Conclusions of the PN-PEMS Inter-Laboratory Comparison Exercise

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Outline

- The PN-PEMS Inter-Laboratory Comparison Exercise
- Intrumentation and test procedure
- Gaseous emissions
- PMP at CVS vs PMP at Tailpipe
- Dynamometer tests
- PN-PEMS accuracy and precision
- Road tests performance
- Warm and cold ambient temperature tests

Purpose of the ILCE

- In the framework of PN-PEMS activities that started in April 2013, after having tested several PN-PEMS on several vehicles at the JRC laboratories, the ILCE aims to assess the accuracy and precision of the PN measurment with two different PN-PEMS on one vehicle in different laboratories.

- Direct involvement of stakeholders (industry and technical services) in the PN-PEMS activities.

Numbers of the PN-PEMS ILCE

- 7 laboratories
- 1 Golden Vehicle, VW Golf, GDI 1.2 l, 63kW
- 2 PN-PEMS
- 1 Gas-PEMS
- 1 Particle Measurement Programme (PMP) PN counter
- 18 NEDC cold tests at 23°C
- 45 WLTC hot tests at 23°C
- 6 extra WLTC hot tests at -4°C to 32°C
- 31 road tests 3°C to 25°C
- **30+ experts** provided exellent support to the ILCE

Laboratories

- Audi (DE)
- Bosmal (PL)
- Honda (DE)
- JRC (IT)
- TUV (DE)
- Volkswagen (DE)
- Volvo (SE)

Intrumentation

- PN-PEMS 1: NanoMet3 (NM3), Testo - Diffusion Charging Sensor (DCS) based
- PN-PEMS 2: Modified Nanoparticle Emission Tester (Mod-NPET) Horiba - Condensation Particle Counter (CPC) based
- Gas-PEMS: Semtech LDV, Sensors. Measuring CO, CO_2, NO_x, Exhaust Flow Meter (EFM), ambient temperature and pressure, GPS
- PMP Tailpipe: Advanced APC 489, AVL

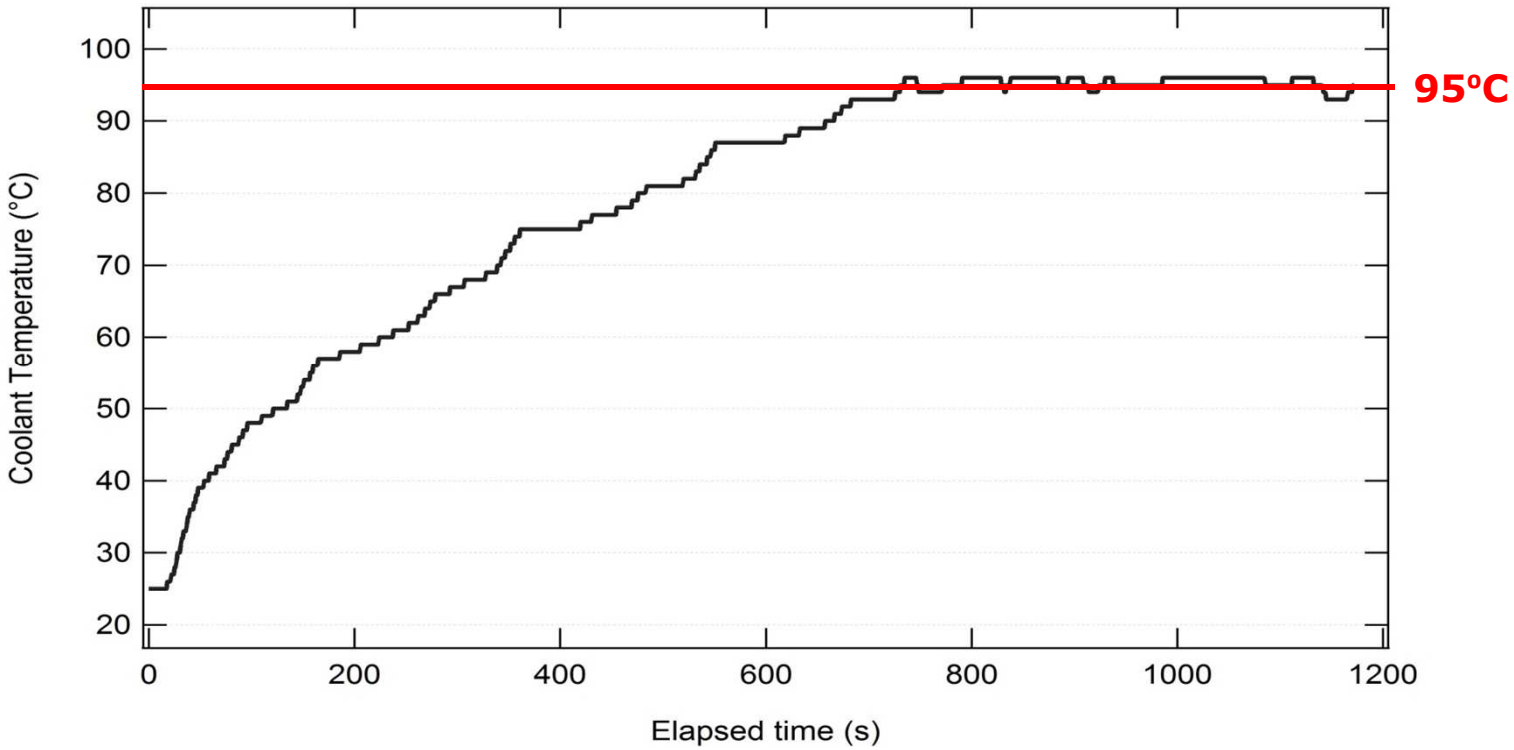
Test matrix

Day 0	Day 1	Day 2	Day 3	Day 4
Preparation of the GV + WLTC + Coast Down + NEDC precond. (NEDC+EUDC)	NEDC cold	NEDC cold	Road test 1	Road test 3
	Warm up + WLTC hot	Warm up + WLTC hot		
	Warm up + WLTC hot	Warm up + WLTC hot	Road test 2	Road test 4
	NEDC precond. (NEDC+EUDC).	Warm up + WLTC hot		

Minimum requirement from each lab:

