EFFECT OF ENGINE-OUT NOX CONTROL STRATEGIES ON PM SIZE DISTRIBUTION IN 2010-COMPLIANT HDDE

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SUMMARY

The wide range of exhaust conditions typical of a diesel engine operation and the temporary deactivation of the selective catalytic reduction (SCR) device due to malfunction require engagement of multiple engine-out calibrations in order to maintain the design performance of the aftertreatment system. However, the use of different calibrations leads to entirely different engine-out emission levels and different exhaust oxidation conditions; hence, different levels of urea injected and soot loading of the diesel particulate filter (DPF). Therefore, particles emitted by a 2010 emission compliant engine are expected to differ in composition, size and morphology while all along meeting the particulate matter (PM) gravimetric limits. The relationship between the DPF penetration pattern and the engine-out PM distribution, and the effects of different urea injection strategies on PM mass, composition and distribution have been reported in literature. This study instead investigates the correlation between SCR-out/engine-out PM when an 11-liter Volvo engine is programmed with multiple calibrations. In particular, this work focuses on three aspects of this correlation: particle concentration and size distributions, PM composition and PM morphology.

Two different PM size-distributions were generated over a single mode in the accumulation mode region with the aid of an original tool, obtained by using statistical techniques and design of experiment. The two engine-out distributions were found to correlate closely with the SCR-out distributions. Images at the Transmission Electron Microscopy (TEM) revealed particles very different in morphology from soot agglomerates typical of diesel combustion and further analyses at the Scanning Electron Microscope (SEM) were conducted to identify their elemental composition. Drops in the DPF fractional efficiency have been measured with the Scanning Mobility Particle Sizer (SMPS) for certain steady state modes of the European Stationary Cycle (ESC). The DPF fractional efficiency, as opposed to the traditional gravimetric measurement, captures the DPF filtration performance across the whole size spectrum of PM emissions. Measurement of particle number and distribution were conducted under transient cycles as well with a Differential Mobility Spectrometer (DMS) since studies have shown that for these conditions the largest number of particles could be emitted in regions of the accumulation mode where the DPF is least efficient. Ion Chromatograph analysis on gravimetric filters at the SCR-out has revealed the presence of sulfates, whose level was found to be dependent upon the different calibrations engaged. Further analysis was conducted on the gravimetric filters to identify the presence of products of urea decomposition and ammonia compounds.
The two typical aspects of the diesel PM distribution, nuclei mode and accumulation mode particles, were investigated with two size-specific sampling measurement systems: an ejector diluter, with hot first dilution stage, and the legislated constant volume sampler (CVS) coupled with a mini dilution tunnel, at variable residence time and dilution ratios.

A correlation was found in the accumulation mode region between the different combustion strategies to optimize the aftertreatment performance for the 2010 emission limits and the particles detected downstream of the SCR. The morphology of the sampled particles was observed to be very different from the agglomerated particles, typically found in diesel engine exhaust streams. The SEM analysis exhibited a shining crystalline shape and the ion chromatography analysis revealed the presence of sulfates. The exhaust aftertreatment system tested over transient conditions did not reveal any drop in the filtration efficiency, with minimal PM concentrations downstream of the SCR for different engine calibrations.

The PM concentrations and size distributions in the nucleation region, downstream of the SCR, were found to be dependent by the engine calibrations for a high load mode (Mode 6) of the ESC cycle. The fuel efficient calibration (low-FC) produced SCR-out particles smaller than those generated by the EGR-based calibration (low-NOx). For both calibrations, the number of nanoparticles emitted was higher than the engine-out concentrations. This was found to be true for the high load - high exhaust temperature mode; hence, these particles were most likely nucleated particles derived from sulfates generated by the DOC. It was also found that, for this mode, the DPF enhanced the nucleation, and that the SCR increased the number and size of nanoparticles in the exhaust stream; this may be attributed to byproducts of urea decomposition.

