Title: Multi-instrumental Assessment of Various Filter Media in Diesel Exhaust under Transient conditions

Abstract: (min. 300 - max 500 words)

As different Diesel Particulate Filter (DPF) designs and media are becoming widely adopted research efforts on characterization of their influence on the particle emissions intensifies. In the present work the influence of a Diesel Oxidation Catalyst (DOC) and five different Diesel Particulate Filters (DPFs) under steady and transient engine operating conditions on the particulate and gaseous emissions of a common-rail diesel engine has been studied. An array of particle measuring instrumentation (SMPS, EEPS, ELPI, CPC, DC, PAS) has been employed, all measuring at the same time from the engine exhaust. Each instrument measures a different characteristic/metric of the diesel particles (mobility size distribution, aerodynamic size distribution, total number, total surface, active surface,...) and their combination assists in building a complete characterization of the particle emissions at the various measurement locations: engine out, DOC out and DPF out. The results provide useful guidelines for selection of various filter media and measuring methodologies. In the presentation among other themes to be discussed are the inter-comparison of SMPS and EEPS measurements which are found to exhibit small but systematic differences, the evolution of the collection efficiency of each filter medium (evaluated with respect to each of the characteristic metrics measured by each instrument) under steady state and transient conditions as a function of soot load of the filter and the particle emissions during filter regeneration.

Short CV:

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Multi-instrumental Assessment of Various Filter Media in Diesel Exhaust under Transient Conditions

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• Steady state tests: instrument comparison

• Transient tests:
  ➢ instrument comparison
  ➢ assessment of transient filtration efficiency as function of soot load

• Concluding Remarks
PARTICLE MEASUREMENT SYSTEMS EMPLOYED

- SMPS (TSI Long DMA and Ultrafine CPC model No. 3025)
- Standalone CPC (TSI Model No. 3022)
- EEPS
  All 3 measuring from an in-house 3-stage heated diluter
- ELPI
  Measuring from a DEKATI 2-stage heated diluter
- NANOMET (PAS & DC)
  Measuring from a MATTER ENG. rotary heated diluter
Common rail, 1.9 L Diesel Engine, rated at 80 HP

### Steady state points

<table>
<thead>
<tr>
<th>Engine point</th>
<th>Speed, rpm</th>
<th>BMEP, bar</th>
<th>Soot mass concentration, mg/m³</th>
<th>Exhaust mass flow, kg/h</th>
<th>Exhaust temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1500</td>
<td>3</td>
<td>50.2</td>
<td>75</td>
<td>259</td>
</tr>
<tr>
<td>2</td>
<td>1500</td>
<td>4</td>
<td>70.0</td>
<td>77</td>
<td>292</td>
</tr>
<tr>
<td>3</td>
<td>1500</td>
<td>5</td>
<td>59.3</td>
<td>86</td>
<td>327</td>
</tr>
<tr>
<td>4</td>
<td>2350</td>
<td>3.8</td>
<td>25.4</td>
<td>126</td>
<td>307</td>
</tr>
<tr>
<td>5</td>
<td>2250</td>
<td>6.7</td>
<td>25.9</td>
<td>157</td>
<td>381</td>
</tr>
<tr>
<td>6</td>
<td>2450</td>
<td>8.8</td>
<td>35.0</td>
<td>207</td>
<td>448</td>
</tr>
<tr>
<td>7</td>
<td>2500</td>
<td>5</td>
<td>28.4</td>
<td>153</td>
<td>348</td>
</tr>
<tr>
<td>8</td>
<td>1700</td>
<td>5.5</td>
<td>62.8</td>
<td>104</td>
<td>351</td>
</tr>
</tbody>
</table>

Transient cycle NEDC
## DPFs studied

<table>
<thead>
<tr>
<th>DPF</th>
<th>Type / Material</th>
<th>Dimensions (in)</th>
<th>Filtration area (m²)</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Non-oxide ceramic wall-flow monolith</td>
<td>5.66x6</td>
<td>1.90</td>
<td>42</td>
</tr>
<tr>
<td>2</td>
<td>High porosity oxide ceramic wall-flow monolith</td>
<td>5.66x6</td>
<td>2.00</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>Standard porosity wall-flow monolith</td>
<td>5.66x6</td>
<td>1.13</td>
<td>48</td>
</tr>
<tr>
<td>4</td>
<td>Coarse grain non-oxide ceramic wall-flow monolith</td>
<td>5.66x8.4</td>
<td>1.70</td>
<td>42</td>
</tr>
<tr>
<td>5</td>
<td>Fibrous filter</td>
<td>5 x 3</td>
<td>0.08</td>
<td>85</td>
</tr>
</tbody>
</table>
Engine out - Soot concentration vs. PAS
Engine point: 2250 rpm, 6.7 bar, Engine OUT

