12th ETH-Conference on Combustion Generated Nanoparticles
Zurich, Switzerland
June 23rd -25th 2008

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.

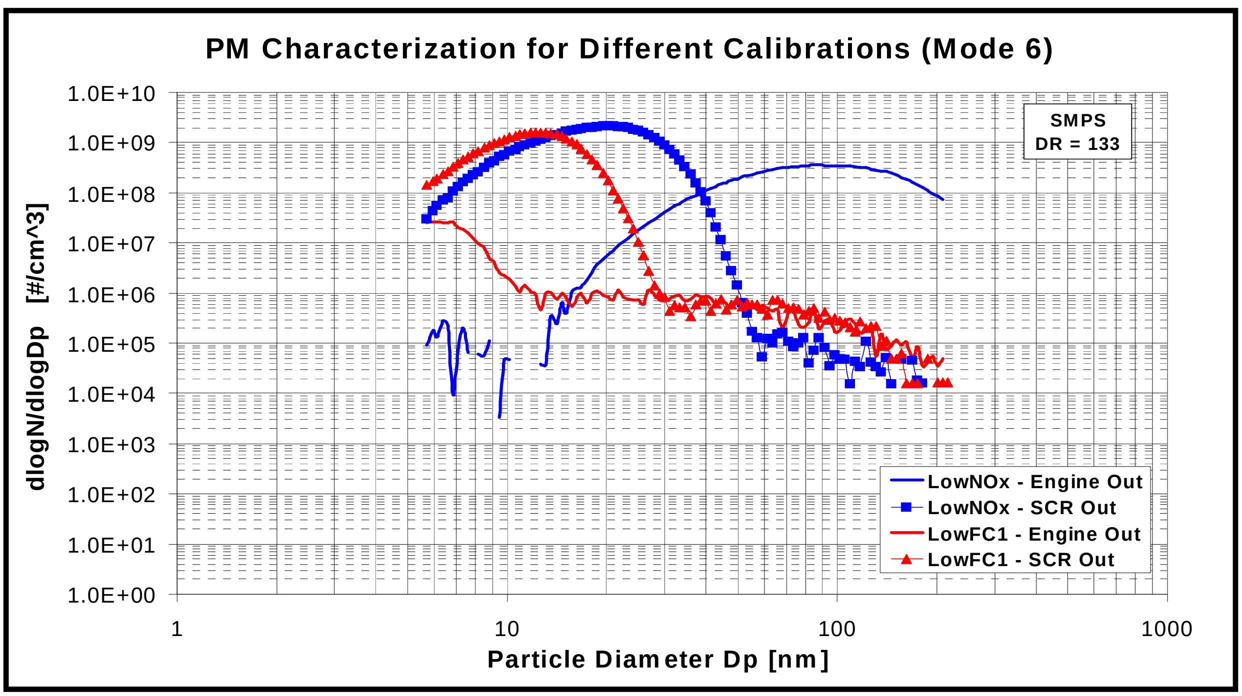

Figure 1: Engine-out/SCR-out correlation in the nuclei mode region (single mode)

EFFECT OF ENGINE-OUT NOx CONTROL STRATEGIES ON PM SIZE DISTRIBUTIONS IN HEAVY-DUTY DIESEL ENGINES DEVELOPED FOR 2010

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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.