![PM Characterization for Different Calibrations (Mode 6)](image)

Figure 1: Engine-out/SCR-out correlation in the nuclei mode region (single mode)
EFFECT OF ENGINE-OUT NOx CONTROL STRATEGIES ON PM SIZE DISTRIBUTIONS IN HEAVY-DUTY DIESEL ENGINES DEVELOPED FOR 2010

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Department of Mechanical and Aerospace Engineering, West Virginia University

Matt Miyasato and Adewale Oshinuga

South Coast Air Quality Management District
Outline

• Hypothesis
• Objective
• Experimental setup
• Approach
  – Technique for engine calibration
  – Characterization of SCR-out particles morphology and distribution for different engine calibrations
• Results
  – Accumulation Mode Particles – Steady State and Transient
  – Nucleation Mode Particles – Steady State and Transient
• Conclusion
Hypothesis

• The different combustion strategies developed to optimize exhaust aftertreatment systems for in-use operation significantly affect characteristics of particulate matter (PM) emissions.

• Different engine calibrations will affect SCR-out PM characteristics.
Objectives

- To investigate the impact of engine-out PM emissions on SCR-out PM concentrations and size distributions for steady state and transient modes of engine operation.

- To investigate the effect of engine calibrations on SCR-out PM characteristics.
Experimental Set up: Accumulation Mode PM

1st Stage Dilution
- Ejector Diluter
- Dilution Air Temperature: 150 - 180°C
- Residence Time: ~0.6s
- Dilution Ratio: => 24

2nd Stage Dilution
- Ejector Diluter
- Dilution Air Temperature: 16°C +/-2°C
- Relative Humidity: Dry Air
- Residence Time: => ~0.6s
- Dilution Ratio: => 11
Experimental Set up: Nucleation Mode PM

<table>
<thead>
<tr>
<th>1st Stage Dilution</th>
<th>2nd Stage Dilution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CVS</td>
<td>Ejector Diluter</td>
</tr>
<tr>
<td>Dilution Air Temperature</td>
<td>Dilution Air Temperature</td>
</tr>
<tr>
<td>30°C +/-5°C</td>
<td>24°C +/-3°C</td>
</tr>
<tr>
<td>Dilution Air Relative Humidity</td>
<td>Dilution Air Relative Humidity</td>
</tr>
<tr>
<td>38 - 40%</td>
<td>Dry Air</td>
</tr>
<tr>
<td>Residence Time</td>
<td>Residence Time</td>
</tr>
<tr>
<td>1.3s</td>
<td>2.0s</td>
</tr>
<tr>
<td>Dilution Ratio</td>
<td>Dilution Ratio</td>
</tr>
<tr>
<td>Mode 6 =&gt; 5 / Mode 9 =&gt; 9</td>
<td>24</td>
</tr>
</tbody>
</table>
Experimental Set up: 2007 Compliant Engine

VOLVO MY07 MD11

Engine Output: 339 hp @ 1800 / 1298 lb-ft @ 1306 rpm

- High injection pressure (2400bar)
- High exhaust gas recirculation rate
- Variable geometric turbocharger
Experimental Set up: Aftertreatment for 2010

DPF system

- The DPF is a compact saver Fleetgard equipped with DOC, temperature and pressure sensors
- A seventh injector is available for active regeneration

SCR System

- SCR manufactured by Johnson Matthey.
- Urea pump equipped with independent controller based on urea, NO₂/NO ratio, exhaust temperature maps.

Catalyst Substrate
Approach: Engine Calibration

- Mode selection (ESC, AVL8)
- Implementation of strategy
- Optimization with ANOVA tool
- Generation of engine maps (LowNOx / LowFC)
Approach: Accumulation Mode Testing

- Effect of different engine calibrations (Low-NOx and Low-FC) on PM distribution over steady state and transient testing

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Low-FC</th>
<th>Baseline</th>
<th>Low-NOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine-Out</td>
<td>ESC with DMS/SMPS</td>
<td>FTP/ESC with DMS/SMPS</td>
<td>FTP/ESC with DMS/SMPS</td>
</tr>
<tr>
<td>DPF-Out</td>
<td>ESC with DMS/SMPS</td>
<td>FTP/ESC with DMS/SMPS</td>
<td>FTP/ESC with DMS/SMPS</td>
</tr>
<tr>
<td>SCR-Out</td>
<td>ESC with DMS/SMPS</td>
<td>FTP/ESC with DMS/SMPS</td>
<td>FTP/ESC with DMS/SMPS</td>
</tr>
</tbody>
</table>

