Particle Number (PN) Measurement Experiences from 2016 AECC GDI GPF Project

Jon Andersson, Ricardo

AECC Technical Seminar on Real-Driving Emissions of Particles (RDE PN)
Brussels, 4th July 2016

Content

- **Objectives**
- Measurement Installations
- PN measurement approaches
- Initial Chassis Dyno Findings
- Discussion
- Conclusions

2016 GPF RDE Test Programme – PN-related Objectives

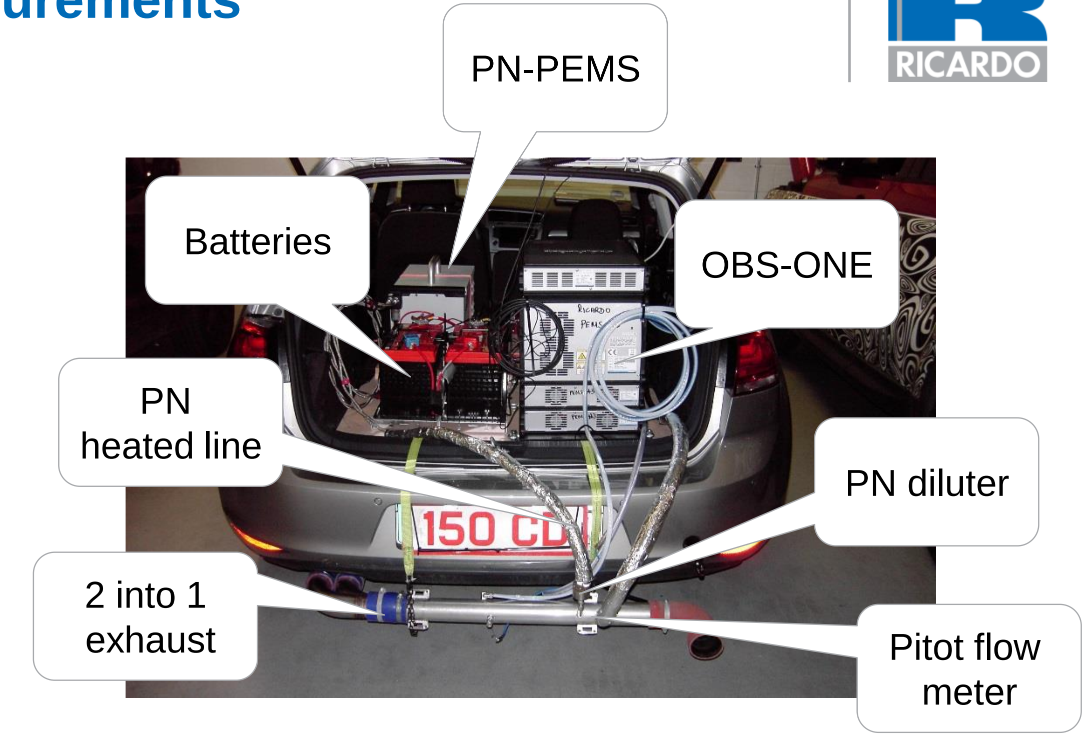
- To evaluate RDE PN emissions with both 10nm and 23nm cut-offs (both with and without GPF)
- To assess any impact of a TWC on PN reduction
- To assess the impact of a specific GPF on PN emissions
- To consider the presence of volatile particles in data measured after different approaches to volatile particle removal
- To compare lab-based PN measurements sampling both directly from the exhaust and from the regulatory dilution tunnel
- To investigate the impact of using on-board exhaust flow measurement for quantifying PN via PEMS in comparison with the add-on pitot flow measurement device required by the RDE regulation

