In-Use NTE PM Measurement Methodology using an In-Line, Real-Time Exhaust PM Emissions Sensor

Marc C. Besch\textsuperscript{1}, Arvind Thiruvengadam\textsuperscript{1}, Hemanth Kappanna\textsuperscript{1}, Alessandro Cozzolini\textsuperscript{1}, Peter Bonsack\textsuperscript{1}, Daniel K. Carder\textsuperscript{1}, Juha Tikkanen\textsuperscript{2}, Mridul Gautam\textsuperscript{1}

Department of Mechanical and Aerospace Engineering
West Virginia University

\textsuperscript{1}Pegasor Ltd, Tampere, Finland
Content

• Particle Sensor Technology
• NTE Measurement Methodology
• Experimental Setup
• Results and Discussion
  ➢ Engine Dynamometer Results
  ➢ Chassis Dynamometer Results
  ➢ (On-Road Testing Results)
• Conclusions
In-use Emissions Compliance Measurements/Testing:
- Quantification of PM mass emitted during Not-to-Exceed (NTE) events
- Establishing mass reference for aerosol in real-time

Other Fields of Application
- On-board Diagnostics Applications
- PM Sensor for Development and Implementation of DPF Regeneration Strategies
- Combustion Research and Engine Base Calibration Applications
Sensor - Description of Technology

- Measurement based on escaping current principle

### Advantages:
- Real-time
- Continuous operation
- No PM sample collection
- No external dilution of exhaust needed

### Operational Parameters:
- Sampling rate up to 100 Hz
- Sensor output can be calibrated to [mg/m³] or [#/m³]

**Picture provided by Pegasor Oy**
NTE In-use Measurement Method

Calculation of PM mass [mg] during NTE event:

\[
PM_{\text{Mass NTE}} = PM_{\text{Ratio PPS}} \cdot PM_{\text{Mass Total-Cycle}}
\]

\[
PM_{\text{Mass Total-Cycle}} = \text{TPM from gravimetric filter sample}
\]

\[
PM_{\text{Ratio PPS}} = \frac{\int_{t_{\text{Start Test}}}^{t_{\text{End Test}}} PPS(t) \cdot dt}{\int_{t_{\text{Start NTE}}}^{t_{\text{End NTE}}} PPS(t) \cdot dt}
\]
Experimental Setup

**Engine Dynamometer:**
- Full flow dilution tunnel (CVS-SSV)
- No aftertreatment system
- EEPS (TSI, Model 3090)
- CPC (TSI, Model 3025)
- MSS (AVL, Model 483)
- Intake Air Flow Measurement
- Proportional Flow TPM Sampling

**Chassis Dynamometer:**
- Full flow dilution tunnel (CVS-SSV)
- 6.6L Duramax - GMC4500 (2004)
- GVW ~ 12'000 pounds
- Diesel Oxidation Catalyst (DOC)
- Exhaust Flow Measurement
- Horiba OBS and Sensors SEMTECH
- Proportional Flow TPM Sampling

**On-Road Testing:**
- 6.6L Duramax - GMC4500 (2004)
- GVW ~ 12'500 pounds
- Diesel Oxidation Catalyst (DOC)
- Exhaust Flow Measurement
- Horiba OBS and Sensors SEMTECH
- Constant Flow TPM Sampling
Setup - Engine Test Cell/Chassis Dynamometer

\[ C_{\text{CYS}} = C_{\text{Exh}} \cdot \frac{1}{DR_{\text{CYS}}} \]

\[ \alpha_{\text{Loss}} = f \left( L, D, \dot{V}, \Delta T \right) \]

\[ C_{\text{Filter}} = C_{\text{CYS}} \cdot \frac{1}{DR_{\text{Sec PM}}} \]

(Not applied to presented results)

\[ DR_{\text{PPS}} = 0.0053 \cdot [\text{psi}] + 1.3082 \]

\[ DR_{\text{CYS}} = \frac{\dot{m}_{\text{mix}}}{\dot{m}_{\text{Exh}}} \]

\[ DR_{\text{Sec PM}} = \frac{\dot{V}_{\text{sf}}}{\dot{V}_{\text{sf}} - \dot{V}_{\text{sec}}} \]

Dilution System for EEPS and CPC:

1st Stage: Hot, ~ 130C  DR = 6
2nd Stage: Cold, ~ 25C  DR = 24
3rd Stage **: Cold, ~ 25C  DR = 8
** Only for CPC

