Tail-Pipe Measurements of Emissions from LD Vehicles with Diesel Engines: A Direct Comparison of Five Different Measurement Methods

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Overview

• Comparison of different measuring principles applied to diesel engine exhaust measurements
  – Campaign program, scope and setup
  – Using non-counting instruments for particle number measurements
  – Using non-gravimetric methods for particle mass measurement

• Conclusions

• Q & A
Campaign Program and Scope

• Test program (in cooperation with DEKRA and TÜV Nord, other instrumentation manufacturers and developers also participated)
  – 31 test runs during one week on a chassis-dynamometer at DEKRA Technology Center in Klettwitz (Germany)
  – 3 different diesel engine vehicles (all Euro 4, one w/o DPF)
  – Adjustable DPF-bypass in several tests to simulate DPF malfunction
  – European drive cycle tests as well as steady state test cycles were run
• Scope: Demonstrate that tail pipe measurements can identify DPF malfunctions which OBD can’t
Experimental Setup

Climatic Chassis Dynamometer at DEKRA Klettwitz
Experimental Setup

- **EEPS 3090**: Engine Exhaust Particle Sizer, 5.6 nm to 560 nm
- **CPC 3010D**: Engine Exhaust CPC, 23 nm to 3 µm
- **EAD 3070A**: Diffusion Charger & Electrometer, 10 nm to 1 µm
- **DustTrak 8520**: Light Scattering Photometer, 0.1 to 10 µm
- **AVL MSS**: Photoacoustic Micro-Soot Sensor, total soot mass concentration
Experimental Setup
Operating cycle for the Type I test
Example Results

- European test cycle
- Euro 4 diesel engine LD vehicle without DPF
- Particle number measurements with CPC 3010D, EEPS 3090 and EAD 3070A
- Particle mass measurements with EEPS 3090, EAD 3070A and DustTrak 8520
- Soot mass measurement with AVL MSS
Data Analysis

• Step 1: **Synchronize** all instrument data (using the first prominent peak)
• Step 2: Apply a 5 seconds **running average** to all data sets to minimize the influence of instrument response time
• Step 3 Integrate each data set and **normalize** all number (mass) measurements to the integrated data of the CPC 3010D (EEPS 3090)
• Step 4 Compare dynamic concentration range and **data correlation** based on second by second data
Particle Number

New European Drive Cycle, Euro 4 w/o DPF

Time (s)

N (1/cm³)

0.00E+00  5.00E+07  1.00E+08  1.50E+08

0  200  400  600  800  1000  1200

CPC
Particle Number

New European Drive Cycle, Euro 4 w/o DPF

- EEPS
- CPC

Time (s)

N (1/cm³)

0.00E+00
5.00E+07
1.00E+08
1.50E+08

0 200 400 600 800 1000 1200
Particle Number

New European Drive Cycle, Euro 4 w/o DPF

N (1/cm³)

EEPS
CPC
EAD

Time (s)
Particle Number

New European Drive Cycle, Euro 4 w/o DPF

Time (s)

N (1/cm³)

EEPS
CPC
EAD
Number Correlation

Particle Number Concentration
5 seconds running average

$y = 1.0044x$
$R^2 = 0.9881$

Particle Number Concentration
5 seconds running average

$y = 1.0619x$
$R^2 = 0.9833$
EEPS Mass Calculation

Fractal density function for EEPS mass calculations:

$$\rho_p \cdot (g \text{ cm}^{-3}) = C \cdot D_p(nm)^{Df^{-3}} \; ; \; C = 200; \; Df = 1.9$$

$$\rho_p < 2.2 \; g \text{ cm}^{-3} \; \text{estimated density of primary soot particles}$$
Particle Mass

European Drive Cycle, Euro 4 w/o DPF

![Graph showing Particle Mass over time for Euro 4 drive cycle without DPF. The graph plots mass concentration (M) in mg/m³ against time (s) ranging from 0 to 1200 seconds.]
Particle Mass

European Drive Cycle, Euro 4 w/o DPF

Time (s)

M (mg/m³)

0.00E+00 2.50E+01 5.00E+01 7.50E+01 1.00E+02

EEPS  AVL MSS
Particle Mass

European Drive Cycle, Euro 4 w/o DPF

M (mg/m³)

Time (s)

EEPS  EAD  AVL MSS
Particle Mass

European Drive Cycle, Euro 4 w/o DPF

Time (s)