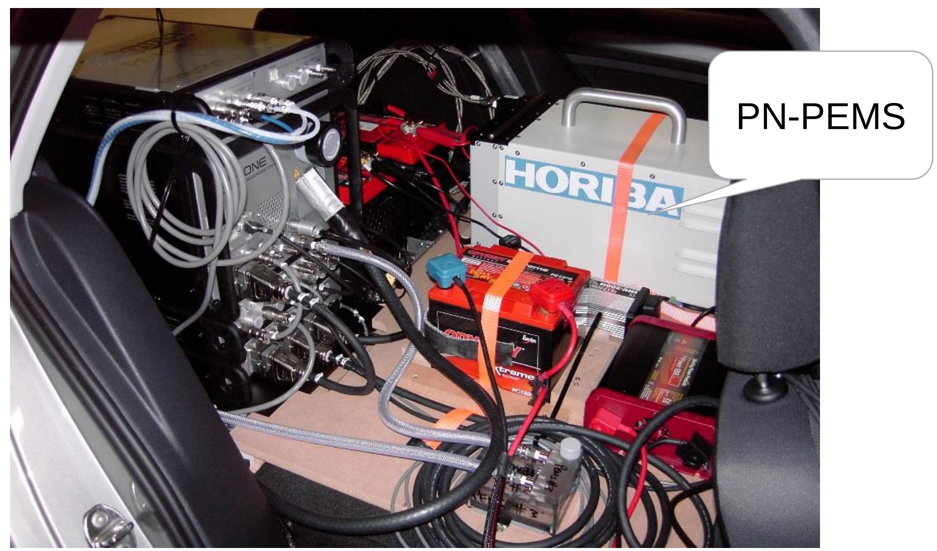
Content

- Objectives
- **Measurement Installations**
- PN measurement approaches
- Initial Chassis Dyno Findings
- Discussion
- Conclusions

PEMS installation and on-road measurements

- Horiba OBS ONE Portable Emissions Measurement System (PEMS) installed in test vehicle
- Internal install, with minimal external componentry
- System includes NO and NOx (CLD), CO and CO_2 (NDIR), PN (cold dilution, heated catalytic stripper, dilution, condensation particle counter (CPC))
- No HC requirement, so PEMS component omitted
- PN-PEMS based upon Horiba NPET system used for in-service DPF testing on NRMM in Switzerland
- PEMS system activated ≥ 2 hours prior to validation using bottled gases
  - ~ 3h prior to on-road or on-dyno emissions test
- GPF fitted in underfloor position for selected tests

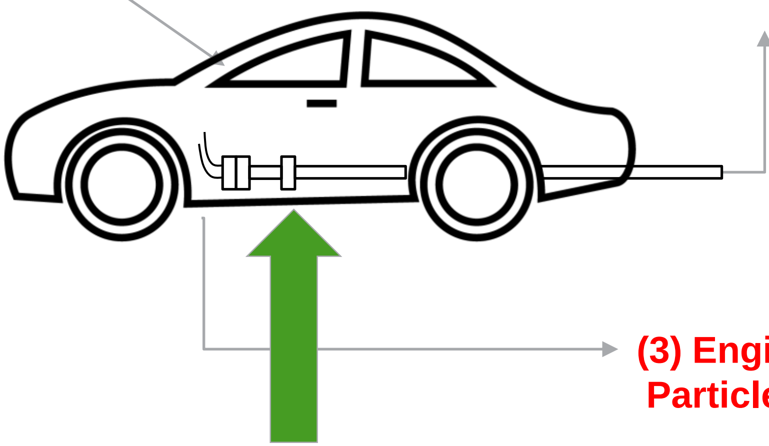




Chassis dyno measurements: NEDC, WLTC & on-dyno RDE

OBD – engine data: speed, load, air and fuel flow etc

Raw



Tailpipe temperature

PEMS gases: CO, CO_2, NO, NOx

(4) PEMS PN (23nm d50)

Continuous raw emissions

(3) Engine-out PN via Horiba MEXA 2100 Solid Particle Counting System (SPCS) (23nm d50)

Engine-out pre-cat temperature

GPF fitted in underfloor position for selected tests

Dilute

Constant Volume Sampler (CVS)

Continuous dilute emissions

Bagged dilute emissions: CO, CO_2, CH_4, THC, NOx, PM

(2) PN via catalytic Instruments cat-stripper (7nm d50, using TSI 3022A CPC)

(1) PN via Horiba MEXA 2000 SPCS (23nm d50)

Content

- Objectives
- Measurement Installations
- **PN measurement approaches**
- Initial Chassis Dyno Findings
- Discussion
- Conclusions

PN Systems' Sampling Configurations
2 raw systems, 2 dilute systems, >7nm system, 3 x >23nm systems

	Initial dilution	Pre-classifier	PND_1 (diluter#1)	Volatile Removal	PND_2 (diluter#2)	PNC (counter)
4: Raw PN-PEMS	[-]	1µm	dilution 10 ambient	DOC 350°C	dilution 10 ambient	d50 23nm
3: Raw SPCS	dilution 10 ≤350°C	<10µm	dilution 10 ~190°C	Evap tube 350°C	dilution 15 < 35°C	d50 23nm
2: ***Dilute* Catalytic Stripper**	CVS (<30) <52°C	[-]	[-]	DOC 350°C	[-]	**d50 7nm***
1: ***Dilute* SPCS**	CVS (<30) <52°C	<10µm	dilution 10 ~190°C	Evap tube 350°C	dilution 15 < 35°C	d50 23nm