Engine out

![Graph showing particle distribution as a function of diameter (Dp) for Engine point: 2250 rpm, 6.7 bar, Engine OUT. The graph compares EEPS and SMPS data.]
Engine point: 2450 rpm, 8.8 bar, Engine OUT
Engine point: 2500 rpm, 5 bar, Engine OUT
Engine point: 1700 rpm, 5.5 bar, Engine OUT

The graph shows the distribution of particle number concentration (dN/dlogDp) in #/cm³ as a function of particle diameter (Dp in nm). The blue line represents EEPS and the red line represents SMPS.

Key:
- dN/dlogDp: Particle number concentration
- Dp: Particle diameter in nm
- EEPS: Electrical Low Pressure Impactor
- SMPS: Scanning Mobility Particle Sizer

The y-axis represents the logarithmic scale of particle number concentration, and the x-axis represents the particle diameter in a logarithmic scale from 10 to 1000 nm.
Engine point: 1500rpm, 3 bar, DOC OUT

DOC out

EEPS

SMPS

\( \frac{dN}{d\log D_p} \) (#/cm\(^3\))

\( D_p \) (nm)
Engine point: 1500 rpm, 4 bar, DOC OUT

![Graph showing distribution of particle number concentration (N/dlogDp) vs. diameter (Dp) for EEPS and SMPS methods. The graph illustrates the comparison of particle size distributions at different particle diameters (nm). The EEPS method shows a higher peak compared to the SMPS method, indicating a higher concentration of particles at smaller diameters.]
Engine point: 2350 rpm, 3.8 bar, DOC OUT

DOC out

Engine point: 2350 rpm, 3.8 bar, DOC OUT

Graph showing the distribution of particulate matter (PM) as a function of diameter (Dp) with units of diameter normalized logarithm (dN/dlogDp) and concentration in number per cubic centimeter (#/cm³). The graph compares EEPS and SMPS measurements.
Engine point: 2250 rpm, 6.7 bar, DOC OUT

- EEPS
- SMPS
Engine point: 2450 rpm, 8.8 bar, DOC OUT

![Graph showing particle size distribution](image-url)

**Axes:***
- **Dp (nm)**
- **dN/dlogDp (#/cm³)**

**Legend:**
- **EEPS**
- **SMPS**
Engine point: 2500 rpm, 5 bar, DOC OUT

The graph shows the distribution of particles (dN/logDp in #/cm³) as a function of particle diameter (Dp in nm) for two different measurement techniques: EEPS (blue line) and SMPS (red line). The data peaks at around 100 nm, with EEPS showing slightly higher particle counts at this size compared to SMPS.
Engine point: 1700 rpm, 5.5 bar, DOC OUT

![Graph showing particle distribution](image-url)

- **dN/d\logD_p (#/cm^3)**
- **D_p (nm)**

**Legend:**
- **EEPS**
- **SMPS**
y = 1.13x

R^2 = 0.95
DOC out - Total Concentration (#/cm³) - SMPS vs CPC

\[ y = 0.88x \]

\[ R^2 = 0.85 \]
**DOC out - Total Concentration (#/ cm³) - ELPI vs SMPS**

- Equation: \( y = 0.5376x \)
- \( R^2 = 0.6274 \)
DOC out - Total Concentration (#/cm³) - ELPI vs EEPS

\[ y = 0.4044x \]

\[ R^2 = 0.7612 \]
DOC out - Total Concentration (#/cm³) - SMPS vs DC

\[ y = 0.0031x \]

\[ R^2 = 0.6944 \]
DOC out - Total Concentration (#/cm³) - SMPS vs PAS

\[ y = 0.0023x \]

\[ R^2 = 0.8753 \]
DOC out - Total Concentration (#/cm^3) - ELPI vs DC

\[ y = 170.83x \]

\[ R^2 = 0.5164 \]
DOC out - Total Concentration (#/ cm³) - ELPI vs PAS

\[ y = 233.23x \]
\[ R^2 = 0.5765 \]
$y = 1.4396x$

$R^2 = 0.9951$
DOC out – PAS/DC ratio

PAS/DC (fA/um²/cm³)

