EVALUATION OF THE EUROPEAN PMP METHODOLOGIES USING CHASSIS DYNAMOMETER AND ON-ROAD TESTING OF HEAVY-DUTY VEHICLES

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ABSTRACT

As regulatory limits in California and the US for 2007 heavy-duty diesel engines introduce dramatic reductions in PM emissions, there is considerable interest in new emission metrology that can more accurately measure low PM levels. One such metrology, particle number measurement, has been extensively investigated in Europe as part of Europe’s Particle Measurement Program (PMP) for light-duty diesel vehicles. This program has put forth a new methodology, including instrument specifications and sampling protocols, for “solid” particle number measurements. While counting only solid particles may not be indicative of all of diesel PM health effects, this still represents a significant advancement as it is currently the only methodology with low enough detection limits to produce precise measurements of DPF equipped engines. The specific objective of this study was to critically evaluate the proposed PMP method for determining “solid” particle number emissions from heavy-duty vehicles in the laboratory and during over-the-road driving. This study is complementary to the investigation by CARB involving the PMP Golden Vehicle and presented last year.

For this program, testing was conducted on the chassis dynamometer at the CARB heavy-duty vehicle emissions laboratory in Los Angeles and over the road with the CE-CERT mobile emissions laboratory (MEL). Testing over the road is a novel idea uniquely enabled by the MEL and where the interest rests on the investigating the plausibility of “real-world,” yet rigorous emission measurements with the PMP method. One or two PMP compliant dilution systems for measuring solid particle number were tested and compared directly with filter-based PM measurements on two heavy-duty trucks equipped with a DPF. A full suite of other particle measurements and instruments were also used in conjunction with this testing including an EEPS, a Cambustion DMS, CPCs with cut-off size ranges from 3 to 20 nm, a Dekati DMM, and a TSI Dustrak. The test cycles included a 50 mph cruise, UDDS, idle, and some European driving schedules.

On-road testing showed that gravimetric PM filter mass measurements were near detection limits for most of driving cycles, which makes it desirable to explore the new PM measurement
protocol. The CPC particle number count levels follow a trend that is consistent with the size cuts of the respective instruments, with the particle counts for the 3760s (~11 nm) and the 3790 (20 nm) being considerably less than those of the 3022 (7 nm) and the 3025As (3 nm), suggesting the presence of sub-20nm “solid” particles making it through the PMP sampling train. The 3022 CPC, which was connected to the primary tunnel as opposed to below the PMP system, also showed higher counts than the other CPCs below the PMP system when volatile nucleation particles formed as shown in Figure 1. The particle number measurements using PMP method showed a lower coefficient of variation than the PM filter mass measurements as shown in Figure 2. One key advantage of particle number measurements is better repeatability at low mass levels. The results of this study including on-road and laboratory testing on chassis dynamometer will be presented.

**Figure 1. Particle number rate (#/mile) on driving cycles for on-road testing**

**Figure 2. Coefficient of variation for all CPCs and PM mass on driving cycles for on-road testing**
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Overview

• Background
• Objectives
• Experimental setup
• Results
  – Integrated data
  – Real time data
• Conclusion
Background

• Current gravimetric method have increasing difficulty quantifying post-DPF PM mass emissions accurately.
  – Background contribution
  – Insensitive to DPF fill state

• Euro 5/6 standard includes measurement of solid particles (>23nm) as an additional new metric of particles emitted from light-duty diesel vehicle.
Objectives

• Critical evaluation of the proposed European PMP method for determining particle emissions from heavy-duty diesels and its potential in California for PM measurement and in-use screening.

• Particle mass vs particle number.
Lab testing (at CARB MTA lab)
UCR/CE-CERT’s Mobile Emission Lab (MEL) for On-Road Testing

**Diluted Exhaust**: Temperature, Absolute Pressure, Throat $\Delta P$, Flow.

**CVS Turbine**: 1000-4000 SCFM, Variable Dilution.

**Secondary Probe**.

**Gas Sample Probe**.

**Secondary Dilution System**: PM (size, Mass).

**Drivers Aid**.

**GPS**: Pat, Long, Elevation, # Satellite Precision.

**Dilution Air**: Temperature, Absolute Pressure, Throat $\Delta P$, Flow.

**Gas Measurements**: CO$_2$ %, O$_2$ %, CO ppm, NO$_x$ ppm, THC ppm, CH$_4$ ppm.

**Other Sensor**: Dew Point, Ambient Temperature, Control room temperature, Ambient Baro, Trailer Speed (rpm), CVS Inlet Temperature.