Intake Air (LFE) & Fuel Flow Measurement (Engine Test Cell)

Exhaust Flow Measurement, Annubar® (Chassis Dynamometer)

\[ \dot{V}_{\text{intake}} \] & \[ \dot{m}_{\text{fuel}} \]

\[ \dot{V}_{\text{Exh}} \]
Setup - On-Road Testing

\[ C_{Exh} = C_{PPS} \cdot DR_{PPS} \]

\[ C_{Filter} = C_{CVS} \cdot \frac{1}{DR_{Sec\ PM}} \]

\[ y = 0.0053x + 1.3082 \]

\[ R^2 = 0.9688 \]

\[ DR_{PPS} = 0.0053 \cdot [psi] + 1.3082 \]

\[ DR_{Sec\ PM} = \frac{\dot{V}_{sf}}{\dot{V}_{sf} - \dot{V}_{sec}} \]

(Not applied to presented results)

\[ \alpha_{Loss} = f(L, D, \dot{V}, \Delta T) \]
Results - Engine Test Cell

- **PPS Signal Filtering/Smoothing:**
  - Savitzky-Golay (Least-Squares Smoothing Filters)
  - *For Steady-State:*
    - Frame Size - 8.1 sec
    - Filter Order - 3
  - *For Transient Cycle:*
    - Frame Size - 2.1 sec
    - Filter Order - 5

- **Instrument Grounding at On-Road**

PPS Concentration as calculated at different locations in the measurement stream between PPS sample cell (blue line) and gravimetric filter face.
Results - Engine Test Cell (ESC)

• AVL MSS => Corrected for temperature influence and thermophoretic losses
• TPM includes absorbed SOF => PPS and AVL do not measure this fraction => Possible correction based on HC
Results - Chassis Dynamometer

Engine Speed [rpm]

From ECU

Engine Torque [ft-lb]

From ECU

NTE Zone [-]

From OBS

NTE Zones (t > 30sec)

PPS Signal [mV]
Conclusion and Outlook

• Response of PPS to PM emissions during the transient test cycle (FTP) was similar to that of EEPS ($R^2$ Value: 0.8969) and AVL MSS ($R^2$ Value: 0.8479).
• Development of NTE In-use Measurement Method using the PPS Signal to calculate PM during NTE events.
• Demonstration of this method based on engine dynamometer experiments => PPS-Method captures general trends.
  – Possible influence of high exhaust flow rates on sample extraction efficiency
  – Accounting for particle losses within transfer pipes
  – Influence of SOF on gravimetric filter weight
• Chassis Dynamometer and On-Road analysis is ongoing.
Thank You for Your Attention
Results - PPS vs. AVL MSS, Engine-out

- Engine: Mack MP-7 (MY 2004)
- No aftertreatment, engine-out measurement
- FTP-Cycle, Dynamometer

Linear Regression Coefficients:
(Least Squares Method)

\[
\text{PPS [mg/m}^3\text{]} = 0.1787 + 0.0581 \times \text{PPS [mV]}
\]

R-Square Value: 0.8479
Results - PPS vs. EEPS, Engine-out

- Engine: Mack MP-7 (MY 2004)
- No aftertreatment, engine-out measurement
- FTP-Cycle, Engine Dynamometer

Linear Regression Coefficients:
(Least Squares Method)

PPS [#/m^3] = 2.244E4 + 1.777E3 * PPS [mV]

R-Square Value: 0.8969
Sensor – Operational Parameters, cont’

- Low temperature version max 250 °C
- High temperature version max. 850 °C
- High concentration version 10 µg/m³-250 mg/m³
- High sensitivity version ~1µg/m³
- Sensor dimensions 20-40 mm diameter, 100-200 mm long – to be decided together with customers
- Electronics; 80x40x20 mm³
- Sensor output calibrated to mg/m³ or #-particles/cm³
- Sensor is installed outside the tailpipe with only inlet and outlet in the tailpipe
- Environmental conditions up to 85 degrees C, IP 45
Sensor - Description of Technology Cont’d

- RS485 Connector
- Sensor Electronics
- Dilution Air
- Sample Inlet
- Sample Outlet

Flow Rate [lpm]
Pressure [psi]

Dilution Ratio

$y = 0.0053x + 1.3082$
$R^2 = 0.9688$