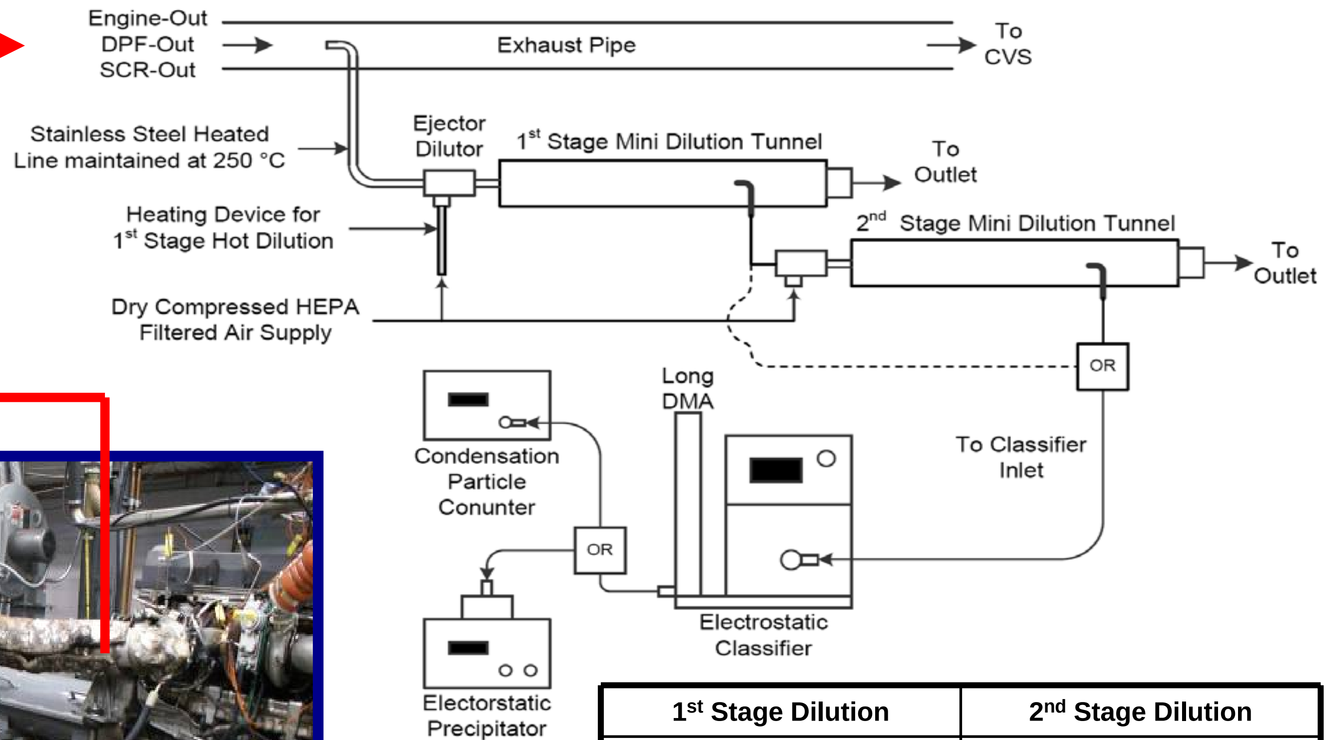
- Different engine calibrations will affect SCR-out PM characteristics.

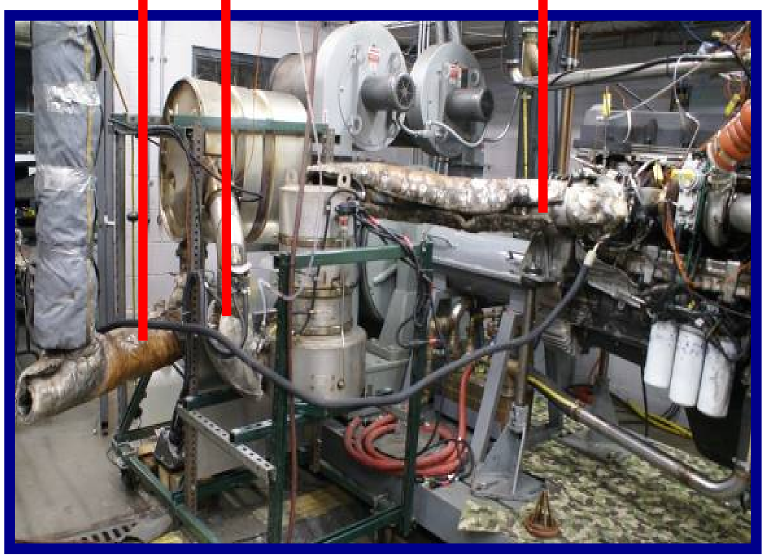
Objectives

- 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

Engine Out





1st Stage Dilution	2nd Stage Dilution
Ejector Diluter	Ejector Diluter
Dilution Air Temperature 150 - 180°C	Dilution Air Temperature 16°C +/-2°C
Relative Humidity Dry Air	Relative Humidity Dry Air
Residence Time => ~0.6s	Residence Time => ~0.6s
Dilution Ratio => 24	Dilution Ratio => 11