**Exhaust**: Temperature, $\Delta P$ (Exhaust-Ambient), Flow.

**Engine Broadcast**: Intake Temperature, Coolant Temperature, Boost Pressure, Baro Pressure, Vehicle Speed (mph), Engine Speed (rpm), Throttle Position, Load (% of rated).

Gravimetric vs PMP measurements

Vehicle exhaust

Clean Air
Raw Exhaust
Dilute Sample

2.5 um size cut
Primary dilution at PMP (150°C)
Evaporation tube (300°C)
Secondary dilution at PMP
Condensation particle counter (cut-off at 23nm)

TSI 3790
Golden system Clone PMP system

2.5 um size cut
Secondary dilution
Filter sampling system
Pump

Courtesy of W. Robertson for MD-19 diagram
Alternative PMP system

Modified from ISO 8178 partial flow single venturi fractional flow sampler

<table>
<thead>
<tr>
<th>PMP Design</th>
<th>PND1</th>
<th>VPR</th>
<th>PND2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DR</td>
<td>Temp (C)</td>
<td>Length (in)</td>
</tr>
<tr>
<td>MEL</td>
<td>10</td>
<td>150</td>
<td>36</td>
</tr>
<tr>
<td>MD-19</td>
<td>30</td>
<td>150</td>
<td>6</td>
</tr>
</tbody>
</table>
Flow diagram of PM measurement system

Lab test

Primary dilution

Secondary dilution

Sampling & Measurement

CVS

Filter sampling train (gravimetric)

TSI 3022 CPC (7 nm)

TSI 3025A CPC (3 nm)

TSI 3790 CPC (23 nm)

TSI 3025 CPC (3 nm)

PMP diluter

(Clone system)

PMP CPC

On-road test

Primary dilution

Secondary dilution

Sampling & Measurement

MEL CVS

Filter sampling train (gravimetric)

MEL secondary diluter

TSI 3790 CPC (23 nm)

TSI 3760 CPC (11 nm)

TSI 3025 CPC (3 nm)

PMP diluter

(Alternative system)

TSI 3760 CPC (11 nm)

TSI 3025 CPC (3 nm)

TSI 3022 CPC (7 nm)

F-SMPS and EEPS at MEL CVS and PMP diluter
## Experimental conditions

<table>
<thead>
<tr>
<th></th>
<th><strong>Lab test</strong></th>
<th><strong>On-road test</strong></th>
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</thead>
<tbody>
<tr>
<td><strong>Base</strong></td>
<td>Chassis dynamometer</td>
<td>Mobile Emission Lab</td>
</tr>
<tr>
<td><strong>PMP system</strong></td>
<td>Clone system</td>
<td>Clone &amp; Alternative systems</td>
</tr>
<tr>
<td><strong>Vehicle</strong></td>
<td>1999 International 4900</td>
<td>Freightliner class 8</td>
</tr>
<tr>
<td><strong>Engine</strong></td>
<td>International DT 466E (7.6L)</td>
<td>Caterpillar C-15 (14.6L)</td>
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<tr>
<td><strong>Fuel</strong></td>
<td>ULSD</td>
<td>ULSD</td>
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<tr>
<td><strong>Lube oil</strong></td>
<td>SAE 15W-40</td>
<td>SAE 15W-40</td>
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<tr>
<td><strong>DPF</strong></td>
<td>Engelhard DPX</td>
<td>JM CRT</td>
</tr>
<tr>
<td><strong>Vehicle weight</strong></td>
<td>27,000 lb</td>
<td>65,000 lb</td>
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<tr>
<td><strong>Cycles</strong></td>
<td>2x UDDS (35 min)</td>
<td>UDDS (18 min)</td>
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<tr>
<td></td>
<td>50 mph Cruise (45 min)</td>
<td>ETC Cruise (10 min)</td>
</tr>
<tr>
<td></td>
<td>Idle (40 min)</td>
<td>CARB Creep (4 min)</td>
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<tr>
<td></td>
<td><strong>Flow-of-traffic</strong></td>
<td><strong>Flow-of-traffic</strong></td>
</tr>
</tbody>
</table>