**The counting efficiency curve required for a PEMS PN 10nm d50 may be more like the performance of a TSI 3022A particle counter with 7nm d50*

PN measurement systems, differences and losses

RICARDO

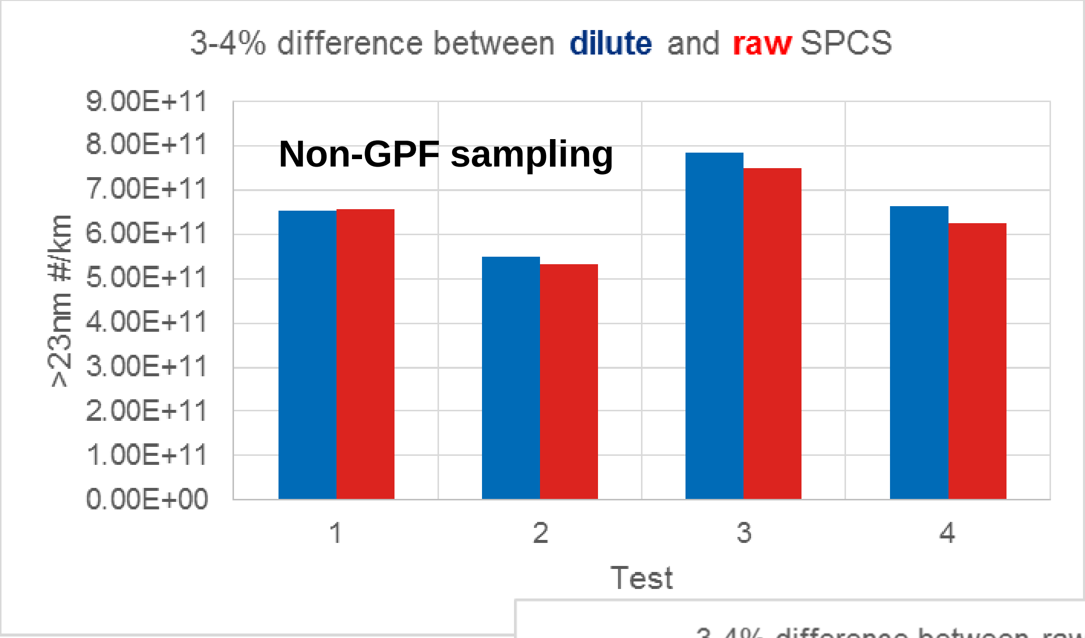
	System	Sampling location	Lower size (d50)	Volatile removal	Opportunities for particle loss	Losses corrected
1	Dilute SPCS	Tailpipe (dilute)	23nm	ET	Transfer to CVS; CVS; transfer line CVS to SPCS	PCRF corrects losses within SPCS
2	Dilute Cat stripper	Tailpipe (dilute)	7nm (10nm)	Oxicat	Transfer to CVS; CVS; transfer line CVS to CS; Oxicat	~32% losses in Oxicat (penetration curve supplied)
3	Raw SPCS	Pre-TWC / Pre-GPF (raw)	23nm	ET	Transfer to PND_0	PCRF corrects losses within SPCS
4	Raw PN-PEMS (based on NPET)	Post-TWC / post-TWC+GPF (raw)	23nm	Oxicat	PEMS vehicle exhaust sampling apparatus	Calibration includes internal loss correction