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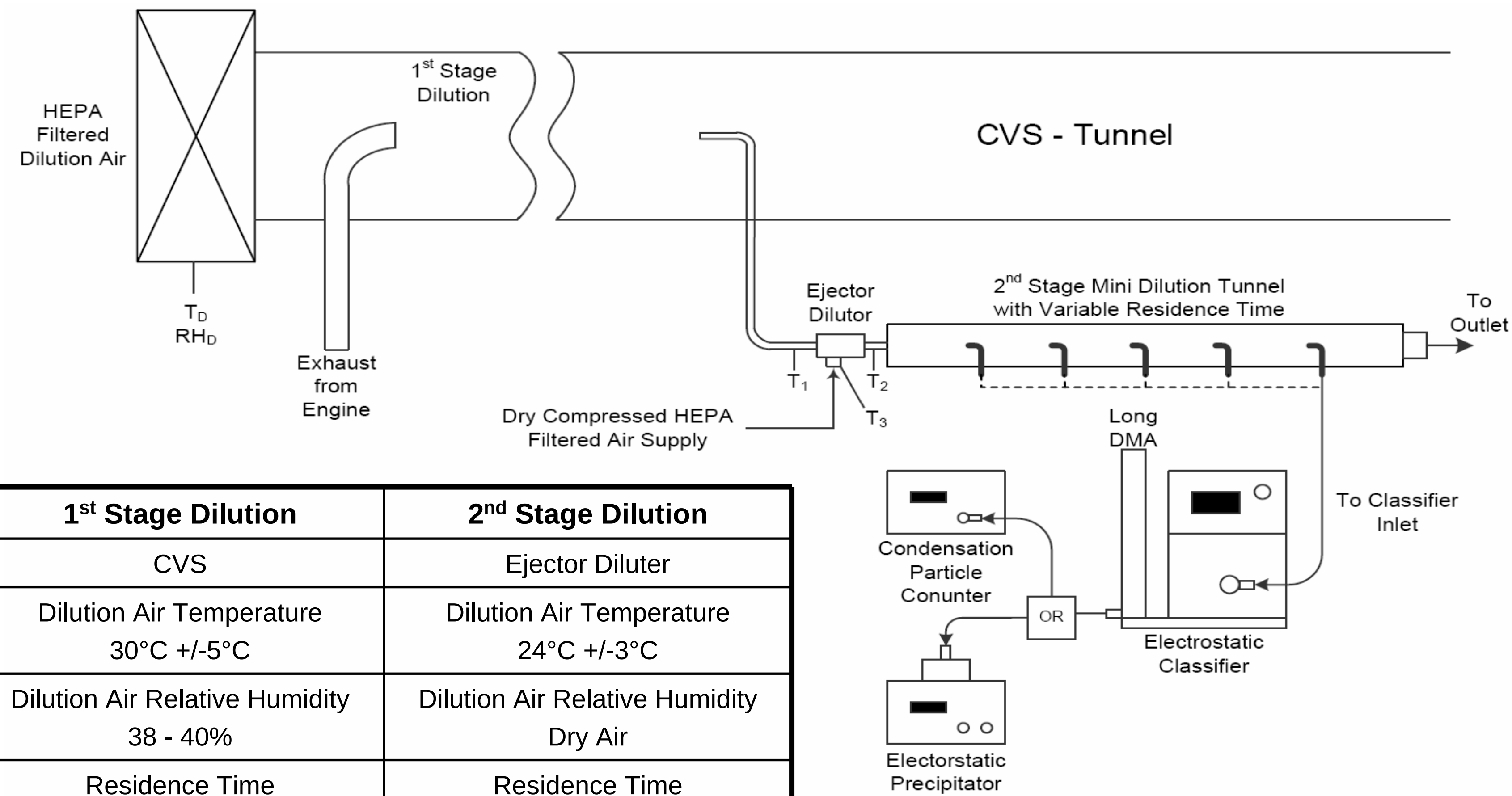
Experimental Set up: Nucleation Mode PM