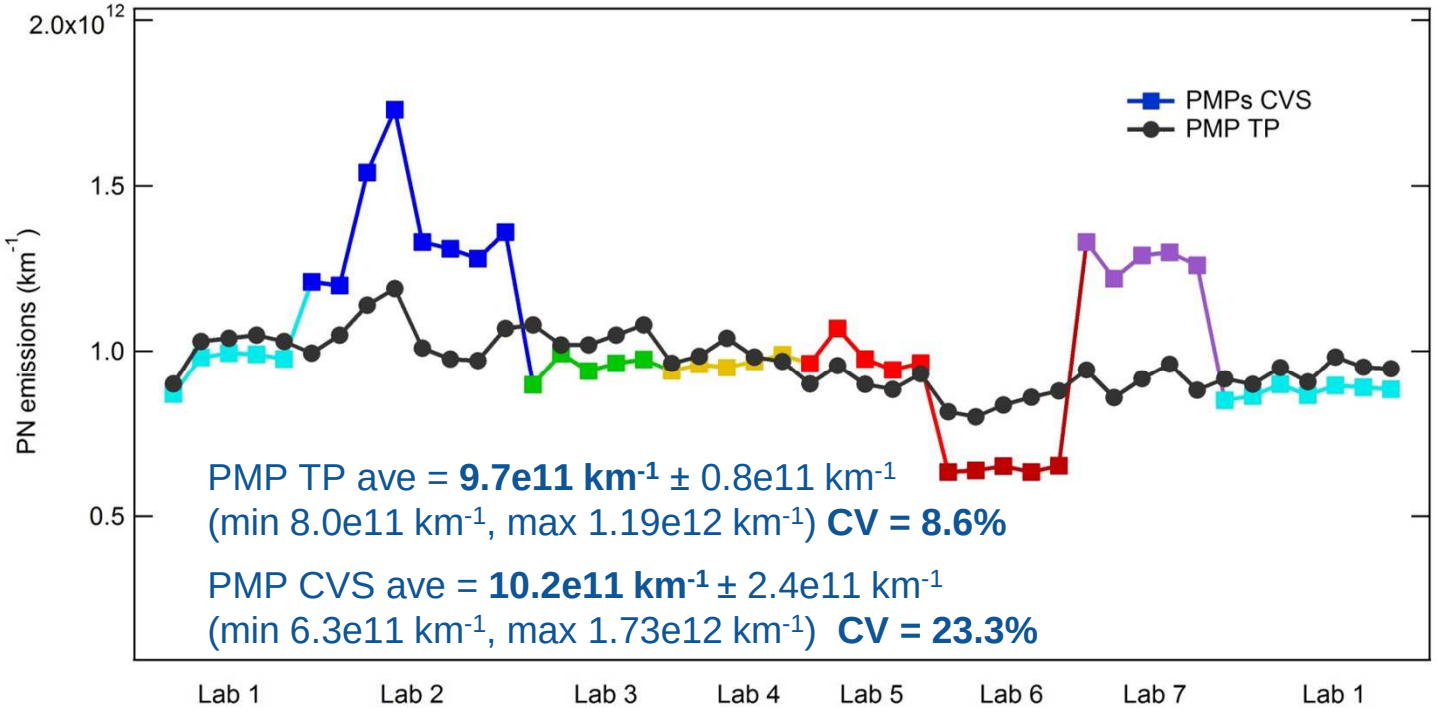
- 2 NEDC
- 5 WLTC
- 3 road

Warm up



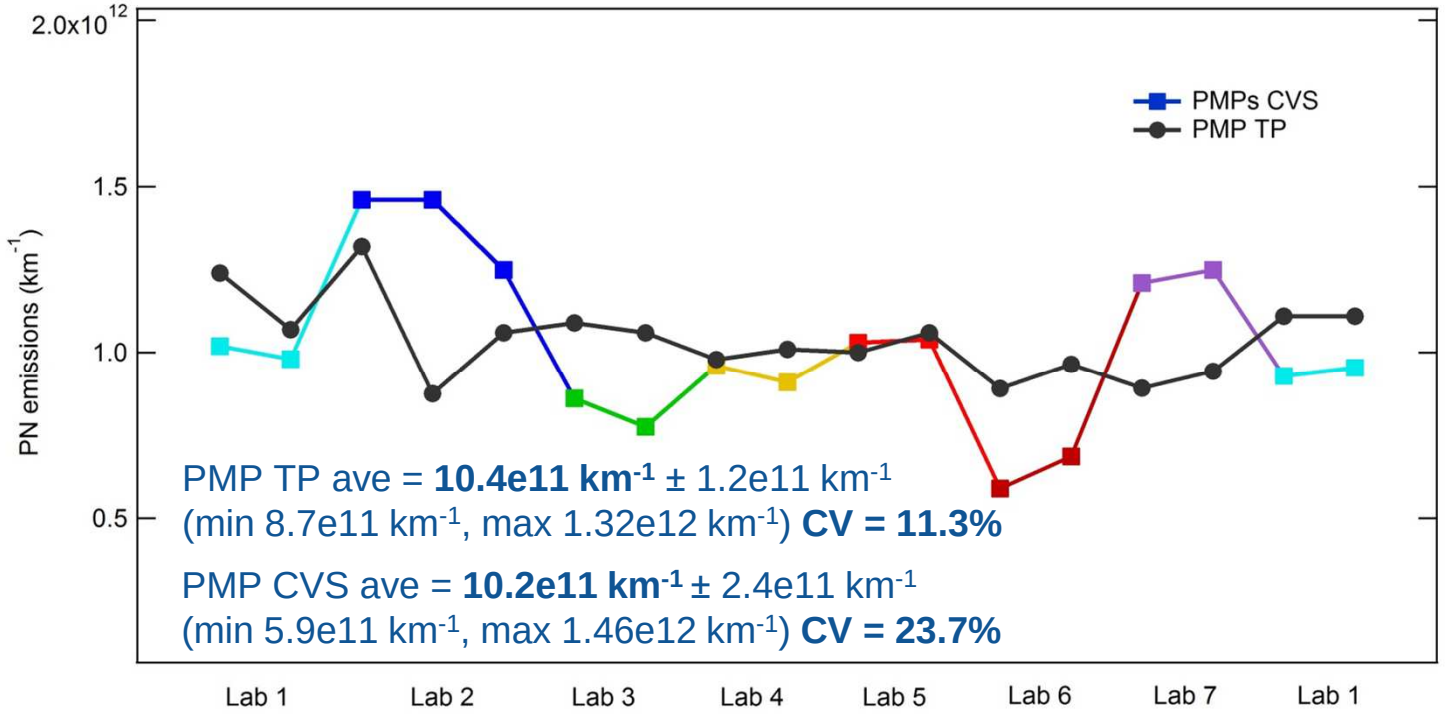
WLTC tests were conducted preconditioning the vehicle at constant speed (~100km/h) until coolant temperature reached 95^0C (stable temperature).

PMP CVS vs PMP tailpipe (WLTC)



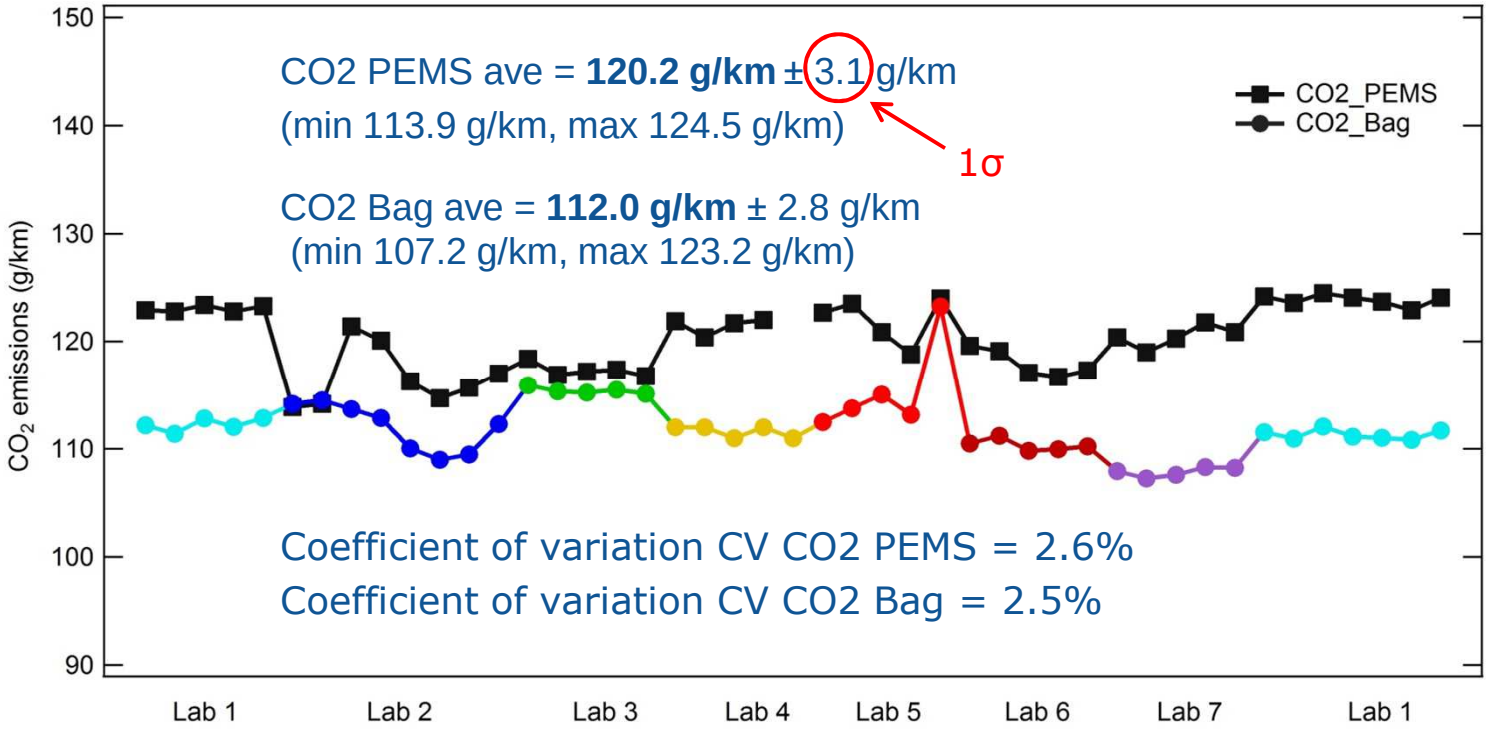
- PMP at tailpipe (PMP TP) is always the same instrument
- PMPs at CVS are 7 different instruments (higher variability, CV)
- PMP TP shows that vehicle PN emissions were stable over the labs

PMP CVS vs PMP tailpipe (NEDC)