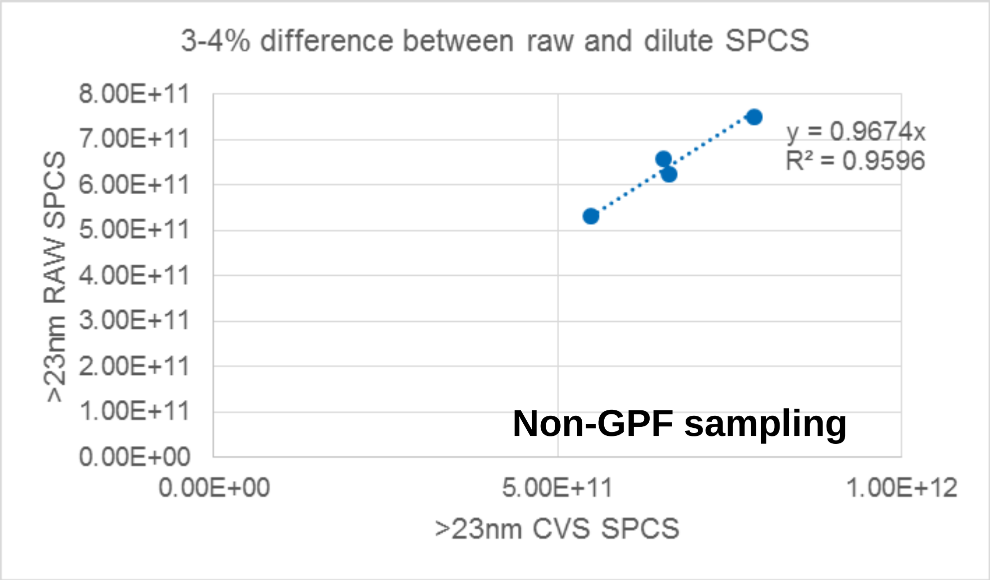
- Relationships between systems can be studied from simultaneous measurements during dyno cycles
- Comparisons between PN systems look for gross changes, for example:
  - If (2) >> (1) then there are large numbers of PN between 7nm and 23nm
  - If (3) ~ (4, no GPF) then losses through the TWC are minimal
  - If (1) ~ (3) then losses in the CVS are minimal

Content

- Objectives
- Measurement Installations
- PN measurement approaches
- **Initial Chassis Dyno Findings**
- Discussion
- Conclusions

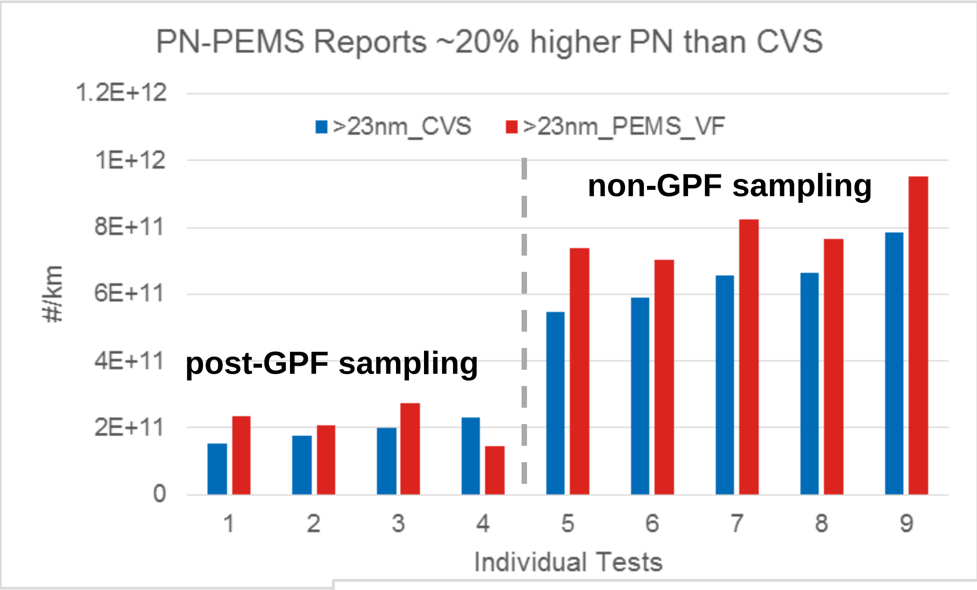
CVS (dilute) and Raw >23nm PN sampling appear sufficiently similar to be considered equivalent

