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

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AECC Technical Seminar on Real-Driving Emissions of Particles (RDE PN)
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Content

- Objectives
  - Measurement Installations
  - PN measurement approaches
  - Initial Chassis Dyno Findings
  - Discussion
  - Conclusions
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
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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 CO₂ (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

GPF fitted in underfloor position for selected tests

Tailpipe temperature
PEMS gases: CO, CO₂, 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

Constant Volume Sampler (CVS)

Dilute

Continuous dilute emissions
Bagged dilute emissions: CO, CO₂, CH₄, 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)
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## PN Systems’ Sampling Configurations

2 raw systems, 2 dilute systems, >7nm system, 3 x >23nm systems

<table>
<thead>
<tr>
<th></th>
<th>Initial dilution</th>
<th>Pre-classifier</th>
<th>$\text{PND}_1$ (diluter #1)</th>
<th>Volatile Removal</th>
<th>$\text{PND}_2$ (diluter #2)</th>
<th>PNC (counter)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>4: Raw PN-PEMS</strong></td>
<td>[-]</td>
<td>1µm</td>
<td>dilution 10</td>
<td>DOC 350°C</td>
<td>dilution 10 ambient</td>
<td>d50 23nm</td>
</tr>
<tr>
<td><strong>3: Raw SPCS</strong></td>
<td>dilution 10 ≤350°C</td>
<td>&lt;10µm</td>
<td>dilution 10</td>
<td>Evap tube 350°C</td>
<td>dilution 15 &lt; 35°C</td>
<td>d50 23nm</td>
</tr>
<tr>
<td><strong>2: Dilute Catalytic Stripper</strong></td>
<td>CVS (&lt;30) &lt;52°C</td>
<td>[-]</td>
<td>[-]</td>
<td>DOC 350°C</td>
<td>[-]</td>
<td>d50 7nm*</td>
</tr>
<tr>
<td><strong>1: Dilute SPCS</strong></td>
<td>CVS (&lt;30) &lt;52°C</td>
<td>&lt;10µm</td>
<td>dilution 10</td>
<td>Evap tube 350°C</td>
<td>dilution 15 &lt; 35°C</td>
<td>d50 23nm</td>
</tr>
</tbody>
</table>

*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

<table>
<thead>
<tr>
<th></th>
<th>System</th>
<th>Sampling location</th>
<th>Lower size (d50)</th>
<th>Volatile removal</th>
<th>Opportunities for particle loss</th>
<th>Losses corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dilute SPCS</td>
<td>Tailpipe (dilute)</td>
<td>23nm</td>
<td>ET</td>
<td>Transfer to CVS; CVS; transfer line CVS to SPCS</td>
<td>PCRF corrects losses within SPCS</td>
</tr>
<tr>
<td>2</td>
<td>Dilute Cat stripper</td>
<td>Tailpipe (dilute)</td>
<td>7nm (10nm)</td>
<td>Oxicat</td>
<td>Transfer to CVS; CVS; transfer line CVS to CS; Oxicat</td>
<td>~32% losses in Oxicat (penetration curve supplied)</td>
</tr>
<tr>
<td>3</td>
<td>Raw SPCS</td>
<td>Pre-TWC / Pre-GPF (raw)</td>
<td>23nm</td>
<td>ET</td>
<td>Transfer to PND&lt;sub&gt;0&lt;/sub&gt;</td>
<td>PCRF corrects losses within SPCS</td>
</tr>
<tr>
<td>4</td>
<td>Raw PN-PEMS (based on NPET)</td>
<td>Post-TWC / post-TWC+GPF (raw)</td>
<td>23nm</td>
<td>Oxicat</td>
<td>PEMS vehicle exhaust sampling apparatus</td>
<td>Calibration includes internal loss correction</td>
</tr>
</tbody>
</table>

- **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
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• PN measurement approaches

**Initial Chassis Dyno Findings**

• Discussion
• Conclusions
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
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**Discussion**

- Conclusions
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, CO₂.
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
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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.