1st Stage Dilution	2nd Stage Dilution
CVS	Ejector Diluter
Dilution Air Temperature 30°C +/-5°C	Dilution Air Temperature 24°C +/-3°C
Dilution Air Relative Humidity 38 - 40%	Dilution Air Relative Humidity Dry Air
Residence Time 1.3s	Residence Time 2.0s
Dilution Ratio Mode 6 => 5 / Mode 9 => 9	Dilution Ratio 24

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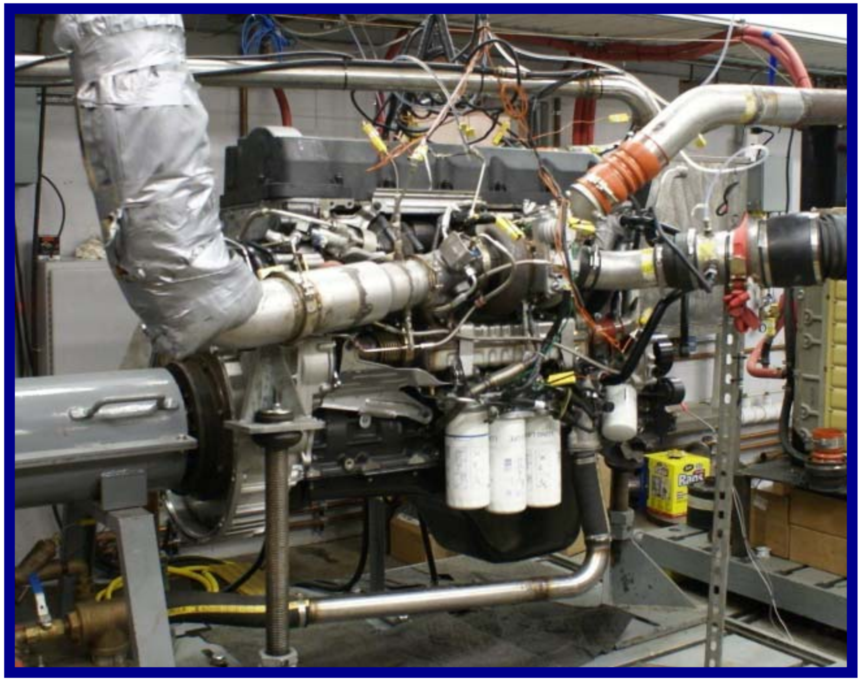
Experimental Set up: 2007 Compliant Engine

VOLVO MY07 MD11

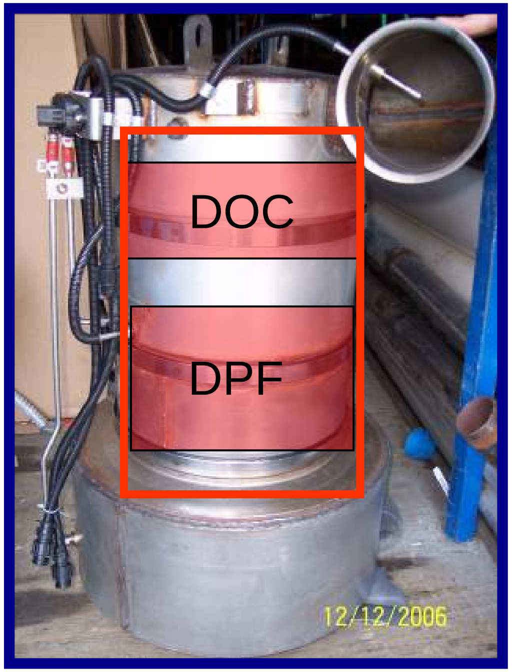
Engine Output: 339 hp @ 1800 / 1298 lb-ft @ 1306 rpm



- 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

Urea injector

SCR System

- SCR manufactured by Johnson Matthey.
- Urea pump equipped with independent controller based on urea, NO_2/NO ratio, exhaust temperature maps.