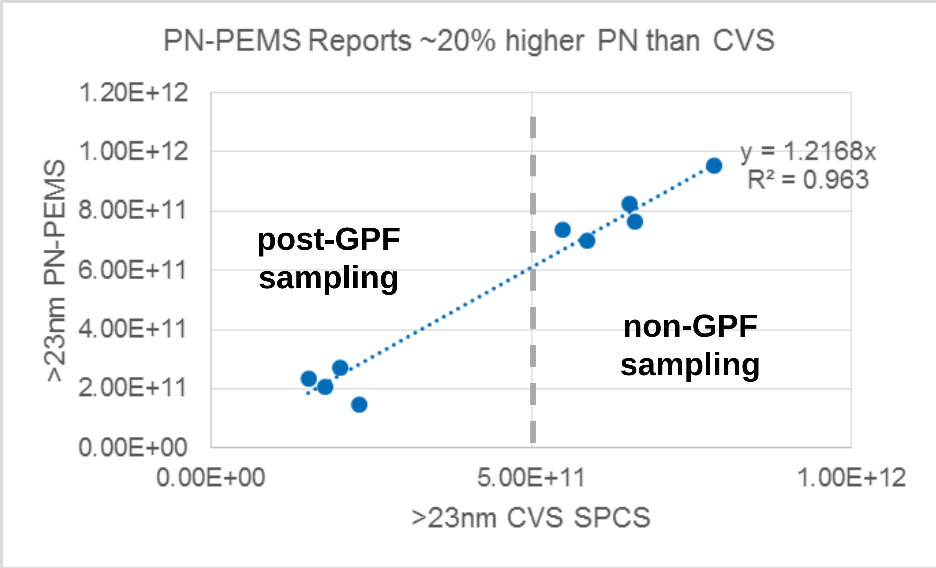




- Comparison of raw and dilute SPCS systems indicates <5% difference
- CVS levels are lightly higher
  - May indicate CVS background contribution not present in raw sample
  - Other differences exist though
    - Additional raw diluter
    - Different pre-classifier

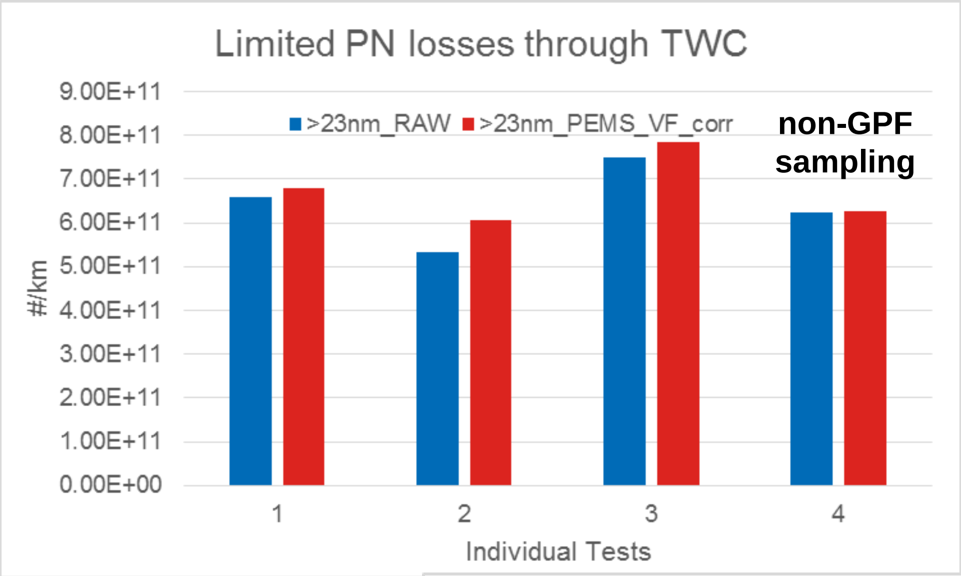
PN-PEMS system shows good correlation with CVS-based >23nm system, but ~20% higher levels