- Effect of different engine calibrations (Low-NOx and Low-FC) on PM distribution and morphology over single mode (Low-D, High-D)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Low-D</th>
<th>High-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine-Out</td>
<td>SMPS/SEM</td>
<td>SMPS/SEM</td>
</tr>
<tr>
<td>DPF-Out</td>
<td>SMPS/SEM</td>
<td>SMPS/SEM</td>
</tr>
<tr>
<td>SCR-Out</td>
<td>SMPS/SEM</td>
<td>SMPS/SEM</td>
</tr>
</tbody>
</table>
**Approach:** Nucleation Mode Testing

- Effect of different engine calibrations on PM size distributions over steady state and transient cycles

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Calibration</th>
<th>Test Type</th>
<th>Sampling instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Out</td>
<td>Baseline</td>
<td>FTP / ESC</td>
<td>DMS</td>
</tr>
<tr>
<td></td>
<td>LowNOx</td>
<td></td>
<td>Gravimetric TPM</td>
</tr>
<tr>
<td></td>
<td>LowFC</td>
<td></td>
<td>Gaseous Emissions</td>
</tr>
<tr>
<td>DPF Out</td>
<td>LowNOx</td>
<td>FTP / ESC</td>
<td>DMS</td>
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<tr>
<td></td>
<td>LowFC</td>
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<td>Gravimetric TPM</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Gaseous Emissions</td>
</tr>
<tr>
<td>SCR Out</td>
<td>LowNOx</td>
<td>FTP / ESC</td>
<td>DMS</td>
</tr>
<tr>
<td></td>
<td>LowFC</td>
<td></td>
<td>Gravimetric TPM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gaseous Emissions</td>
</tr>
</tbody>
</table>

- More accurate measurement of PM distributions over two selected steady state modes to investigate PM count, size and morphology

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<thead>
<tr>
<th>Configuration</th>
<th>Calibration</th>
<th>Test Type</th>
<th>Sampling instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Out</td>
<td>Baseline</td>
<td>ESC Mode 6 (1249rpm / 1006ft-lb)</td>
<td>SMPS</td>
</tr>
<tr>
<td>DPF Out</td>
<td>LowNOx</td>
<td>ESC Mode 6 (1249rpm / 1006ft-lb)</td>
<td>SEM</td>
</tr>
<tr>
<td>SCR Out</td>
<td>LowNOx</td>
<td>ESC Mode 6 (1249rpm / 1006ft-lb)</td>
<td>Gravimetric TPM</td>
</tr>
<tr>
<td></td>
<td>LowFC</td>
<td>ESC Mode 9 (1513rpm / 302ft-lb)</td>
<td>Gaseous Emissions</td>
</tr>
</tbody>
</table>
Results: Engine-out / DPF-out - Steady State

Accumulation Mode PM

PM Characterization for Different Calibrations (ESC Mode 4)

Baseline Engine-Out
Baseline DPF-Out
LowNOx Engine-Out
LowNOx DPF-Out

SMPS
DR = 264
**Results:** DPF Fractional Efficiency - Steady State

Accumulation Mode PM

DPF Fractional Efficiency (ESC Mode 4)

- Baseline
- LowNOx

Steady State Accumulation Mode PM

<table>
<thead>
<tr>
<th>Fractional Efficiency [%]</th>
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</thead>
<tbody>
<tr>
<td>100%</td>
</tr>
<tr>
<td>95%</td>
</tr>
<tr>
<td>90%</td>
</tr>
<tr>
<td>85%</td>
</tr>
<tr>
<td>80%</td>
</tr>
<tr>
<td>75%</td>
</tr>
<tr>
<td>70%</td>
</tr>
<tr>
<td>65%</td>
</tr>
<tr>
<td>60%</td>
</tr>
<tr>
<td>55%</td>
</tr>
<tr>
<td>50%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Particle Diameter Dp [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
</tr>
<tr>
<td>50</td>
</tr>
<tr>
<td>70</td>
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<tr>
<td>90</td>
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<tr>
<td>110</td>
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<tr>
<td>130</td>
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<tr>
<td>150</td>
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<tr>
<td>170</td>
</tr>
<tr>
<td>190</td>
</tr>
<tr>
<td>210</td>
</tr>
<tr>
<td>230</td>
</tr>
</tbody>
</table>

