Particulate Mass Measurements from a Heavy-Duty Diesel Engine Using 2007 CVS PM Sampling Parallel to QCM and TEOM

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Acknowledgements

- David Bookers, Bookers System
Background

- Real Time Particulate Mass Measurement
  Instruments are needed for:
  - Onboard Vehicle Testing
  - Engine and Vehicle Emissions Research and Development
- Instruments Basic Requirements
  - Equivalent to US EPA 2007 Filter Method
  - Detection of very low level of particulate matter mass

Outline

- Instruments Under Consideration
  - Tapered Element Oscillating Microbalance (TEOM)
  - Quartz Crystal Microbalance (QCM)
- Evaluation and Comparison
  - EPA 2007 PM Protocol with and without Traps
    - Steady State
    - FTP Transient Cycle
    - Backhoe Loader Cycle
1105A TEOM Diesel Aerosol Monitor

TEOM Principle of Operation

Diagram:
- Sample flow
- Exchangeable filter cartridge
- Tapered element
- To flow controller
- Electronic feedback system
- Data processing unit
RPM – 100 QCM System

QCM Principle of Operation

[Diagram showing aerosol flow, high voltage, collected particles, and piezoelectric crystal]

EPA

SRI
1998 Detroit Diesel Series 60

Steady State Tests
Using US 2-D Diesel Fuel

<table>
<thead>
<tr>
<th>Mode</th>
<th>Speed</th>
<th>Load (%)</th>
<th>Sampling Time, Sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rated</td>
<td>100%</td>
<td>600</td>
</tr>
<tr>
<td>2</td>
<td>Rated</td>
<td>50%</td>
<td>1500</td>
</tr>
<tr>
<td>3</td>
<td>Rated</td>
<td>25%</td>
<td>600</td>
</tr>
<tr>
<td>4</td>
<td>Low Idle</td>
<td>No Load</td>
<td>1500</td>
</tr>
</tbody>
</table>

Three repeats at each mode of engine operation will be performed.
FTP and BHL Transient Cycles

SWRI 2007 PM Sample Configuration

CVS Tunnel
Secondary Dilution
Sample Transport Tube
Traps Used During Tests

- Engelhard DPX
- Johnson Matthey CRT

Note: Both traps were operated using 2007 ultra-low sulfur diesel fuel, <15ppm sulfur.

CVS/Instrument PM Sample

Sample Distribution Y
Cyclone
PM Filter Holder
Sample Media

- 2007 Filter Method – 47mm TX40 and Zefluor (Pall Corp.)
  - TX40 is made of Borosilicate Micro-Glass Fibers, Glass Cloth, and Teflon
  - Zefluor is all Teflon
- Current Filter Method- 90 mm T60A20 (Pall Corp.)
  - T60A20 is made of borosilicate glass fiber and fluorocarbon
- TEOM – 13mm TX40 (Pall Corp.)
- QCM – Quartz crystal (Booker systems, Ltd.)

Instrument Sample Equilibration

- Sensor Temperature
  - TEOM = 47 °C
  - QCM = 40 °C
- Nominal Zero Air Dew Points
  - TEOM = 33.2 °C
  - QCM = 26.6 °C

*This is consistent with 2007 Filter Face Temperature
**This is equivalent to the Weigh Room conditions of 22 °C and 9.5 % dew point
Humidification System

TEOM
TEOM Sample Configuration

- Vacuum Valve
- Clean Air Valve
- Sample Valve

TEOM Sample Timing

- Average no-flow
- Tare here
- Average flow
- Tare here
- Average flow total mass here
- Average no-flow total mass here

Time (seconds)
TEOM Mass for Engine Without Trap, FTP-4

TEOM Concentration for Engine Without Trap, FTP - 4
TEOM Loading Sensitivity

\[ y = 4 \times 10^{-6}x^3 - 0.0007x^2 + 0.0378x + 0.0378 \]

\[ R^2 = 0.961 \]

Difference Relative to CVS, %

TEOM Mass, µg

QCM
RPM-101 Sample Configuration

Sample Valve
Clean Air Valve
Heated Sample Lines

QCM Example for Engine Without Trap

Transient Illustration: BHL “Engine Out” Tests

Sampling Period
Dilution Ratio 20:1
BHL - 2: Mass 0.60 ug, Conc 1.02 mg/m³
BHL - 3: Mass 0.61 ug, Conc 1.03 mg/m³
BHL - 4: Mass 0.59 ug, Conc 0.98 mg/m³

Mass (ug)

Time (sec.)