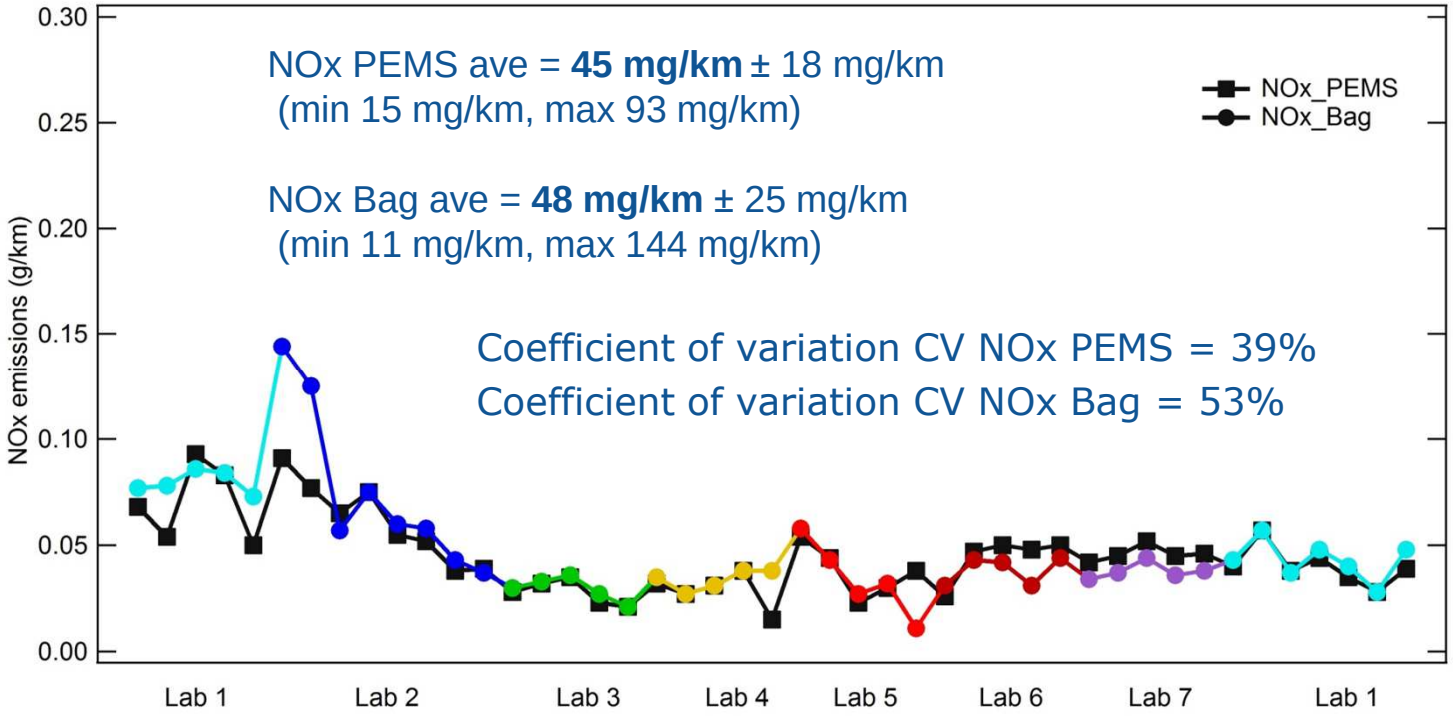
- PMP CVS and PNP TP shows identical average PN emissions
- Slightly higher PMP CVS standard deviation

CO_2 Bag vs CO_2 PEMS (WLTC)



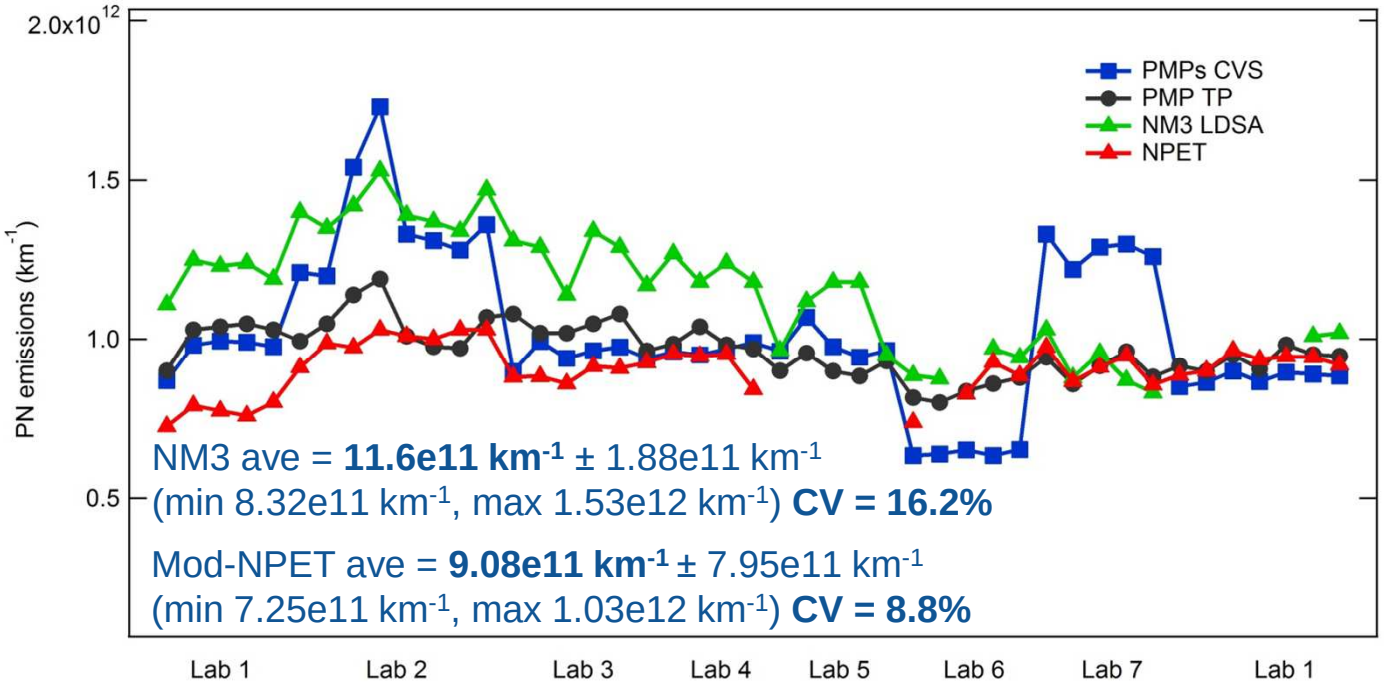
Average PEMS to bag deviation 7.4% ± 3.7%
(min -0.3%, max 12.4%)

NOx Bag vs NOx PEMS (WLTC)



Average PEMS to bag deviation 4.1% ± 40.4%
(min -38.7%, max 241.0%)

PN-PEMS (WLTC)



NM3 ave = **11.6e11 km^{-1}** ± 1.88e11 km^{-1}
(min 8.32e11 km^{-1}, max 1.53e12 km^{-1}) **CV = 16.2%**

Mod-NPET ave = **9.08e11 km^{-1}** ± 7.95e11 km^{-1}
(min 7.25e11 km^{-1}, max 1.03e12 km^{-1}) **CV = 8.8%**

PMP TP ave = **9.7e11 km^{-1}** ± 0.8e11 km^{-1}
(min 8.0e11 km^{-1}, max 1.19e12 km^{-1}) **CV = 8.6%**

PMP CVS ave = **10.2e11 km^{-1}** ± 2.4e11 km^{-1}
(min 6.3e11 km^{-1}, max 1.73e12 km^{-1}) **CV = 23.3%**

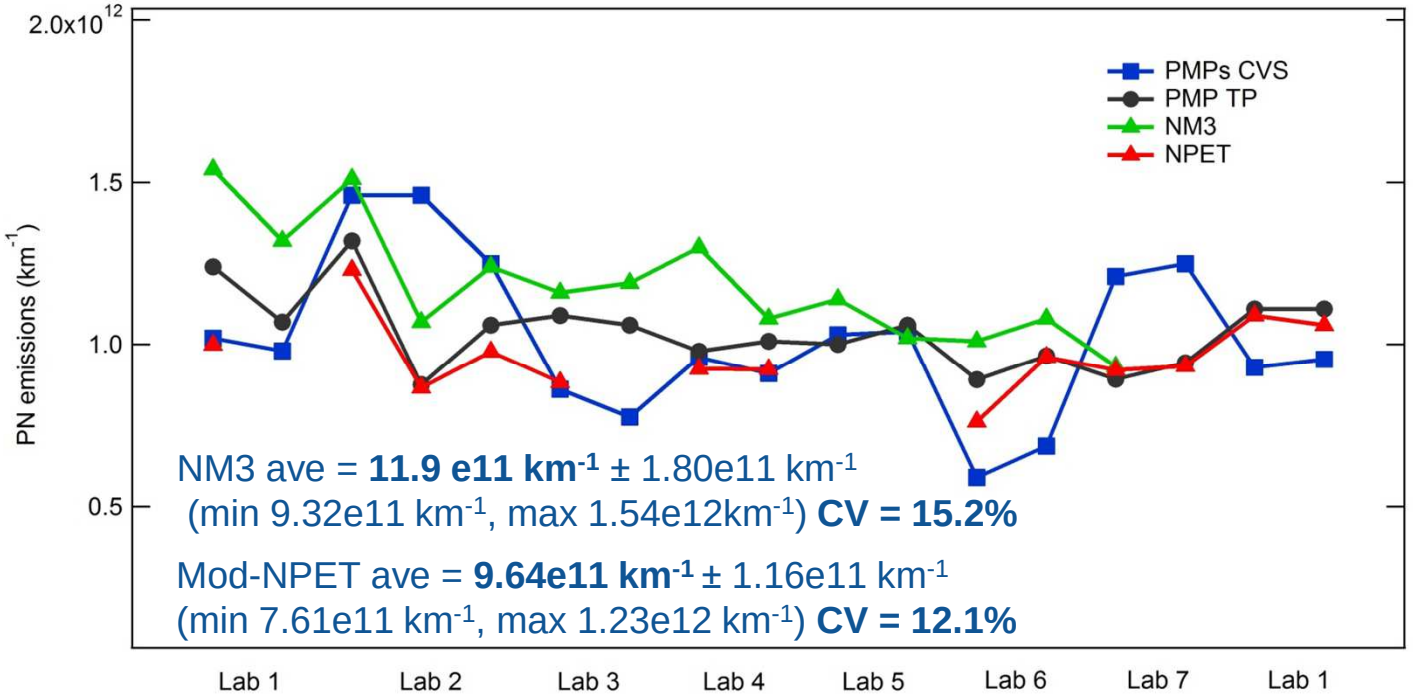
NM3:

6 void tests over 45 (**yield 87%**)

Mod-NPET:

6 void tests over 45 (**yield 87%**)

PN-PEMS (NEDC)