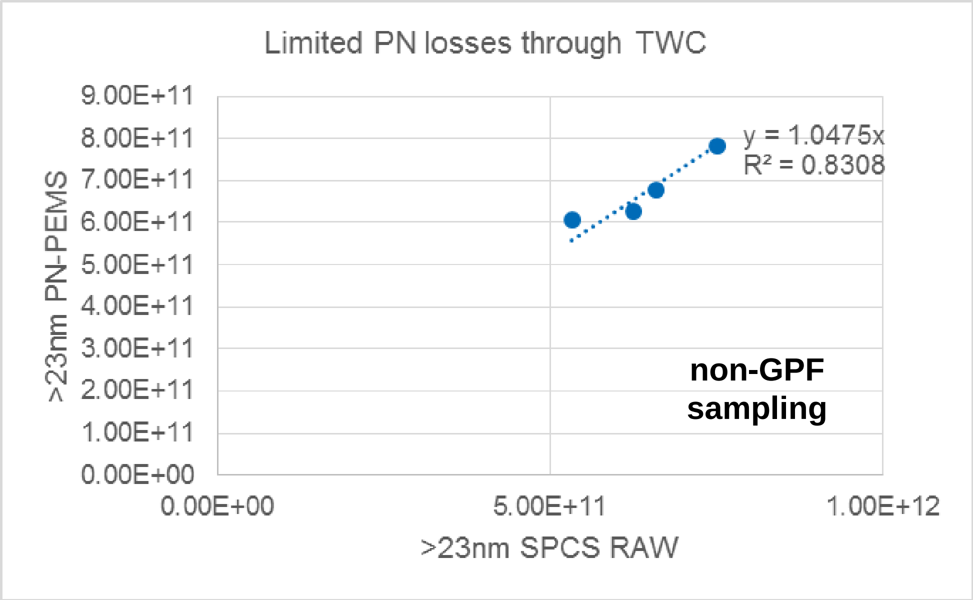




- Draft RDE regulation requires measured PEMS emissions to be ±50% of CVS levels
  - Easily achieved
- Higher PEMS-PN levels indicative of differences in:
  - Methodology for corrections of losses
  - Absolute losses (raw v dilute)
- Good linearity of relationship allows ‘correction’ of PN-PEMS data to estimate CVS levels

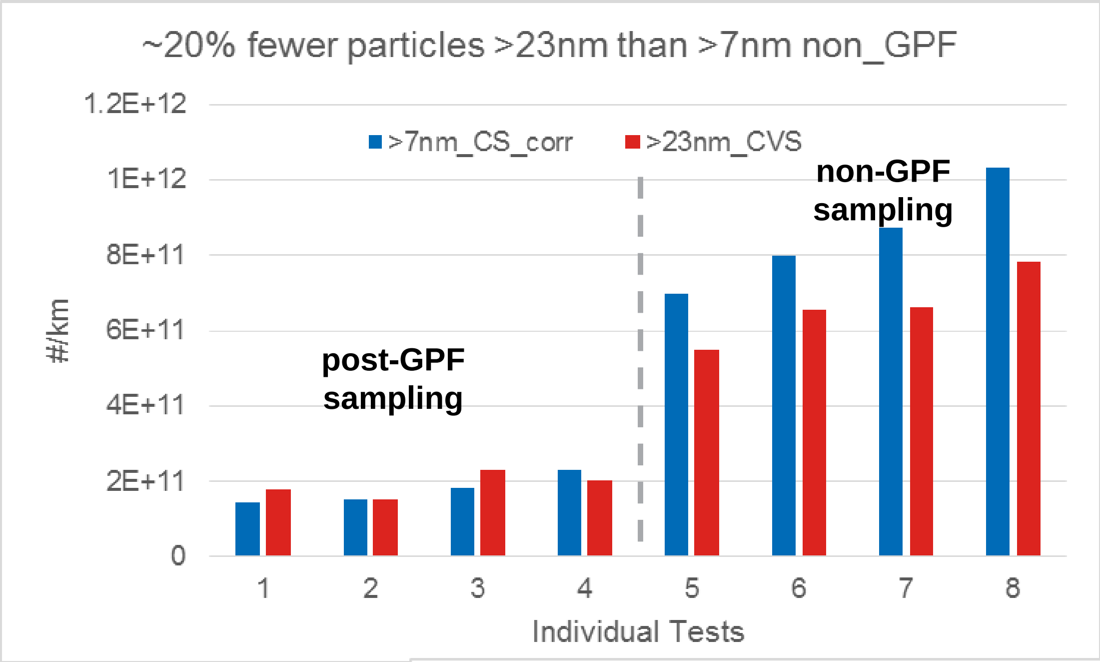
The Three-way catalyst (TWC) is not a major source of particle removal or loss