M (mg/m³)

EEPS  EAD  AVL MSS  DustTrak
Particle Mass

European Drive Cycle, Euro 4 w/o DPF

Time (s) vs. Particle Mass (mg/m³)

EEPS  EAD  AVL MSS
Particle Mass

European Drive Cycle, Euro 4 w/o DPF

Time (s) vs. M (mg/m³)

Graph showing the particle mass data for the European Drive Cycle, Euro 4 without DPF. The data is plotted over time from 0 to 1200 seconds, with the y-axis representing mass concentration in mg/m³. The graph includes data from EEPS, EAD, AVL MSS, and DustTrak instruments.
Mass Correlations

Mass Correlation

\[ y = 0.9449x \]
\[ R^2 = 0.9763 \]

Mass Correlation

\[ y = 1.037x \]
\[ R^2 = 0.9516 \]
Mass Correlations

\[ y = 0.6767x \]
\[ R^2 = 0.6193 \]

\[ y = 0.7708x \]
\[ R^2 = 0.8249 \]
Overall Correlation

– Average number concentration and mass concentration was calculated for each test run

– Instruments used in the test runs were then correlated based on these average values
Overall Correlations
based on average data of all test runs

EEPS Number Concentration vs. CPC Number Concentration

\[ y = 1.1975x \]

\[ R^2 = 0.9663 \]
Overall Correlations
based on average data of all test runs

EAD Number Concentration vs. CPC Number Concentration

EAD Number Conc. [1/cm³] = EAD Diam. Conc [mm/cm³] x 2.85E4 mm⁻¹

y = 0.999x
R² = 0.9663
Overall Correlations
based on average data of all test runs

EAD Mass Concentration vs. EEPS Mass Concentration

EAD Mass Conc. [mg/m³] = EAD Diam. Conc [mm/cm³] x 0.0102 (mg/m³)/(mm/cm³)

y = 0.9901x
R² = 0.9874
Overall Correlations
based on average data of all test runs

EEPS Mass Concentration vs. AVL MSS Soot Concentration

\[ y = 0.7706x \]
\[ R^2 = 0.9453 \]
Overall Correlations
based on average data of all test runs

EAD Mass Concentration vs. AVL MSS Soot Concentration

EAD Mass Conc. [mg/m³] = EAD Diam. Conc [mm/cm³] x 0.0102 (mg/m³)/(mm/cm³)

\[ y = 0.7758x \]

\[ R^2 = 0.9784 \]
Overall Correlations
based on average data of all test runs

DustTrak Mass Concentration vs. EEPS Mass Concentration

\[ y = 0.9889x \]
\[ R^2 = 0.9431 \]

DustTrak Diesel Soot Mass Conc. [mg/m³] = ISO-dust Mass Conc [mg/m³] \times 2.11 \frac{mg_{\text{Diesel Soot}}}{mg_{\text{ISO-dust}}}
## Overall Correlations

<table>
<thead>
<tr>
<th>$R^2$</th>
<th>Number Concentration</th>
<th>Mass Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CPC</td>
<td>EEPS</td>
</tr>
<tr>
<td>CPC</td>
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<td>0.966</td>
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<tr>
<td>EEPS</td>
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<td>-</td>
</tr>
<tr>
<td>EAD</td>
<td>-</td>
<td>-</td>
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<tr>
<td>DustTrak</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
<tr>
<td>AVL MSS</td>
<td>N.A.</td>
<td>N.A.</td>
</tr>
</tbody>
</table>
Conclusions – Particle Number

• Considering the applied high dilution, CPC, EEPS and EAD demonstrated the necessary sensitivity and dynamic concentration range for particle number measurements.
• Particle number correlations were good for CPC vs EEPS and CPC vs EAD, respectively.
• For the typically stable soot size distributions, EAD can be calibrated for number measurement.
Conclusions – Particle Mass

- Considering the applied high dilution, EEPS, EAD and MSS demonstrated the necessary sensitivity and dynamic concentration range for particle mass measurements
- Particle mass correlations were acceptable for MSS vs EEPS and MSS vs EAD, respectively
- For the typically stable soot size distributions, EAD can be calibrated for mass measurement
- DustTrak measurements were strongly influenced by relatively small changes in particle size distribution
The End

Thank you very much for your attention!

Questions?