NM3 ave = **11.9 e11 km^{-1}** ± 1.80e11 km^{-1}
(min 9.32e11 km^{-1}, max 1.54e12km^{-1}) **CV = 15.2%**

Mod-NPET ave = **9.64e11 km^{-1}** ± 1.16e11 km^{-1}
(min 7.61e11 km^{-1}, max 1.23e12 km^{-1}) **CV = 12.1%**

PMP TP ave = **10.4e11 km^{-1}** ± 1.2e11 km^{-1}
(min 8.7e11 km^{-1}, max 1.32e12 km^{-1}) **CV = 11.3%**

PMP CVS ave = **10.2e11 km^{-1}** ± 2.4e11 km^{-1}
(min 5.9e11 km^{-1}, max 1.46e12 km^{-1}) **CV = 23.7%**

NM3:

3 void tests over 17 (**yield 82%**)

Mod-NPET:

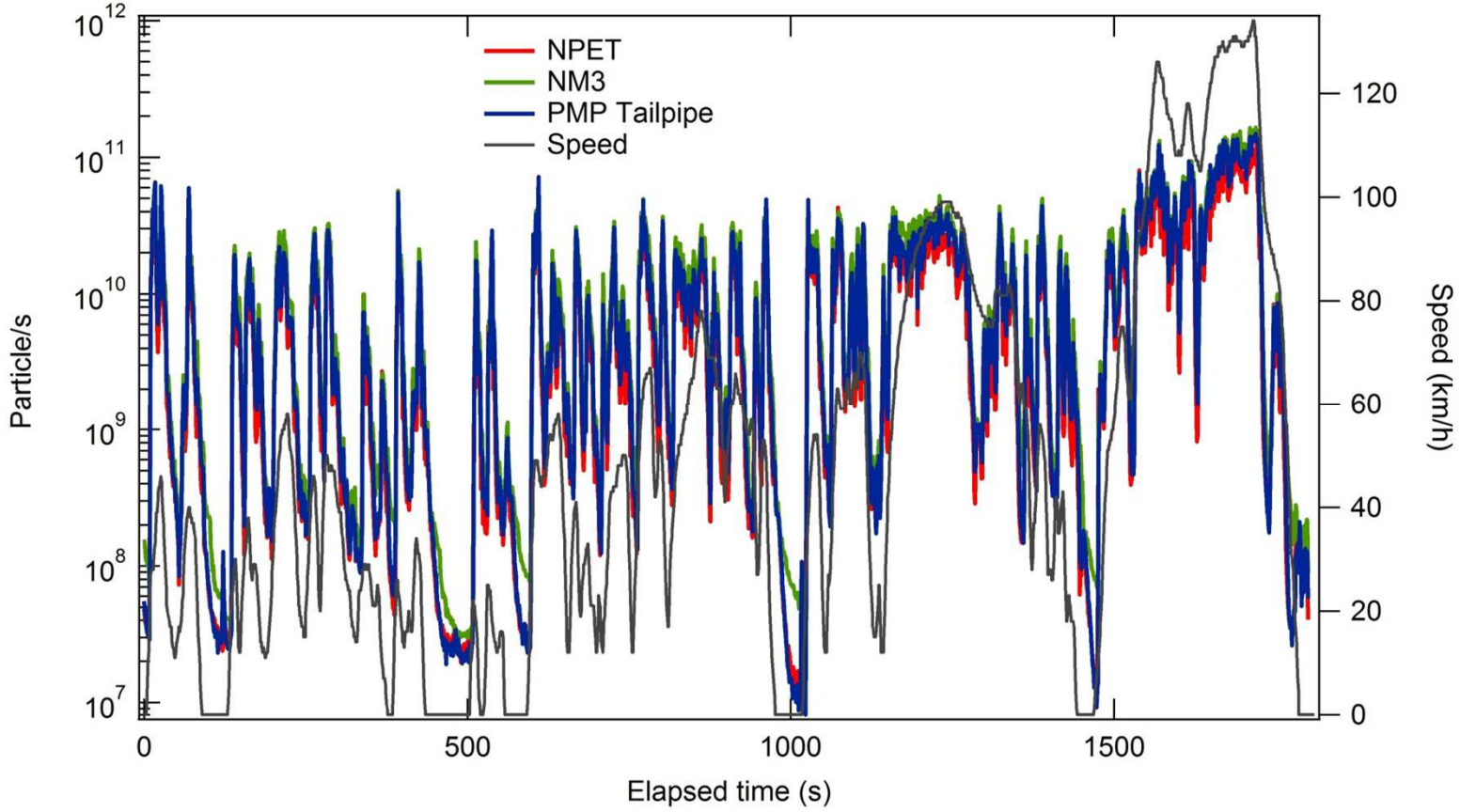
4 void tests over 17 (**yield 76%**)

Reasons for void tests

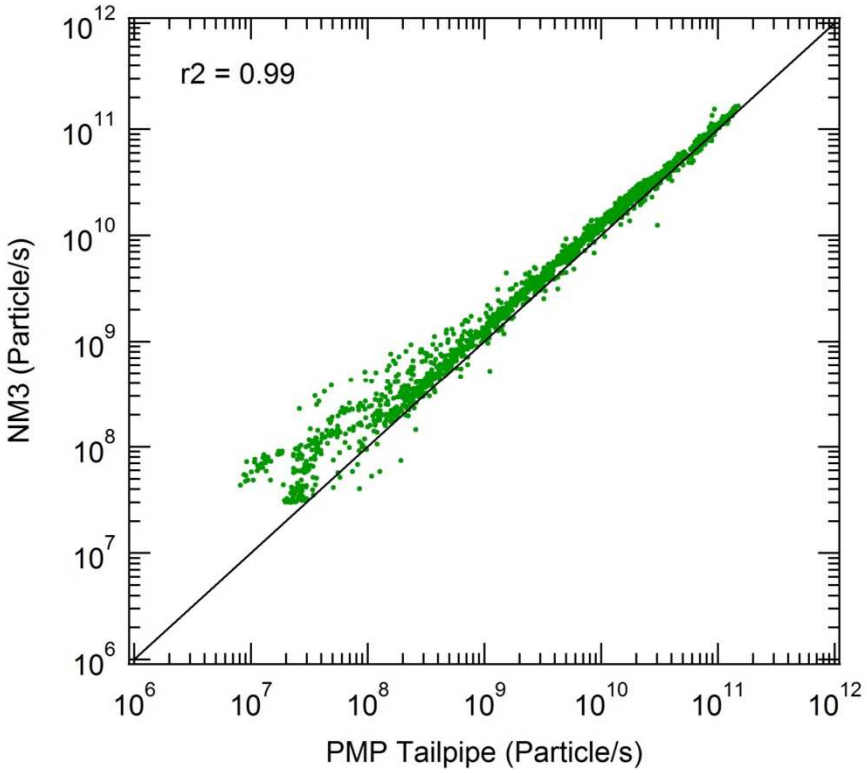
- NM3: Water in sensor (due to low dilution) fixed upon suggestion of Testo (auto dilution mode),
  SD card unintentionally not properly inserted

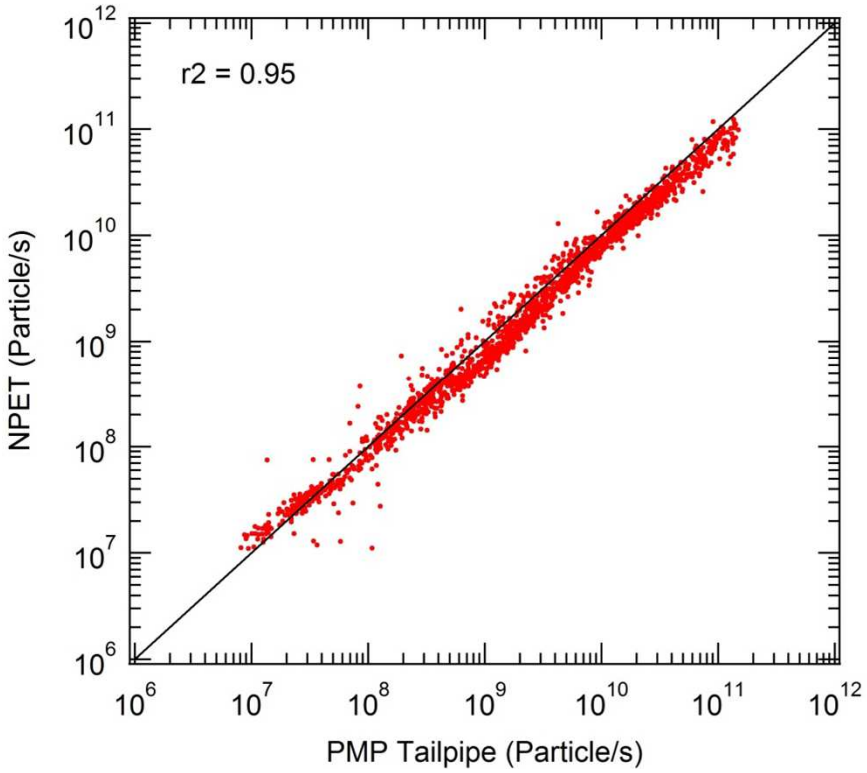
- Mod-NPET: Broken water trap and main board connectors due to accidental maloperation, disconnected tubing (root cause unclear), heater temperature out of range