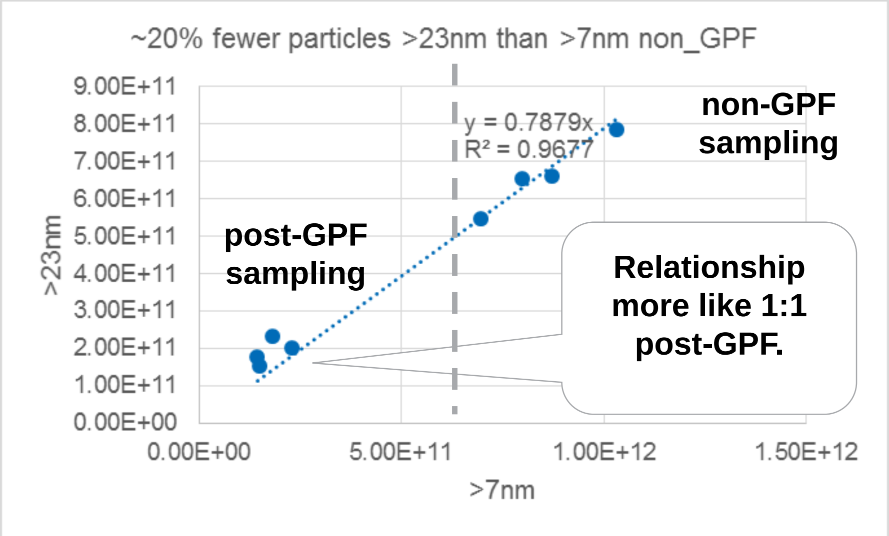




- Equating measurements from the raw SPCS with the ‘corrected’ PN-PEMS shows <5% difference
- Losses / elimination of particles in the TWC are <10%
  - With the difference between raw and dilute SPCS factored-in

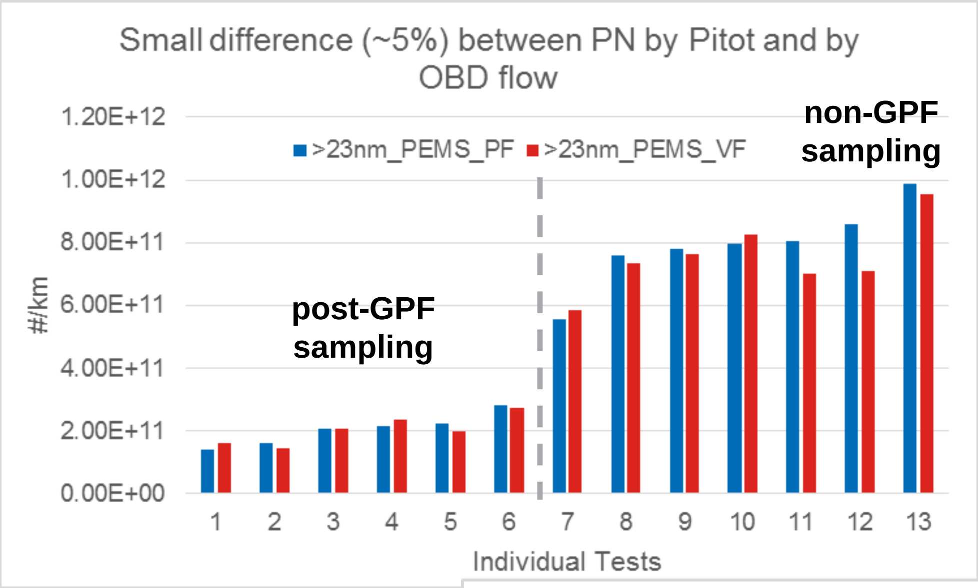
There are relatively few emissions of <23nm particles from the test vehicle: ~20% extra particles >7nm, than >23nm