-300 200 700 1200
Steady State Response

Steady State Dilute
Baseline Comparison Without Trap
CRT Dilute Comparisons TX-40 Filter Media
(TEOM Filter Was Not Changed for Repeats Within a Mode of Engine Operation)

$$\text{TEOM} = 0.63 \text{ CVS} - 0.004$$
$$R^2 = 0.95$$

$$\text{QCM} = 0.13 \text{ CVS} + 0.008$$
$$R^2 = 0.82$$

DPX Dilute Comparisons Using TX-40 CVS Filter Media
(TX-40 TEOM Filter Was Not Changed for Repeats Within a Mode of Engine Operation)

$$\text{TEOM} = 0.28 \text{ CVS} + 0.02$$
$$R^2 = 0.13$$

$$\text{QCM} = 0.04 \text{ CVS} + 0.01$$
$$R^2 = 0.29$$
CRT Dilute Comparisons Using Zefluor CVS Filter Media

When the TEOM Used Zefluor Filters Like the CVS, the Total Mass Collected by TEOM was Negative

\[ \text{TEOM} = 4.2823 \text{ CVS} + 0.014 \]
\[ R^2 = 0.9687 \]

\[ \text{QCM} = 0.6454 \text{ CVS} + 0.0092 \]
\[ R^2 = 0.9239 \]

CRT Dilute Comparisons Using T60A20 CVS Filter Media

(Current Sampling Methodology was Used, Transient and Steady-State Data)

\[ \text{TEOM} = 1.1595 \text{ CVS} - 0.075 \]
\[ R^2 = 0.8345 \]

\[ \text{QCM} = 0.3321 \text{ CVS} - 0.022 \]
\[ R^2 = 0.5602 \]
Transient Response

FTP PM Emissions For Engine Without and With Traps-TX-40 Filter Media
FTP CVS Filter Weight Gain For Without and With Traps- TX-40 Filter Media

BHL PM Emissions For Engine Without and With Traps-TX-40 Filter Media
Transient Comparisons Using CVS TX-40 Filters
(One TEOM Filter Was Used for All Three Repeats of an FTP)

<table>
<thead>
<tr>
<th>Transient Cycle</th>
<th>TEOM/CVS</th>
<th>QCM/CVS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline FTP</td>
<td>0.88</td>
<td>1.19</td>
</tr>
<tr>
<td>Baseline BHL</td>
<td>0.94</td>
<td>1.22</td>
</tr>
<tr>
<td>CRT Trap FTP</td>
<td>0.23</td>
<td>0.44</td>
</tr>
<tr>
<td>CRT Trap BHL</td>
<td>0.60</td>
<td>0.24</td>
</tr>
<tr>
<td>DPX Trap FTP</td>
<td>0.10</td>
<td>0.51</td>
</tr>
<tr>
<td>DPX Trap BHL</td>
<td>0.16</td>
<td>0.37</td>
</tr>
</tbody>
</table>
CVS Filter Tunnel Blank Using Different Filter Media

Comparison of PM Emissions Using Different Filter Media
Influence of CVS Filter Media on the FTP Transient Emission Level for an Engine Equipped with Trap

**Conclusions**

- This work was exploratory in nature, and more work is needed utilizing the new information learned during this study to make more robust conclusions. The following statements, however, can be made:
  - Filter Media selected for PM collection seemed to affect the PM emission level significantly. The Zefluor filters, which are Teflon Based, gave the lowest emission level.
  - The data presented were not corrected for Tunnel Blank where filter collection from the CVS was taken without engine running. Tunnel Blank PM mass was very close to the amount of mass collected during testing with a Trap.
  - Significant PM emission variability was observed with Zefluor Filters, possibly due to the very low emission level which was one order of magnitude below the 2007 PM standard.
  - The TEOM filter change after every test seemed to increase the emission level reported and improve the correlation with CVS. However, other Zefluor Filters were used for the TEOM test and negative.
  - The use of Zefluor Filters improved the correlation between the TEOM and the FTP. However, other Nanoscale filters that were examined for the collection of Ambient material may present the possibility of finding an alternative method for the filter method.
  - More detailed analysis of this work should be made available in future publications.