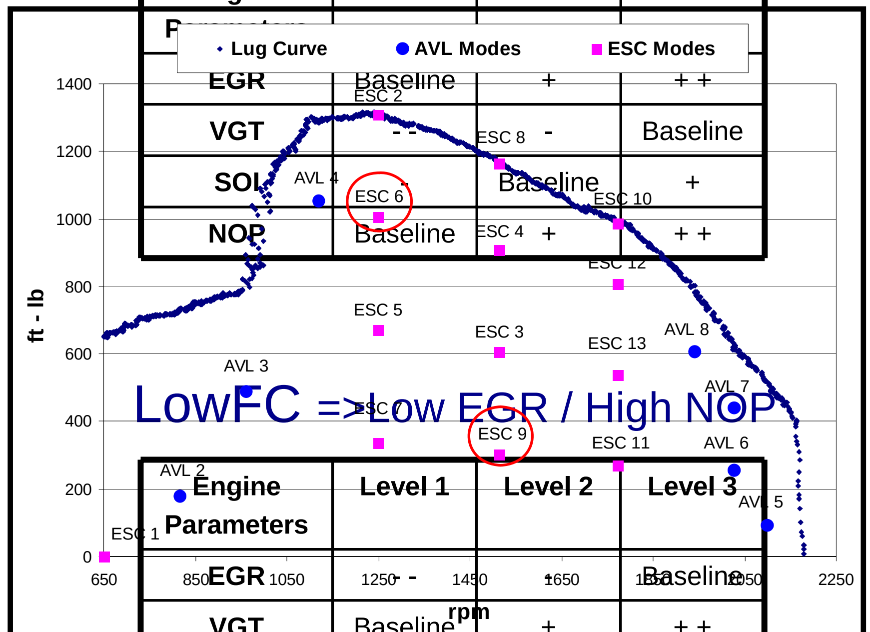
Catalyst Substrate

Approach: Engine Calibration

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

LowNOx =>High EGR / High NOP

Engine Parameters	Level 1	Level 2	Level 3
EGR	Baseline	+	+ +
VGT	- -	-	Baseline
SOI	-	Baseline	+
NOP	Baseline	+	+ +



LowFC =>Low EGR / High NOP

Engine Parameters	Level 1	Level 2	Level 3
EGR	- -	-	Baseline
VGT	Baseline	+	+ +
SOI	Baseline	+	+ +
NOP	Baseline	+	+ +

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Approach: Accumulation Mode Testing

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

Configuration Calibrations

	Low-FC	Baseline	Low-NOx
Engine-Out	ESC with DMS/SMPS	FTP/ESC with DMS/SMPS	FTP/ESC with DMS/SMPS
DPF-Out	ESC with DMS/SMPS	FTP/ESC with DMS/SMPS	FTP/ESC with DMS/SMPS
SCR-Out	ESC with DMS/SMPS	FTP/ESC with DMS/SMPS	FTP/ESC with DMS/SMPS

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

Configuration Calibrations

	Low-D	High-D
Engine-Out	SMPS/SEM	SMPS/SEM
DPF-Out	SMPS/SEM	SMPS/SEM
SCR-Out	SMPS/SEM	SMPS/SEM