PN-PEMS vs PMP TP - Example

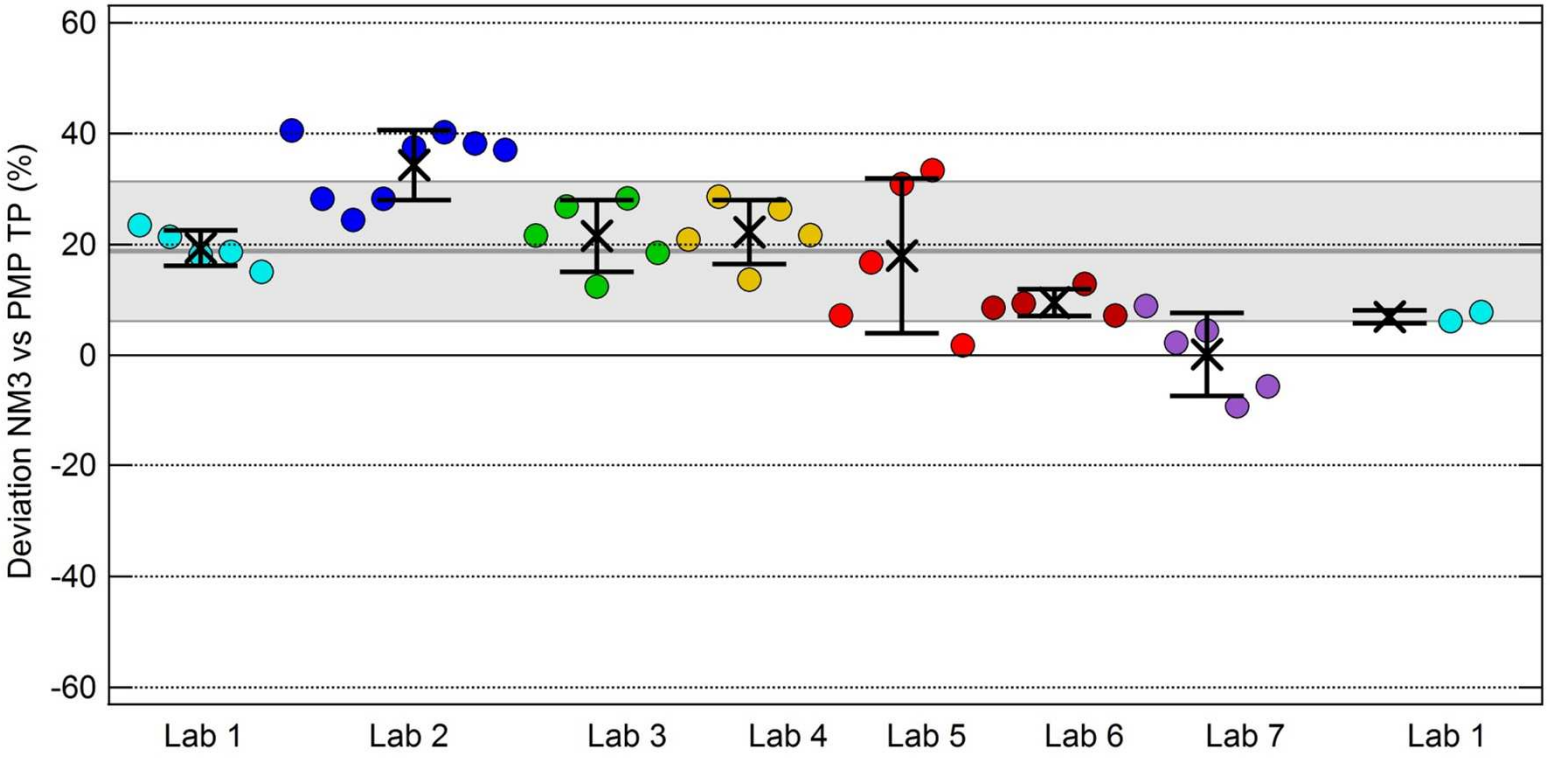


Good sec to sec correlation





Deviations NM3 vs PMP TP (WLTC)

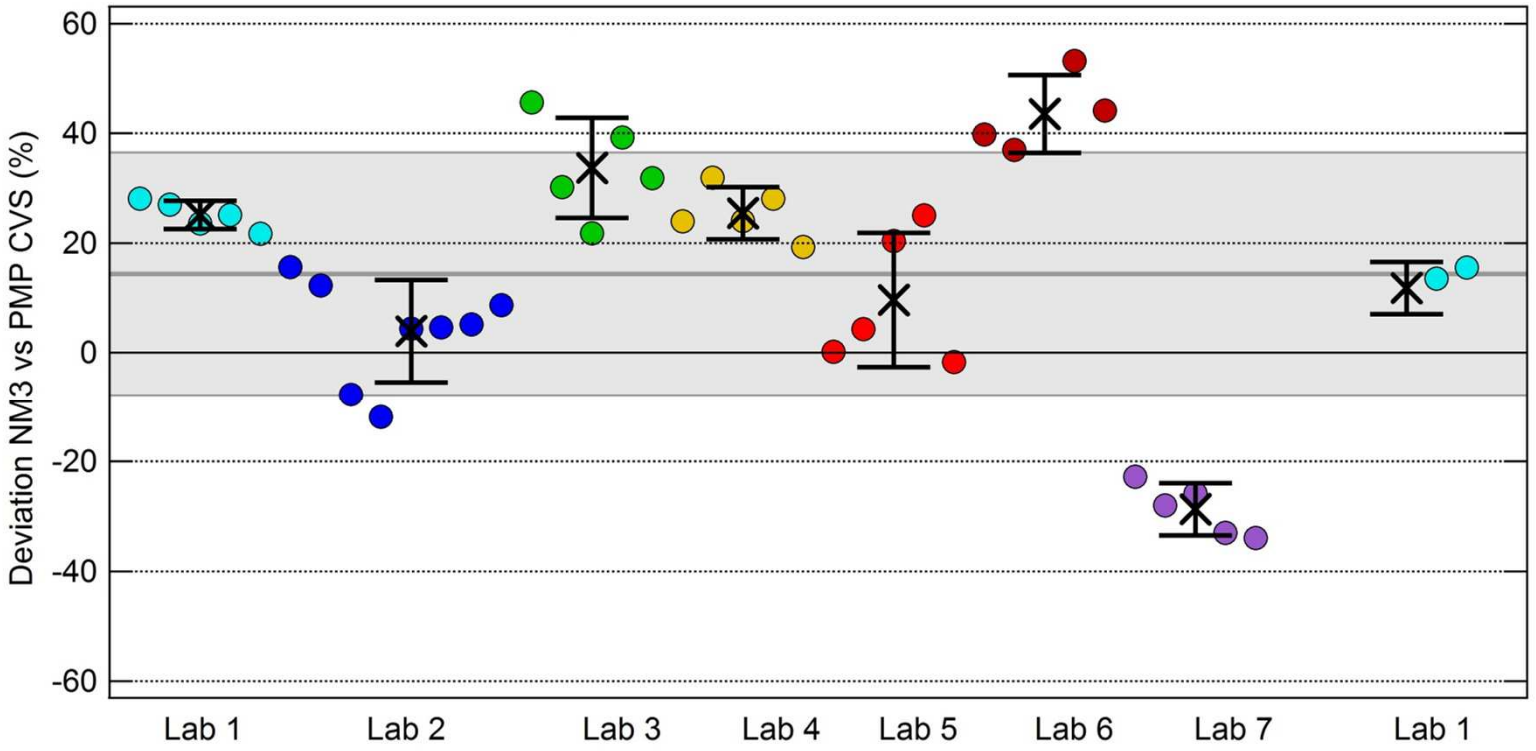


Ave ± StDev:
18.8% ± 12.6%

Deviations are calculated as (NM3 – PMP_TP)/PMP_TP*100 (km^{-1})

