type-approval demonstration. The instruments measurement uncertainty at the moment is on the order of 30% (even during regenerations) until the detection limits of the instruments with potential of reduction based on the results of one CPC based system. The DC based systems have a detection limit slightly lower than  $1 \times 10^{11}$  p/kWh; the CPC based two orders of magnitude lower. Nevertheless, these detection limits are sufficient for ISC testing given their measurement uncertainty of 30%. Similar measurement uncertainty was found during the light-duty vehicles evaluation phase when comparing to the reference system at the tailpipe.

The tests at sub-0°C were challenging for a few systems with low sampling flow rates. They could damage the systems in some cases due to condensates entering the system (either due to non-ideal setup or inadequate heating capacities). At low temperatures the setup is very important to avoid any condensation in the first place. Active heating of the adaptor connecting the system to the tailpipe solved the problem. It should be noted that some systems could measure at low temperatures without any issues.

Comparison of the two PN-PEMS systems with the PMP system at the dilution tunnel (PMP-CVS) for all tested vehicles showed that the uncertainty is <35% which is lower than 50% estimated theoretically (and also found in the light-duty evaluation program), probably due to lower particle dynamics between vehicle and dilution tunnel at the emission levels of HDVs ( $< 1 \times 10^{11}$  p/km). This confirms the suitability of the PN-PEMS for measuring the PN emissions of HDV.

What hasn't been investigated in this report is the sensitivity of the PN-PEMS to shocks, vibration, aging, variability in temperature and air pressure as well as electromagnetic interferences and other impacts related to on-road vehicle and PN-PEMS operation. Dedicated tests should be conducted.

In addition further testing with cracked DPF, low ambient temperatures, biofuels and especially CNG engines where more experience with PN-PEMS would be desirable.

## References

- AA (2016). Administrative Arrangement SI2.730104 between DG GROW and DG Joint Research Centre (DG JRC), Ref. Ares(2016) 1659670 - 07/04/2016
- Amanatidis, S., Ntziachristos, L., Giechaskiel, B., Bergmann, A., Samaras, Z. (2014). Impact of selective catalytic reduction on exhaust particle formation over excess ammonia events. *Environ. Sci. Technol.* 48, 11527–11534.
- Bonnel, P., Carriero, M., Forni, F., Alessandrini, S., Montigny, F., Demircioglu, H., & Giechaskiel, B. (2010). *EUPEMS PM Evaluation Program - First Report*, JRC Scientific and Technical Report, EUR 24543 EN, ISBN 978-92-79-17031-7
- Giechaskiel, B., Cresnoverh, M., Jörgl, H., and Bergmann, A. (2010). Calibration and accuracy of a particle number measurement system. *Meas. Sci. Technol.* 21(4): 045102. doi: 10.1088/0957-0233/21/4/045102
- Giechaskiel, B., Massimo, C., Bonnel, P., Schindler, W., Scheder, D., Bassoli C., and Niemelä, V. (2011). PEMS feasibility of particulate mass and number measurement with portable emission measurement systems (PEMS) for in-use testing, SAE 2011-24-0199.
- Giechaskiel, B., Riccobono, F., & Bonnel, P. (2015a). Feasibility study on the extension of the Real Driving Emissions (RDE) procedure to Particle Number (PN): Experimental evaluation of portable emission measurement systems (PEMS) with diffusion chargers (DCs) to measure particle number (PN) concentration Chassis dynamometer evaluation of portable emission measurement systems (PEMS) to measure particle number (PN) concentration: Phase II. EU JRC report EUR 27451 EN
- Giechaskiel, B., Riccobono, F., Vlachos, T., Mendoza, P., Suarez, R., Fontaras, G., Bonnel, P., Weiss, M. (2015b). Vehicle emission factors of solid nanoparticles in the laboratory and on the road using Portable Emission Measurement Systems (PEMS). *Front. Environ. Sci.* 3(82), doi: 10.3389/fenvs.2015.00082.
- Mamakos, A., Bonnel, P., Perujo, A., & Carriero, M. (2013). Assessment of portable emission measurement systems (PEMS) for heavy-duty diesel engines with respect to particulate matter. *Journal of Aerosol Science*, 57, 54–70.
- Mamakos, A., Carriero, M., Bonnel, P., Demircioglu, H., Douglas, K., Alessandrini, S., Forni, F., Montigny, F., & Lesueur D. (2011a). *EU-PEMS PM EVALUATION PROGRAM - Second Report - Study on Post DPF PM/PN Emissions*. EUR 24883 EN
- Mamakos, A., Carriero, M., Bonnel, P., Demircioglu, H., Douglas, K., Alessandrini, S., Forni, F., Montigny, F., & Lesueur D. (2011b). *EU-PEMS PM EVALUATION PROGRAM - Third Report – Further Study on Post DPF PM/PN Emissions*. EUR 24883 EN
- Mendoza Villafuerte, P., Perujo Mateos del Parque, A., Bonnel, P., Carriero, M., Forni, F., & Riccobono, F. (2015). *EU-PEMS PM Pilot Program: Testing, data analysis and results*. Report EUR 27326 EN
- Perujo Mateos del Parque, A., & Mendoza Villafuerte, P. (2015). PEMS emissions testing of heavy duty vehicles/engines: Assessment of PEMS procedures in fulfilment of article 14(3) to regulation (EU) 582/2011, EUR 27251 EN
- Perujo Mateos del Parque, A., Bonnel P., & Mendoza Villafuerte P. (2015). PEMS based in-service testing: Practical recommendations for heavy-duty engines/ vehicles. EUR 27338 EN
- Riccobono, F., Giechaskiel, B., Mendoza, P. (2016). Particle Number PEMS Inter-Laboratory Comparison Exercise: Performance of PN-PEMS for the extension of the RDE test procedure to PN. EU report 28136 EN
- Riccobono, F., Giechaskiel, B., Weiss, M., & Bonnel, P. (2014). How to extend the real drive emission test procedure to particle number. Presentation at the 18th ETH

Conference on Combustion Generated Nanoparticles, 25th June 2014, Zurich,  
Switzerland

## List of abbreviations and definitions

ACEA	European Automobile Manufacturers' Association
APC	AVL Particle Counter
CLD	ChemiLuminescence Detector
CNG	Compressed Natural Gas
CPC	Condensation Particle Counter
CVS	Constant Volume Sampler
DC	Diffusion Charger
DPF	Diesel Particulate Filter
EC	European Commission
EFM	Exhaust Flow Meter
ET	Evaporation Tube
FTIR	Fourier Transform InfraRed spectrometer
GPS	Global Positioning System
HDV	Heavy Duty Vehicle
HEPA	High Efficiency Particulate Air filter
HFID	Heated Flame Ionization Detector
ISC	In-Service Conformity
JRC	Joint Research Centre
MS	Member State
NDIR	Non-Dispersive InfraRed sensor
NDUV	Non-Dispersive Ultra-Violet sensor
OBD	On-Board Diagnostics
PCRF	Particle Number Concentration Reduction Factor
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
PMP	Particle Measurement Programme
PN	Particle Number
RDE	Real Driving Emissions
SCR	Selective Catalytic Reduction
SICO	Simplified Constant Speed Test
THC	Total Hydrocarbons
TP	Tailpipe
UNECE	United Nations Economic Commission for Europe
VECTO	Vehicle Energy consumption Calculation Tool
VELA	Vehicle Emissions Laboratories
VPR	Volatile Particle Remover

WHTC World Harmonized Transient Cycle  
WHVC World Harmonized Vehicle Cycle

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