On-Road Particle Matter Emissions from a MY2010 Compliant HD Diesel Vehicle Driving Across the US

Marc C. Besch, Arvind Thiruvengadam, Daniel K. Carder and Mridul Gautam
Department of Mechanical and Aerospace Engineering
West Virginia University

Project Sponsors:
Adewale Oshinuga, Randell Pasek
South Coast Air Quality Management District, Diamond Bar, CA

Alberto Ayala, Tao Huai, Shaohua, Hu
California Air Resources Board, Sacramento, CA
Content

• Motivation and Background
• Experimental Methodology
• Laboratory and Measurement Setup
• Results and Discussion
   Gravimetric TPM
   Particulate Emissions under flat highway conditions
   Particulate Emissions under mountainous highway conditions
• Conclusions
Background and Motivation

• In-use Emissions Compliance Measurements and On-Road Testing
  - Evaluation of PM emissions from a 2010 compliant heavy-duty Diesel tractor equipped with advanced aftertreatment technology, under real-world conditions
    - Comparison to US EPA 2010 emissions standards (engine dynamometer based)
    - Quantification of PM mass emitted during Not-to-Exceed (NTE) events => PM: 150% of the FTP emissions standard (g/bhp-hr) for the given model year
    - Particle concentration with regard to proposed Particulate Number (PN) limit for Euro VI legislation
  - Reported increase of nano-sized particles for catalyzed DPF’s under high temperature conditions (~> 380°C) ¹, ²
    - Possible sulfuric acid based particles formed as a result of sulfur oxidation (originating from lube oil) over the catalyst surfaces at high temperatures

• Evaluation of In-line, Real-time Particle Sensor
  - On-board Diagnostics (OBD) Applications
    - US EPA HD-OBD in effect by 2013 (all engine families)
    - EU Regulations for OBD effective by 2014
  - Establishing mass reference for aerosol in real-time

Methodology - Test Plan

- Morgantown, WV to Riverside, CA => Total distance: ~2450 miles (3943 km)
- Route: I-70W, I-15S, I-215S
- Journey Total Time: 6 days
- Highest Elevation: 11’990 ft (Loveland Pass, CO)
- Net Elevation Change: -57 ft (final destination lower than Morgantown, WV)
- Environmental Conditions:  
  - Temperature range 37 to 97°F (3 to 36°C)
  - Relative humidity range 12 to 78%
  - Barometric pressure range 65.5 to 100.5 kPa
# Methodology - Test Vehicle

## Test Vehicle Specifications:

<table>
<thead>
<tr>
<th>Test Vehicle Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chassis Manufacturer / Model</td>
<td>Mack Trucks Inc. / CXU613</td>
</tr>
<tr>
<td>VIN</td>
<td>1M1AW07Y1CM017126</td>
</tr>
<tr>
<td>Class</td>
<td>8</td>
</tr>
<tr>
<td>Vehicle Model Year (MY)</td>
<td>2011</td>
</tr>
<tr>
<td>Aftertreatment System</td>
<td>DOC / DPF / urea-SCR</td>
</tr>
<tr>
<td>Fuel</td>
<td>Standard ULSD (&lt;15ppm)</td>
</tr>
<tr>
<td>Emission Family</td>
<td>BVPTH12.8S01</td>
</tr>
<tr>
<td>Curb Weight [lbs]</td>
<td>15'000</td>
</tr>
<tr>
<td>Gross Vehicle Weight (GVW) [lbs]</td>
<td>66'740</td>
</tr>
</tbody>
</table>

## Test Engine Specifications:

<table>
<thead>
<tr>
<th>Test Engine Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Manufacturer</td>
<td>Mack Trucks Inc.</td>
</tr>
<tr>
<td>Engine Model</td>
<td>MP8-445C</td>
</tr>
<tr>
<td>Engine Model Year</td>
<td>2011</td>
</tr>
<tr>
<td>Displacement [L]</td>
<td>12.8</td>
</tr>
<tr>
<td>Configuration / # of Cylinders</td>
<td>In-line / 6 cylinder</td>
</tr>
<tr>
<td>Rated Power [hp]</td>
<td>445 @ 1500rpm</td>
</tr>
<tr>
<td>NOx [g/bhp-hr]</td>
<td>0.2*</td>
</tr>
<tr>
<td>PM [g/bhp-hr]</td>
<td>0.01*</td>
</tr>
</tbody>
</table>

* Certification values

- Engine complies with 2010 EPA HD emission standards (NOx: 0.2 g/bhp-hr, PM: 0.01 g/bhp-hr)
- Vehicle equipped with DOC, DPF and urea based SCR system
Laboratory and Measurement Setup