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Integrated Results
(using Clone PMP system)

Vehicle exhaust

2.5 um size cut
Primary dilution at PMP (150°C)

Evaporation tube (300°C)

Secondary dilution at PMP

Condensation particle counter (cut-off at 23nm)

Golden system
Clone PMP system

2.5 um size cut
Secondary dilution

Filter sampling system

Pump

CVS Blower

Courtesy of W. Robertson for MD-19 diagram
PM mass
(from gravimetric method)
**PM number**

- **PMP CPC**

![Graph showing particle count and concentration](image)

- **Lab test (Euro 5/6 Light Duty Standard)**
  - Particle count (#/mi):
    - Cruise: $10^{10}$
    - 2 UDDS: $10^{11}$
    - ETC Urban: $10^{12}$
    - ETC Cruise: $10^{13}$
    - ARB Creep: $10^{14}$
    - UDDS: $10^{15}$
    - Route 1: $10^{16}$
    - Route 2: $10^{17}$

- **On-road test**
  - Particle count (#/mi):
    - Cruise: $10^{10}$
    - 2 UDDS: $10^{11}$
    - ETC Urban: $10^{12}$
    - ETC Cruise: $10^{13}$
    - ARB Creep: $10^{14}$
    - UDDS: $10^{15}$
    - Route 1: $10^{16}$
    - Route 2: $10^{17}$

- **Particle concentration (#/cc)**
  - ETC Urban: $10^0$
  - ETC Cruise: $10^1$
  - Creep: $10^2$
  - UDDS: $10^3$

*Means at VS and ** means at MEL PMP system*
Coefficient of Variation (COV)

Lab test
- 3790 (23nm)
- 3025 (3nm)
- 3022*(7nm)
- PM Mass

On-road test
- 3790 (23nm)
- 3025 (3nm)
- 3022*(7nm)
- PM Mass

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Results
(Real time data)
Concentrations normalized to those at CVS for comparison.

Vehicle exhaust

Golden system
Clone PMP system

2.5 um size cut

Primary dilution at PMP (150°C)

Evaporation tube (300°C)

Secondary dilution at PMP

Condensation particle counter (cut-off at 23nm)

CVS Blower

Alternative PMP system
European Transient Cycle (ETC) Cruise

A spike showed up in the beginning of ETC cruise cycles all the time due to gear shift before the cycle.

3 hypotheses:

- Solid particle penetration-
  - Size distribution from previous studies using EEPS and DMS
  - Need to confirm with f-SMPS or nano-SMPS
  - Continuous ash particle emissions at DPF? -> Unlikely

- Partial evaporation of large particle
- Re-nucleation of sulfate
US EPA Urban Dynamometer Driving Schedule (UDDS a.k.a FTP 72 and LA-4)

CPCs under PMP

F-SMPS at CVS
Real time data (flow-of-traffic)

Comparison of MEL vs MD19 Dilution System for CPC's 3760 11nm and 3790 20nm
Normalized to MD19 Dilution (MEL DR ~100 MD19 DR~300)

CPCs under PMP

Hydrated sulfate concentration contributes to 45% of mass

EEPS at CVS
Real time data (flow-of-traffic)

EEPS at CVS

F-SMPS under Alternative PMP system

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Conclusion

• The overall results indicate that particle number can provide a more repeatable measurement with particle emission levels well below the 2007 U.S. PM mass standard.
Conclusion

• Under more aggressive, on-road driving conditions, significant nucleation was observed, with very high count levels below the PMP system. These particles had a large sulfate contribution that may not have been eliminated by the current PMP dilution system. This finding suggests that certification level tests are not sufficient to understand or characterize particle count levels that may occur on the road.

• Re-nucleation or penetration under PMP system should be understood and need further study.