Approach: Nucleation Mode Testing

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

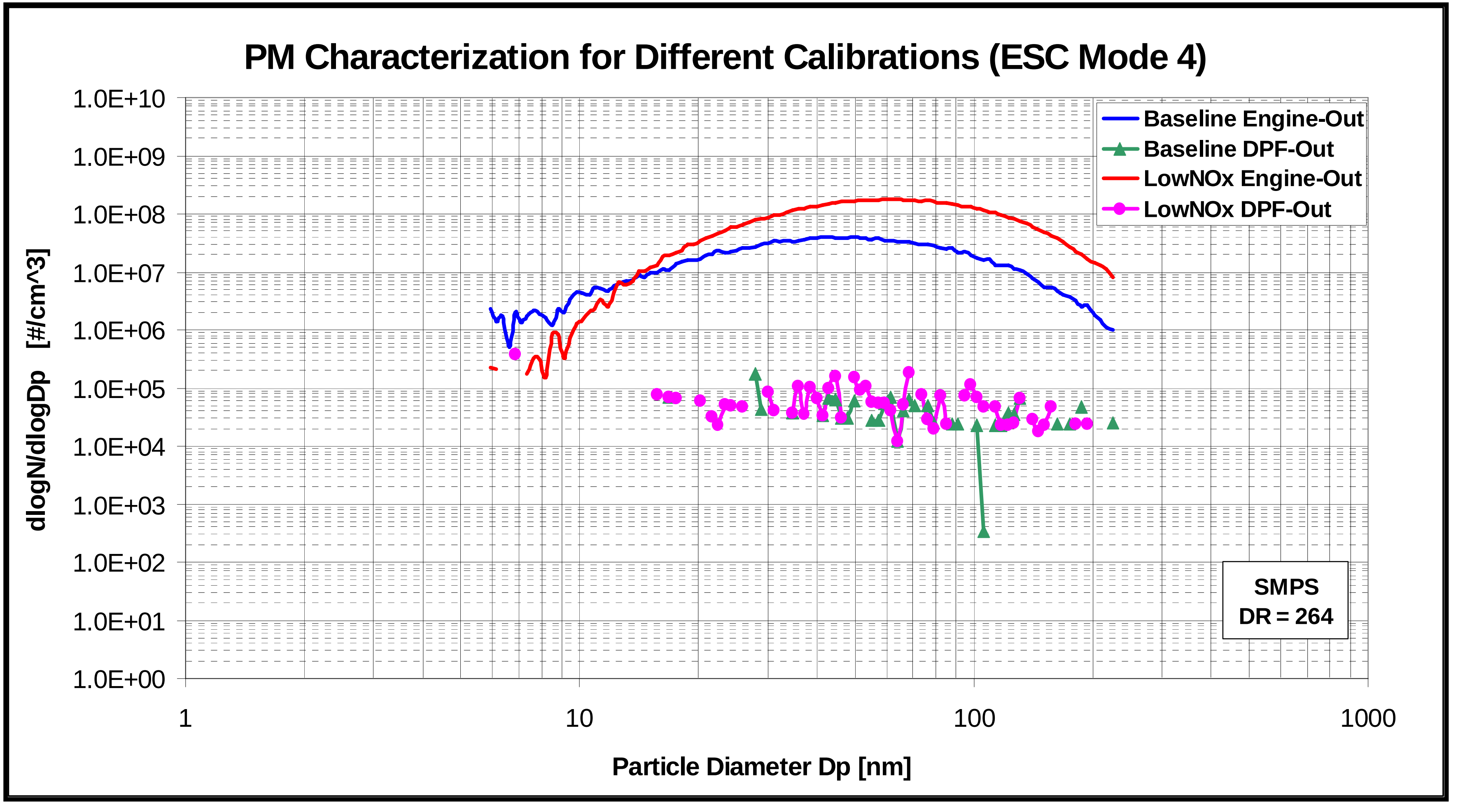
Configuration	Calibration	Test Type	Sampling instrument
Engine Out	Baseline LowNOx LowFC	FTP / ESC	DMS Gravimetric TPM Gaseous Emissions
DPF Out	LowNOx LowFC	FTP / ESC	DMS Gravimetric TPM Gaseous Emissions
SCR Out	LowNOx LowFC	FTP / ESC / ETC	DMS Gravimetric TPM Gaseous Emissions

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

Configuration	Calibration	Test Type	Sampling instrument
Engine Out **DPF Out** **SCR Out**	Baseline LowNOx LowFC	ESC Mode 6 (1249rpm / 1006ft-lb) ESC Mode 9 (1513rpm / 302ft-lb)	SMPS SEM Gravimetric TPM Gaseous Emissions