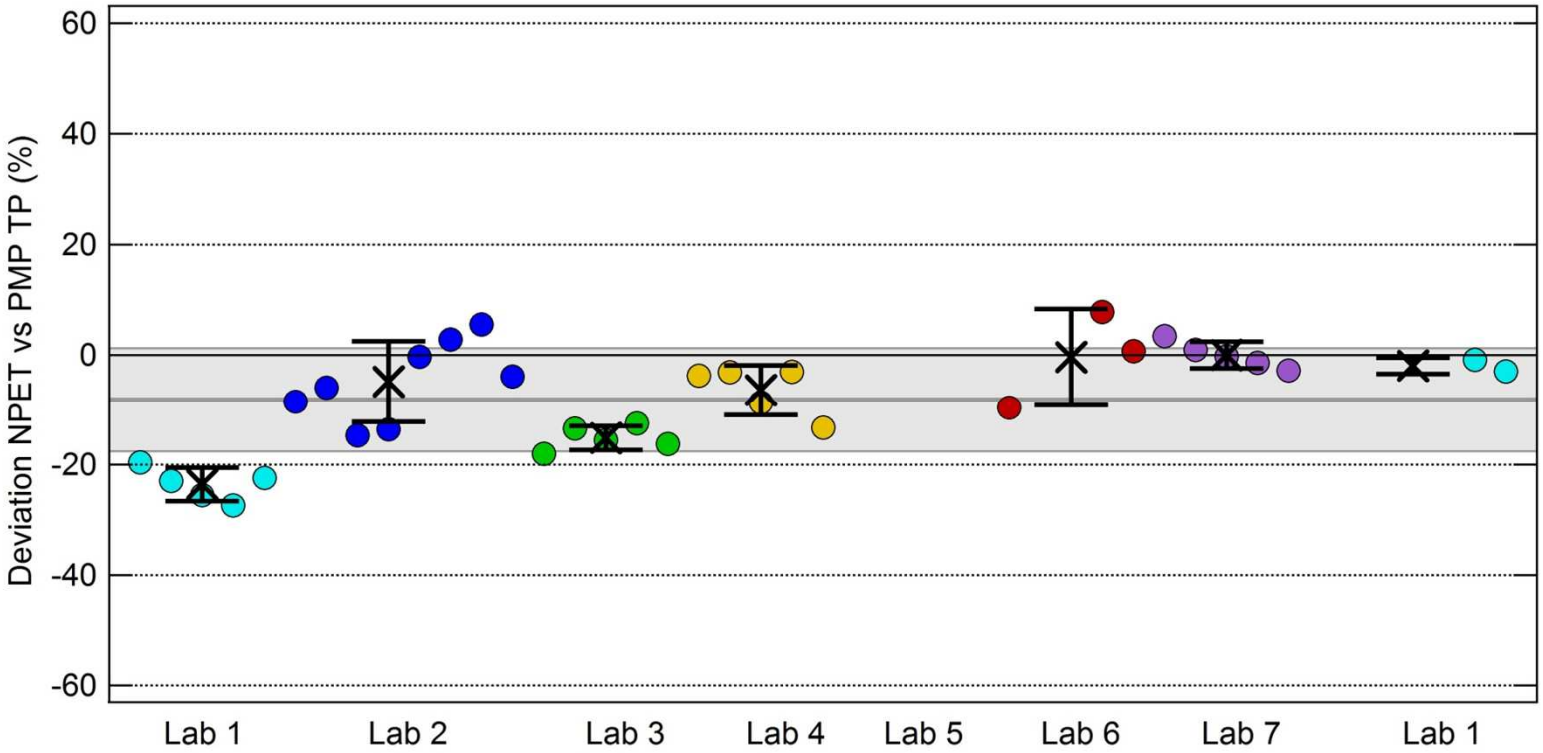
Black marks shows average and standard deviation of each laboratory.
Grey lines shows average and standard deviation of all laboratories.

Deviations NM3 vs PMP CVS (WLTC)



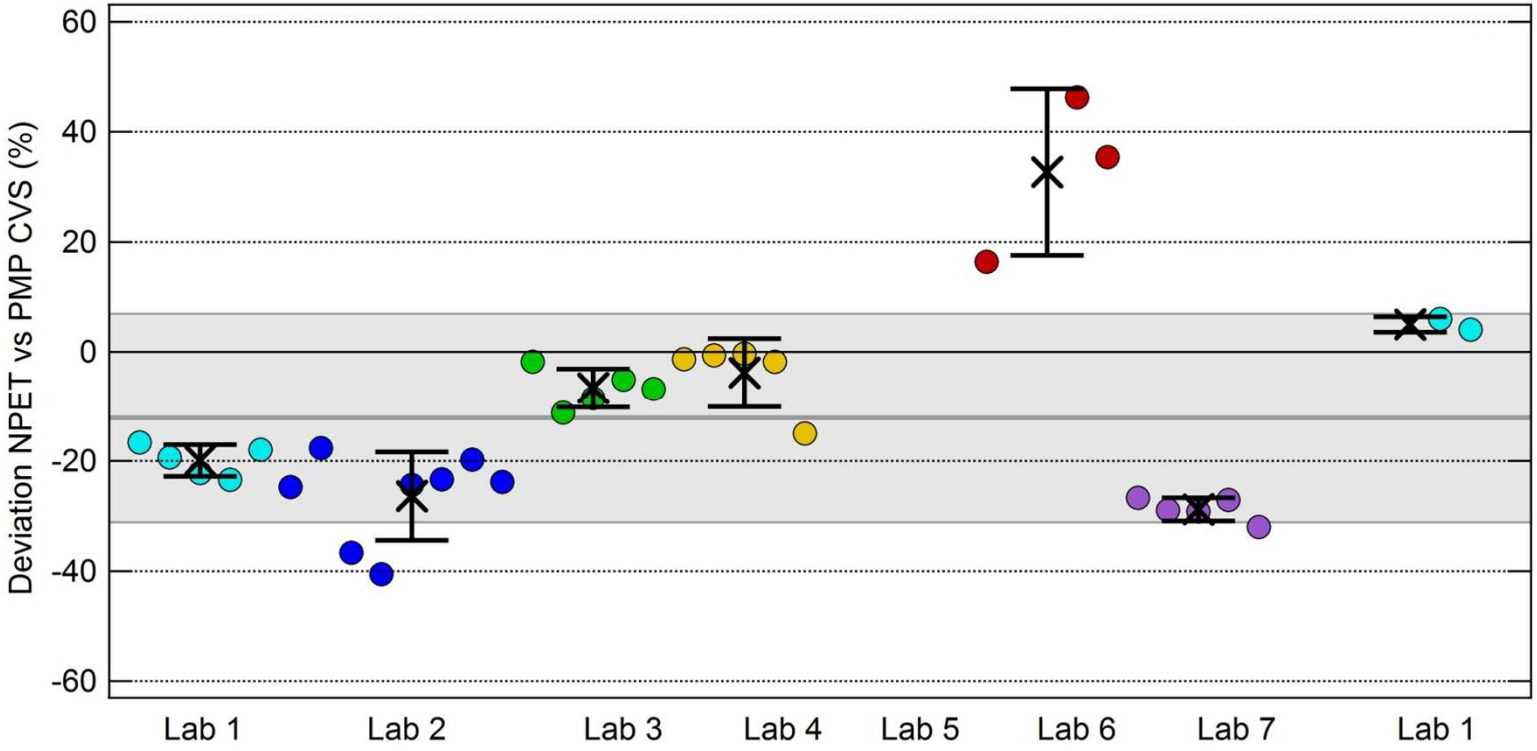
Ave ± StDev:
14.4% ± 22.2%

Deviations Mod-NPET vs PMP TP (WLTC)



Ave ± StDev
-8.2% ± 9.4%

Deviations Mod-NPET vs PMP CVS (WLTC)



Ave ± StDev:
-12.1% ± 19.0%

Dynamometer tests summary

- Deviations of the **PN-PEMS to PMP CVS** over WLTC are found **close** to the deviations of **PMP TP** to **PMP CVS**:
  - PMP TP deviation from PMP CVS: **-1.6% ± 18.2%** (range -31.3 to 35.7)
  - PN-PEMS DCS based deviation from PMP CVS: **14.4% ± 22.2%** (range -33.9 to 53.2)
  - PN-PEMS CPC based deviation from PMP CVS: **-12.1% ± 19.0%** (range -40.6 to 46.3)
- **Variability is smaller** when comparing **PN-PEMS** and **PMP TP** (always same PMP device):
  - DCS based deviation from PMP TP: **18.8% ± 12.6%** (range -9.3 to 40.6)
  - CPC based deviation from PMP TP: **-8.2% ± 9.4%** (range -27.4 to 7.8)

Road tests overview

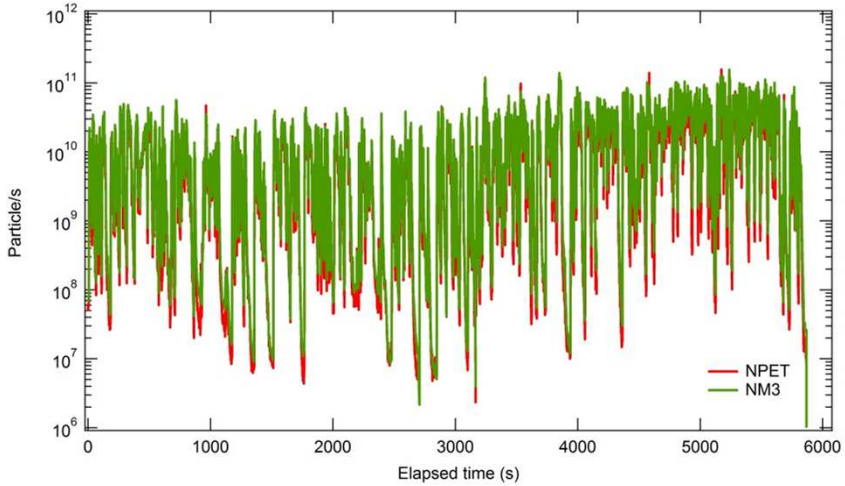
- **31 road tests** in 7 different locations

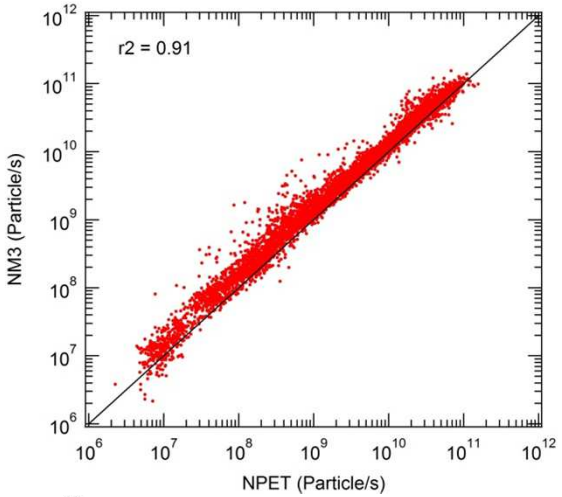
- Ambient **temperature** range **3 to 25°C** (13.2±5.1)
- Ambient **pressure** range **988 to 1081 hPa** (1020±15)