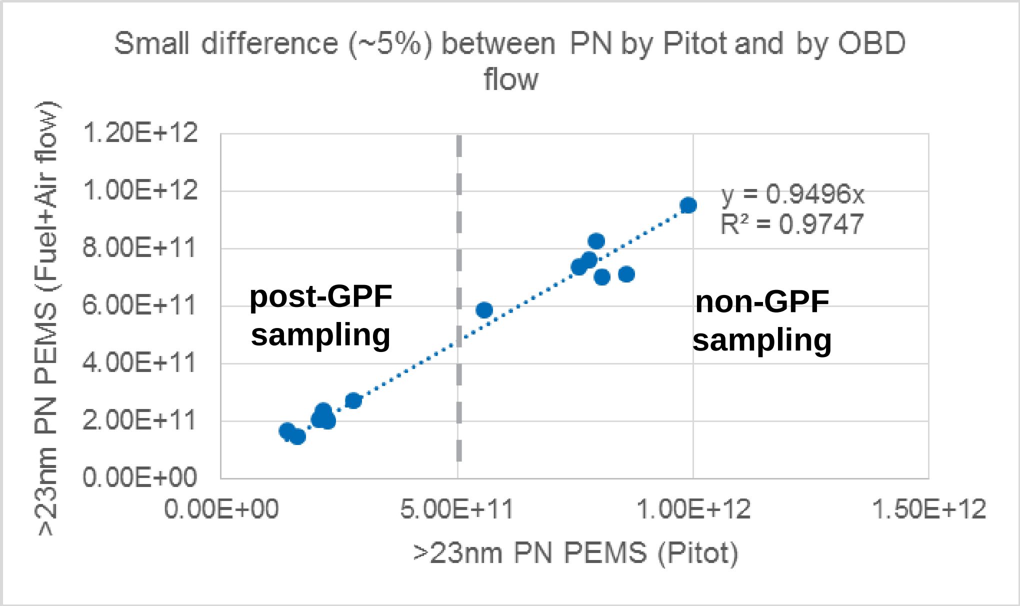




- Sampling for the two particle counters is nominally identical
  - Calibrated loss model applied to the catalytic stripper (>7nm) measurements
    - ~32% losses on average, but size dependent
- There is possibly a different relationship between 7nm and 23nm numbers post GPF
  - Indicates fewer <23nm PN post-GPF
    - GPF more efficiently captures smaller PN / change in the size distribution?
    - Smallest PN preferentially lost during sampling?
    - Calibration for <23nm measurement critical

Similar Results from PN-PEMS when using Pitot and OBD-based flow measurement





- PN-PEMS results similar from OBD (fuel and air calculation) and pitot-based flow measurements
  - Typically ~5% different
- OBD information provides an opportunity to validate pitot flow data and help quantify errors

Content

- Objectives
- Measurement Installations
- PN measurement approaches
- Initial Chassis Dyno Findings
- **Discussion**
- Conclusions

Discussion#1

- Measurements have been made with several PN systems, including prototype PN-PEMS
- No operational problems were encountered with running the PN-PEMS during many weeks of operation and both in-lab and on-road
- Consistency of measured PEMS results on a test-to-test basis is highly dependent on reliable flow measurement, and pitot flow measurement may be less reliable on the road than on the chassis dyno. This does impact data quality.
- The availability of OBD-derived exhaust flow data presents opportunities:
  - To validate pitot flow data
  - To, conversely, enable use of the more repeatable and stable OBD data by validation using the pitot flow data
- Interestingly, PN data proved to be less susceptible to issues with the pitot flow than gases
  - This may be due to a lower relative range in PN emissions, than seen with, for example, CO_2.

Discussion#2

- In chassis dyno tests, there are strong correlations between different instruments and different size ranges
  - It's unlikely that any volatile particles, that would likely increase variability, are reaching the particle counters of either evap tube or cat stripper (DOC) based systems
- The PMP WG has discussed the need for reducing the lower PN size limit to 10nm
  - Evidence is that it may not be necessary currently
    - JRC survey and experience showed PN_{10nm} / PN_{23nm} generally 1.3 to 1.4
    - This study showed ~1.2, so supports the prior findings
    - Use of GPF may further reduce the ratio to closer to one, if collection efficiency for the smallest particles is greater than for those slightly larger
      - But this may also be a measurement artefact
        - Losses of <23nm may be high and hard to correct accurately
        - Change in particle size distribution across the GPF could interact with the counting efficiency of the particle counter, creating a similar effect
    - In case future engine technologies could impact the ratio, PMP continues to consider <23nm PN

Content

- Objectives
- Measurement Installations
- PN measurement approaches
- Initial Chassis Dyno Findings
- Discussion
- **Conclusions**

Conclusions

- Ricardo experienced reliable operation over many weeks using a PN-PEMS
- CVS (dilute) and Raw >23nm lab-based PN sampling appear sufficiently similar to be considered equivalent
- >23nm PN-PEMS particle number emissions proved to be ~20% higher than CVS-based levels, consistent with Horiba's data and compliant with the ±50% in the draft RDE requirements
- Comparing engine-out (pre-TWC) and tailpipe (non-GPF, post-TWC) >23nm PN using two different measurement systems indicated that particle loss / removal by TWC is limited to <10%
- There appear to be relatively few particles between 7nm and 23nm on the vehicle tested: ~20% extra relative to the >23nm result
- PN emissions post-GPF may indicate greater reductions in <23nm PN than in >23nm, but this requires further study
- Calculating using OBD-based flows gives PN-PEMS outputs highly similar to, but more repeatable than, pitot flow-derived results. Using validated OBD flow data could eventually help in the reduction of the measurement-related conformity factor contribution