- **Gravimetric TPM**
- **Raw Particle Concentration**
- **Particle Concentration and Size Distribution**
- **NTE TPM Mass**

Diagram showing various measurement setups and devices including FTIR Analyzer, Flexi-Valve, TPM Mass, Particle Concentration, and more.
Setup - Real-Time Particle Sensor (PPS)

- PM detection based on diffusion-charging and escaping current principle
- Constant dilution air pressure leading to constant sample inlet flow (const. dilution ratio)
- Flow through device
- Sensor shows proportional response to particle surface area concentration

PPS wrapped with tape heater (200°C)

In-line PM Sensor (Pegasor PPS-M)

Dilution Air
(Dry, ~25°C compressed HEPA Filtered Air Supply)

Sensor Electronics

Sample Inlet

Sample Outlet

=> with weather protection cover
**EEPS (Model 3090, TSI Inc.)**
- Engine Exhaust Particle Sizer® (EEPS) Spectrometer
- Diluted exhaust measurement from CVS sampling plane
- Average dilution ratio (DR): ≈ 4
- Dilution air temperature and humidity varying depending on location

**Gravimetric TPM**
- According to 40 CFR, 1065
- 47 mm TX40 filter media
- Total flow across filter: 2.3 scfm
- Secondary dilution flow: 1.1 scfm
Results - Exhaust Temperatures (Post DPF)

- Pre DPF (post DOC) exhaust temperatures during Midwest portion of test route (Ohio to Kansas)
  - ~80% above 300°C

- Pre DPF (post DOC) exhaust temperatures during Mountain portion of test route (Colorado to Nevada)
  - ~70% above 300°C

- Pre DPF (post DOC) exhaust temperatures distribution from entire test route (Morgantown, WV to Riverside, CA)
Results - Total Particle Matter (TPM)

- 5.5% Average Grade for 13 miles
- 0.25% Average Grade for 260 miles
- -1.3% Average Grade for 64 miles
- Junction of I-70 and I-15
- Las Vegas, NV (2030 ft above sea level)
- Denver, CO (5249 ft above sea level)
- Salina, KS (1230 ft above sea level)

- Morgantown, WV to Terre Haute, IN
- Terre Haute, IN to Salina, KS
- Salina, KS to Denver, CO
- Denver, CO to Grand Junction, CO
- Grand Junction, CO to Las Vegas, NV
- Las Vegas, NV to Riverside, CA

- Altitude Above Sea Level [ft]
- Distance (mi.)
- Altitude Above Sea Level [ft]
- Particulate Matter (PM) [g/mi]
Results - DPF Regeneration Event

Data from test portion C0035-002-66:

Number concentrations not corrected for CVS dilution

Particle distribution shifting to larger particle size
Results - Flat Highway, Midwest (I-70, MO, KS)

Number concentrations not corrected for CVS dilution
Results - Mountain Highway (I-70, CO)

Number concentrations not corrected for CVS dilution.
Conclusions

- Measuring particle emissions from a 2010 compliant HD Diesel tractor while traveling on-road for 2300 miles between Morgantown, WV to Riverside, CA.
- Average gravimetric TPM over entire route was 0.0056 g/mile and 0.0015 g/bhp-hr => well below EPA 2010 PM standard (0.01g/bhp-hr)
- Increased TPM observed for portions that included DPF regeneration events (~0.0735g/mile or ~0.019g/bhp-hr).
- Increase particle concentration (up to three orders of magnitude) in raw exhaust during DPF regeneration events as measured by the PPS (up to 250mV vs. 0.2mV during regular operation).
- Nanoparticle concentration on the order of $2 \times 10^8$ [#/cm$^3$] (CMD ~5-15nm) as measured in diluted exhaust (not dilution corrected) under high exhaust/aftertreatment temperature (>~340°C) conditions.
- DPF inlet temperatures exceeding 350°C for ~45% and are between 350-400°C for ~36% of entire test route => indicating a favorable temperature range for possible nanoparticle formation over catalyzed DPF via possible sulfur oxidation
Thank You for Your Attention

Marc C. Besch - Marc.Besch@mail.wvu.edu

Daniel K. Carder - Daniel.Carder@mail.wvu.edu

Arvind Thiruvengadam - Arvind.Thiruvengadam@mail.wvu.edu

Professor Mridul Gautam - Mridul.Gautam@mail.wvu.edu

CAFEE Center for Alternative Fuels, Engines and Emissions