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

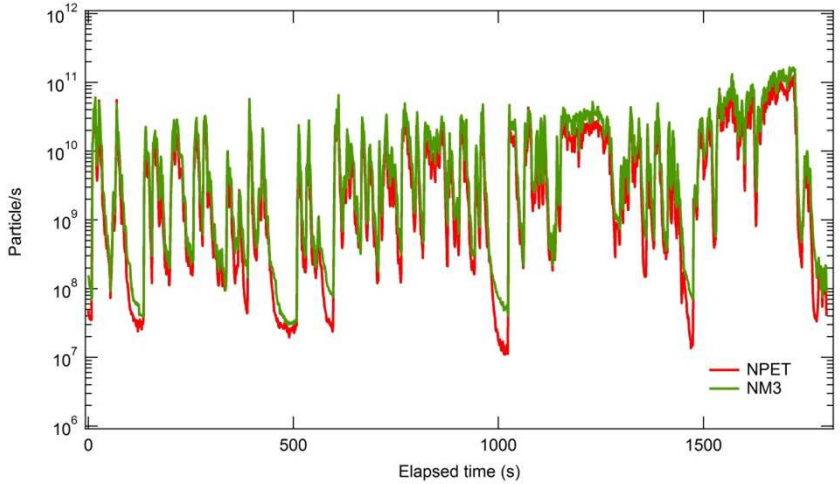
Road tests & WLTC - Examples

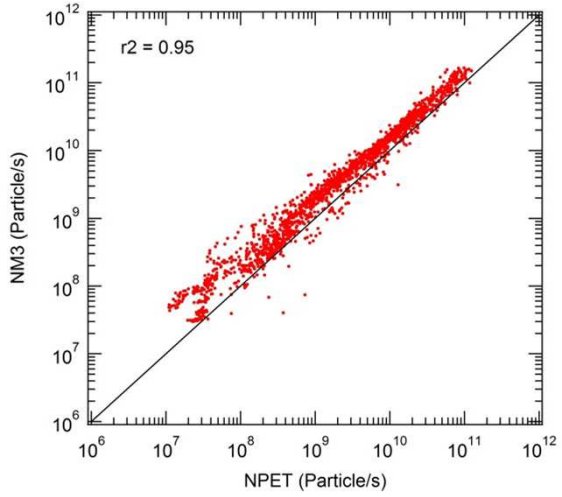
Road



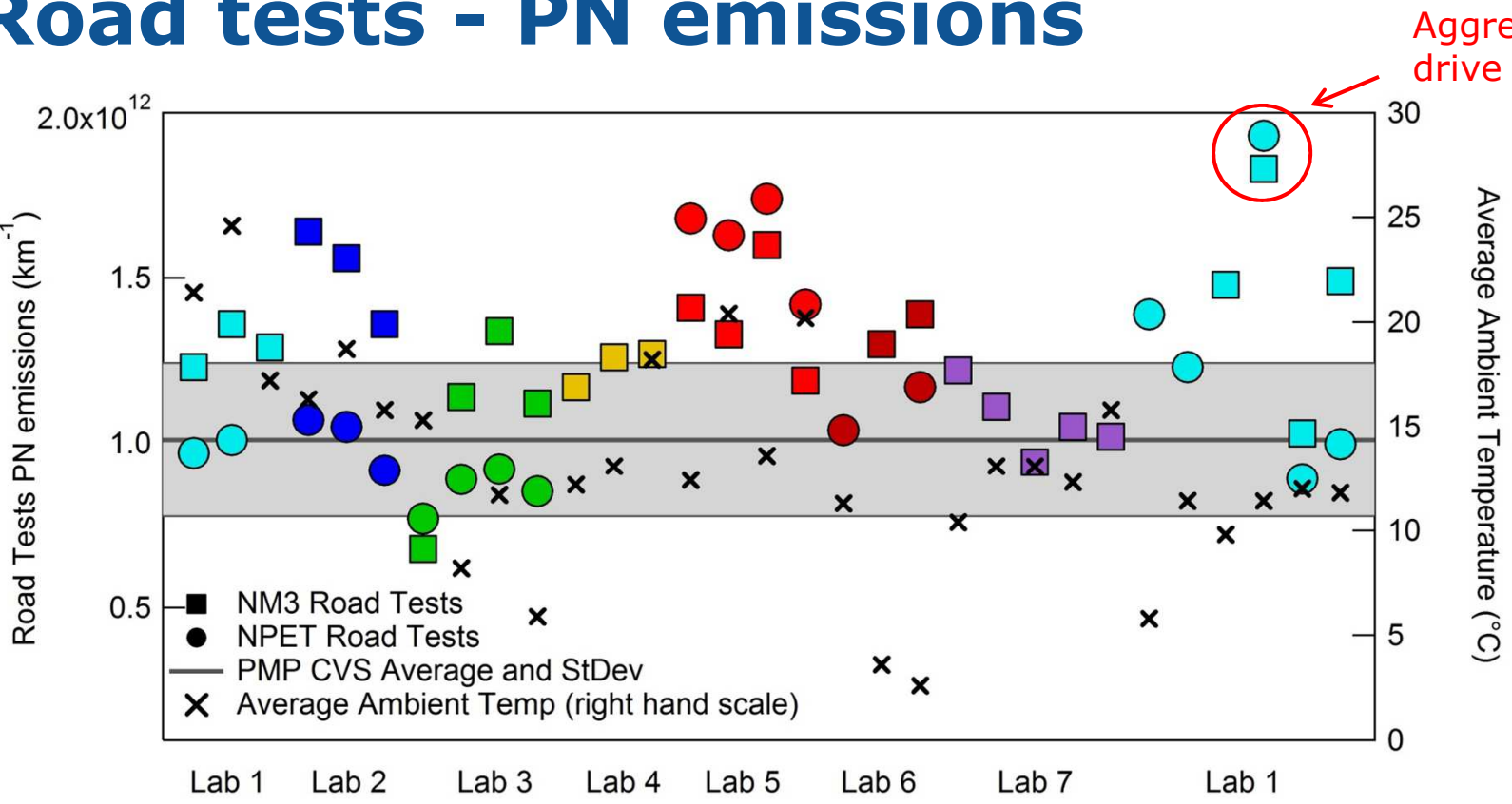


WLTC





Road tests - PN emissions



Average NM3 1.28e12 ± 0.26e12 km^{-1}

Average Mod-NPET 1.18e12 ± 0.34e12 km^{-1}

On road detailed performance

NM3: 3 void tests over 31, **yield 90%**

Mod-NPET: 11 void tests over 31, **yield 65%** (low yield due to maintenance)

On average, Mod-NPET measured slightly lower than NM3 (same as on dyno). The average deviation of the Mod-NPET to the NM3 (Mod-NPET-NM3)/NM3 resulted to be:

On road: range -**35% to +23%** (-12% ± 21%)
On dyno: range **-39% to +12%** (-21% ± 14%)

Even in the absence of a reference PN system, the **stability** of the performance of the two PN-PEMS on road is showed by the deviation of the PN emissions measured by Mod-NPET and NM3, which matches the deviation between the two devices when measuring on the dyno.