Exhaust temperature (°C)
Engine out - PAS/DC ratio

PAS/DC (fA/μm²/cm³) vs. Exhaust temperature (°C)
DPF-out Size Distribution Evolution at Steady State Engine Point

SMPS

ELPI

EEPS
Filtration Efficiency at Steady State Engine Point
Filtration Efficiency at Steady State Engine Point

- Filtration efficiency (-)
  - FE - ELPI
  - FE-SMPS
  - FE-PAS
  - FE-DC
  - FE-CPC
  - FE-EEPS

- Pressure drop (mbar)

Challenge mass load (g/m²)
NEDC CYCLE

Engine Speed (rpm)

Engine Torque (Nm)

Time (s)

Eng Spd

Eng Trq
DOC out - PAS/DC ratio

Steady state data
Effect of DOC- Total Concentration (#/cm$^3$) - ELPI

![Graph showing particle concentration over time for Engine out and DOC out.](image)

- **Y-axis:** Particle concentration (#/cm$^3$)
- **X-axis:** Time (s)

Lines indicate:
- **Pink line:** Engine out
- **Blue line:** DOC out
Effect of DOC - Total Concentration (#/cm³) - EEPS

- Engine out
- DOC out

Particle concentration (#/cm³) vs. Time (s)
NEDC - Total Concentration (#/cm³) - EEPS vs. ELPI

![Graph showing total concentration over time for EEPS and ELPI](image-url)
NEDC - Pressure drop and Challenge Mass Load

DPF No. 4

1st cycle

2nd cycle

Time (s)

Pressure drop (mbar)

Challenge Mass Load (g/m²)
NEDC– EEPS size distribution evolution

DPF No. 4

\[ \frac{dN}{d\log Dp} \text{ (#/cm}^3 \text{)} \]

\[ \ln Dp \text{ (nm)} \]

\[ \text{Time (sec)} \]

[3D graph showing the evolution of particle size distribution]
NEDC– CPC Filtration Efficiency vs. Mass Load

DPF No. 4

Challenge mass load (g/m²)

Particle Concentration (#/cm³)

Filtration efficiency (-)

Upstream

Downstream

Filtration efficiency
NEDC- Filtration Efficiency vs. Mass Load

DPF No. 4

Filtration efficiency vs. Challenge mass load (g/m²)

Legend:
- EEPS
- ELPI
- CPC
NEDC–EEPS size distribution evolution

DPF No. 5

dN/d\ln Dp (#/cm^3)

Time (sec)

lnDp (nm)
NEDC– Filtration Efficiency vs. Mass Load

DPF No. 5

Challenge mass load (g/m²)

Filtration efficiency

0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

0 1 02 03 04 05 06

CPC

0 10 20 30 40 50 60

Challenge mass load (g/m²)
NEDC- Filtration Efficiency vs. Mass Load

DPF No. 5

Filtration efficiency vs. Challenge mass load (g/m²) for DPF No. 5 with data from ELPI and CPC.
NEDC- Filtration Efficiency vs. Mass Load

DPF No. 5

Filtration efficiency

Challenge mass load (g/m²)

ELPI
EEPS
CPC
NEDC– EEPS size distribution evolution

DPF No. 1
NEDC- Filtration Efficiency vs. Mass Load

DPF No. 1

Filtration efficiency vs. challenge mass load (g/m²)

- CPC
- ELPI
- EEPS
NEDC– EEPS size distribution evolution

DPF No. 3
NEDC - Filtration Efficiency vs. Mass Load

DPF No. 3

Challenge mass load (g/m²)

Filtration efficiency

- CPC
- EEPS
- ELPI
Step A lasted 4000 s. During this step a NOx assisted partial filter regeneration occurred. At time=4000 s, fuel was injected upstream of the DOC at a constant rate of 15 g/min. This raised the filter inlet temperature to 720°C. This step lasted for 1100 s and led to a complete filter regeneration (Step B). The fuel injection continued for 100 s more, but at a smaller fuel injection rate (10 g/min; step C). Further fuel injections were performed in following steps (steps E and G).
The filter soot mass load has been calculated with an in-house developed mathematical model which takes into consideration the exhaust conditions, ΔP, filter geometry and soot microstructural properties.