SMPS

DR = 264
Results: Overall fractional efficiency - Steady State
Accumulation Mode PM

DPF & SCR Fractional Efficiency (ESC Mode 4)

Fractional Efficiency [%]

95% 90% 85% 80% 75% 70% 65% 60% 55% 50%

Particle Diameter Dp [nm]

30 50 70 90 110 130 150 170 190 210 230

Low NOx
Low FC

DMS
DR = 264
Results: Correlation between Engine-out Distribution
Single Mode - Accumulation Mode PM

Particle Size Distribution for different calibrations
(ESC Mode 5)

<table>
<thead>
<tr>
<th>Mode (ESC)</th>
<th>Speed [rpm]</th>
<th>Torque [ft-lb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1249</td>
<td>670</td>
</tr>
</tbody>
</table>

Dilution Ratio:
DMS => DR = 264
SMPS => DR = 264

- LowNOx Engine-Out (DMS)
- LowFC Engine-Out (DMS)
- High D Engine-Out (SMPS)
- Low D Engine-Out (SMPS)
Results: Engine-out / SCR-out Correlation

Single Mode - Accumulation Mode PM

Particle Size Distribution for two engine settings

- **High Dp**
  - 88.2 nm
  - 82.0 nm

- **Low Dp**
  - 42.9 nm
  - 54.3 nm

**Dilution Ratio:**
- Engine-Out => DR = 264
- SCR-Out => DR = 24

**SMPS**

West Virginia University
South Coast Air Quality Management District (AQMD)
Results: Chemical Analysis of Gravimetric Filter

Steady State - Accumulation Mode PM

- Ion Chromatography analysis of gravimetric PM filters for the Low-NOx engine calibration over a ESC cycle

<table>
<thead>
<tr>
<th>Sample position</th>
<th>Sulfates [µg/filter]</th>
<th>Nitrates [µg/filter]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine out</td>
<td>0.0</td>
<td>0.9</td>
</tr>
<tr>
<td>DPF out</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>SCR out</td>
<td>1.6</td>
<td>0.4</td>
</tr>
<tr>
<td>SCR out aggressive urea map</td>
<td>20.9</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Results: Engine-out / SCR-out Correlation

Transient Cycle - Accumulation Mode PM

Average Particle Concentration during FTP-Cycle
Engine-Out/SCR-Out

Particle Diameter Dp [nm]

dlogN/dlogDp [#/cm^3]

LowNOx - Engine-Out
LowNOx - SCR-Out

DMS
DR = 264

West Virginia University
South Coast AQMD
Results: Overall Fractional Efficiency - Transient Accumulation Mode PM

DPF & SCR Fractional Efficiency during FTP-Cycle

Fractional Efficiency [%]

Particle Diameter Dp [nm]

LowNOx

DMS DR = 264
Results: Effect of Aftertreatment Components
Single Mode - Nucleation Mode PM

PM Characterization LowFC (Mode 6)

- Engine Out
- DPF Out
- SCR Out

Results:
Effect of Aftertreatment Components
Single Mode
Nucleation Mode PM
Results: Engine-out / SCR-out Correlation

Single Mode - Nucleation Mode PM

PM Characterization for Different Calibrations (Mode 6)
Conclusions

Accumulation-mode

• No drop in DPF filtration efficiency was found for both steady state and transient conditions in the accumulation-mode region

• A correlation was found between engine-out and SCR-out PM distributions was found for single mode testing

Nucleation-mode

• The DPF was found to enhance the formation of nucleation mode particles for high load (high T) modes. For the same load conditions the SCR increased the particle number and mean diameter

• A correlation was found between engine-out and SCR-out PM distributions for high load (high T) conditions for steady state testing
Conclusions

• High concentrations of nanoparticle emission was observed from HDD engines, while all along meeting the 2010 mass-based PM emission limits

• The impact of the different combustion strategies employed to optimize the aftertreatment performance on PM distribution and morphology cannot be neglected
Acknowledgements

- South Coast Air Quality Management District
- Volvo Powertrain
- California Air Resource Board
- U.S. Department of Energy