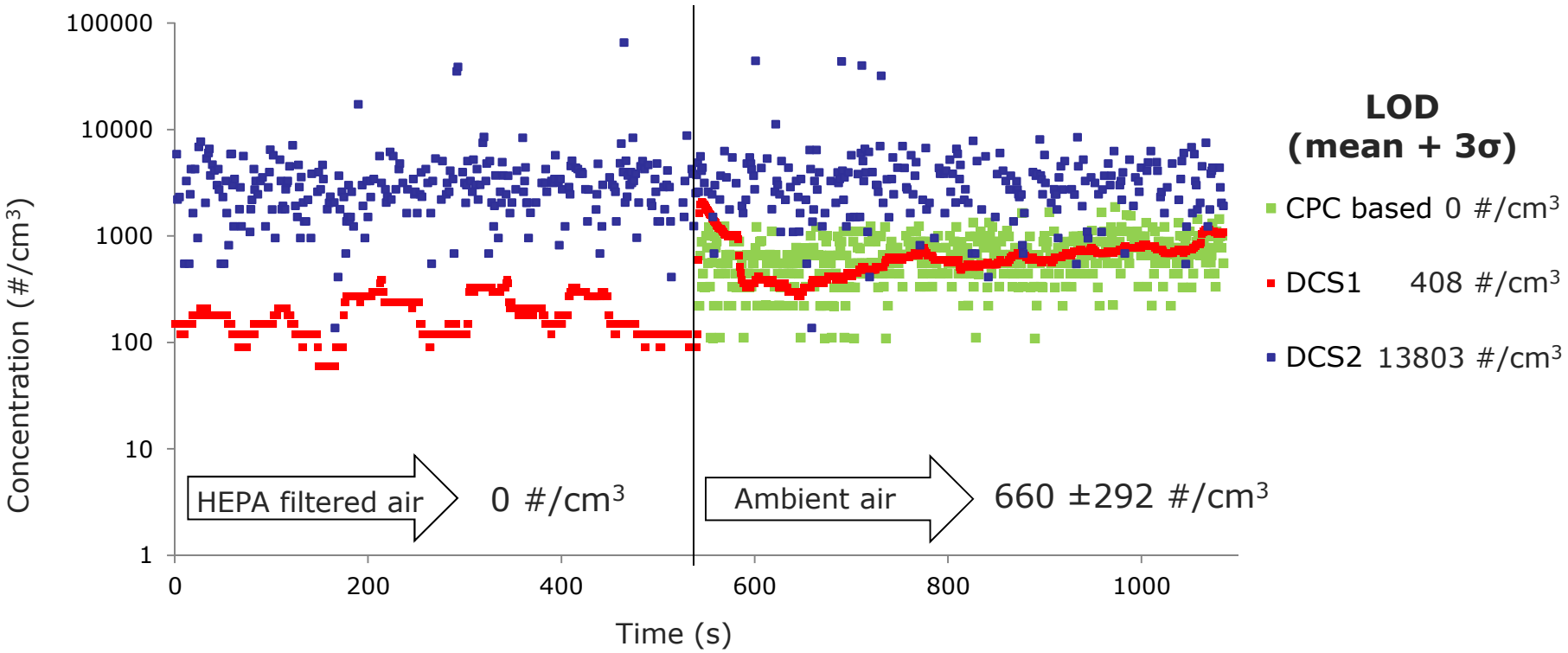
Observed road-lab PN deviations

	NM3	NPET
Road / WLTC (PMP CVS)	1.26	1.16
Road / WLTC (PMP TP)	1.32	1.22
Road / NEDC (PMP CVS)	1.25	1.15
Road / NEDC (PMP TP)	1.24	1.14

Road emissions were on average 22% higher than dynamometer emissions.

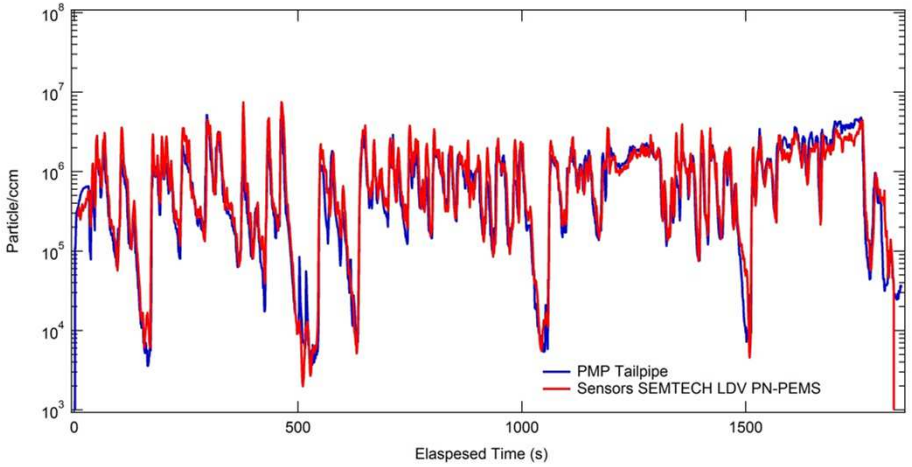
Caveat: The reported emissions and ratios were calculated using the whole integrated second to second data both for dynamometer and road tests (No EMROAD).

Limit Of Detection of PN-PEMS



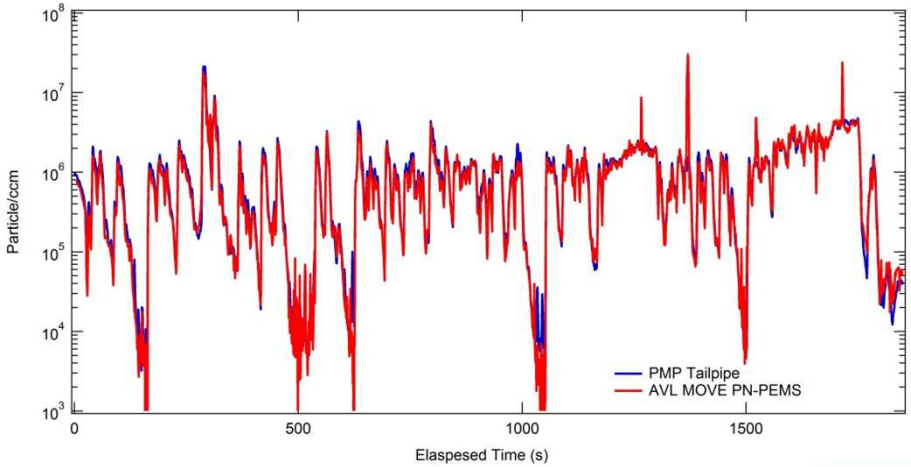
Even if the LOD of NM3 is higher that the LOD of Mod-NPET already at ambient PN concentrations both instrument shows the similar results

Additional PN-PEMS devices tested



Sensors SEMTECH LDV PN-PEMS
CPC based

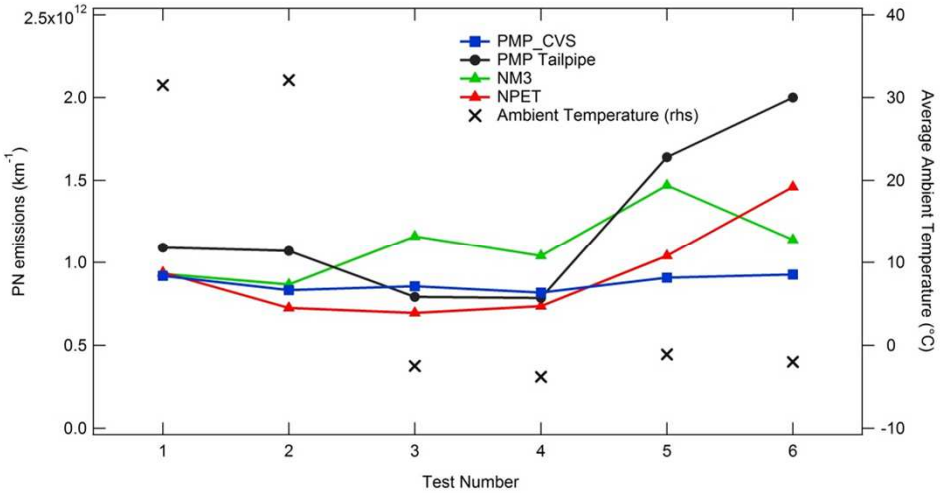
Both additional PN-PEMS tested shows good correlation with PMP tailpipe

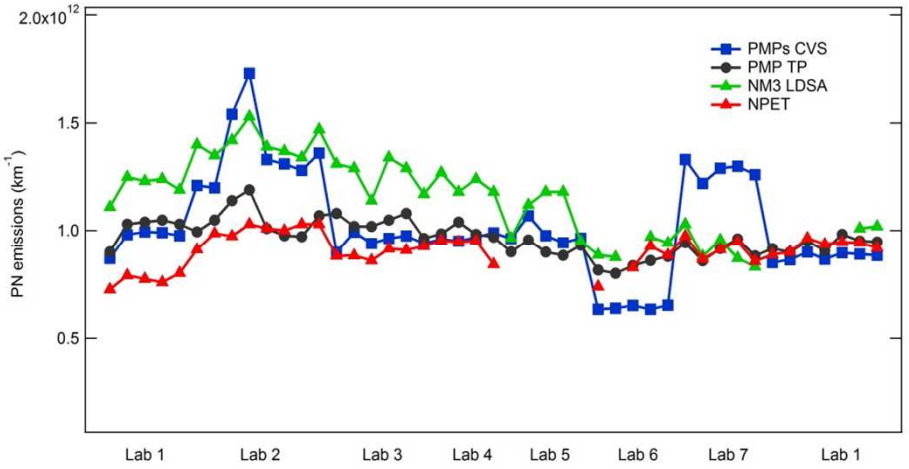


AVL MOVE PN-PEMS
DCS based

Effect of ambient temperature

Extra tests have been performed at the JRC at +32°C and -4°C, deviations from the PMP systems are comparable to the 23°C tests





Conclusions 1/2

- Dynamometer tests showed that for the set of tests performed during the ILCE deviations of the PN-PEMS to (several) PMP CVS are close to the deviations of PMP TP to (several) PMP CVS.
- Similar deviations but with less variability are found when comparing PN-PEMS to (the same) PMP TP (about 10%).
- NM3 yield of 85% on dyno and 90% on road
- Same yield for Mod-NPET on dyno (87%), lower yield (65%) on road due to maintenance for road tests (instrument not available for most of void tests).
- PN-PEMS devices can be considered stable when measuring on dyno and on road.

Conclusions 2/2

- Road PN emissions resulted on average 22% higher than dynamometer emissions.
- Limit of detection of DCS is higher than LOD of Mod-NPET, but does not affect the measurment of GDI vehicles.
- No significant effect of ambient temperature and pressure on PN emissions was observed.
- Relatively good performance of two additional PN-PEMS only partially tested during the ILCE (one DCS and one CPC based).

Thanks to Sensors, Horiba and Testo for providing the PEMS and for the excellent support during the ILCE!

Thanks to all the participating laboratories!

Thank you for your attention!

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