**Step A:** FE is high because the filter is loaded with soot.

**Step B:** FE is decreased to 0.89 (fast regeneration-clean filter).

**Step C:** FE is decreased initially due to temperature decrease. Then starts increasing again (from 0.87 to 0.92) with soot accumulation.

**Step D:** FE initially decreases due to temperature further decrease and then increases as soot accumulates in the filter. Noticeably, it remains constant after a short period at approximately 0.91 because at these conditions no further soot is stored into the filter (CRT® effect).

**Step E:** FE is increased to 0.97 because temperature is increased to 635°C.

**Step F:** FE is again decreased due to temperature decrease.

**Step G:** FE is again increased to 0.97 (due to temperature increase) and then decreases as soot is oxidized.
$\sigma_g = \exp\left(\frac{1}{D_f(2b(D_f)+1)}\ln\left(4 + \frac{2}{q}\right)\right)^{0.5}
$

Konstandopoulos and Kostoglou (2006)
On the $\sigma_g$ of diesel particle size distributions

- 5 engines (1 Euro II, rest Euro III) with engine displacement 1.9-2.4 l
- 35 operating points 3 CR systems with different calibrations

<table>
<thead>
<tr>
<th>Fuel Injection System</th>
<th>$\sigma_g$</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common Rail-1</td>
<td>1.88</td>
<td>± 0.09</td>
</tr>
<tr>
<td>Common Rail-2</td>
<td>1.94</td>
<td>± 0.09</td>
</tr>
<tr>
<td>Common Rail-3</td>
<td>1.86</td>
<td>± 0.15</td>
</tr>
<tr>
<td>Pump Unit Injector</td>
<td>1.90</td>
<td>± 0.14</td>
</tr>
<tr>
<td>Rotary Pump</td>
<td>1.85</td>
<td>± 0.04</td>
</tr>
<tr>
<td>Average</td>
<td>1.89</td>
<td>± 0.08</td>
</tr>
</tbody>
</table>

Including Harris & Maricq’s data the average is 1.84 +/- 0.08 (ie 4%)  

$D_f = 2.4$  
For random binary fragmentation

Konstandopoulos & Kostoglou (2003)
Continuous, binary random fragmentation process with size dependent rate:

\[ S_i = A i^{b(D_f)} = A i^{aD^n_f} = A i^{1/D_f} \]

Fragmentation kernel

\[ C_{i,j} = 2/(j-1) \]

Coagulation kernel (continuum)

\[ B_{i,j} = B_0 (i^{-1/D_f} + j^{-1/D_f})(i^{1/D_f} + j^{1/D_f}) \]
Oxidative fragmentation population dynamics explains all available $\sigma_g$ of diesel particle size distributions

Data: Virtanen et al. (2004)
Theory: This work
Small but systematic differences were found between SMPS and EEPS size distributions under steady state conditions.

Total number concentration between SMPS, CPC and EEPS agrees to within 15% - 30%. ELPI correlates with all instruments but measures lower total concentration.

SMPS, CPC and ELPI correlate linearly with PAS and DC.

PAS/DC ratio decreases across a DOC in a temperature dependent fashion.

CPC, ELPI and EEPS used during transient cycles to measure the filtration efficiency (on a number basis) of various DPF media do not always give the same result, with the CPC being the most noiseless and EEPS the most noisy.
CPC, ELPI and EEPS can pick reduced filtration efficiency events during the transient cycle due to high filtration velocities. These events are diminishing with soot load increase in the filter.

In some higher porosity DPFs blow-off can be observed over the transient cycle, although not all instruments show it to the same extent.

A methodology for measuring the filtration efficiency during regeneration as a function of soot load in the filter was developed.

Our current work focuses on

- Application of the oxidative-fragmentation population dynamics and the extraction of the evolution of the particle morphology during the transient cycle, as we have already reported in the past for steady state tests.
- Extending our transient filtration models to describe mechanistically particle migration in the filter and blow-off
ACKNOWLEDGEMENTS

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- Our APT Lab colleagues