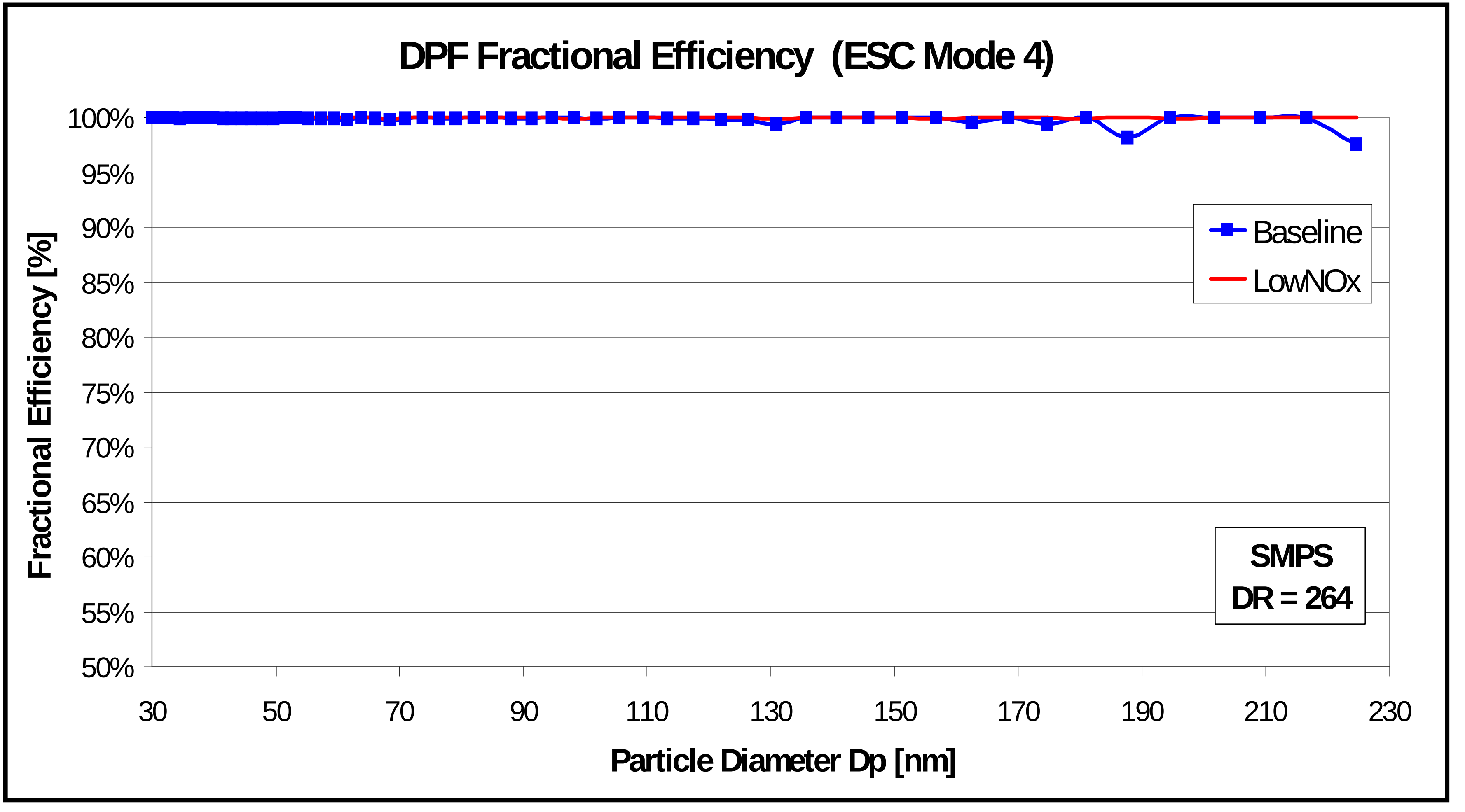
Results: Engine-out / DPF-out - Steady State

Accumulation Mode PM



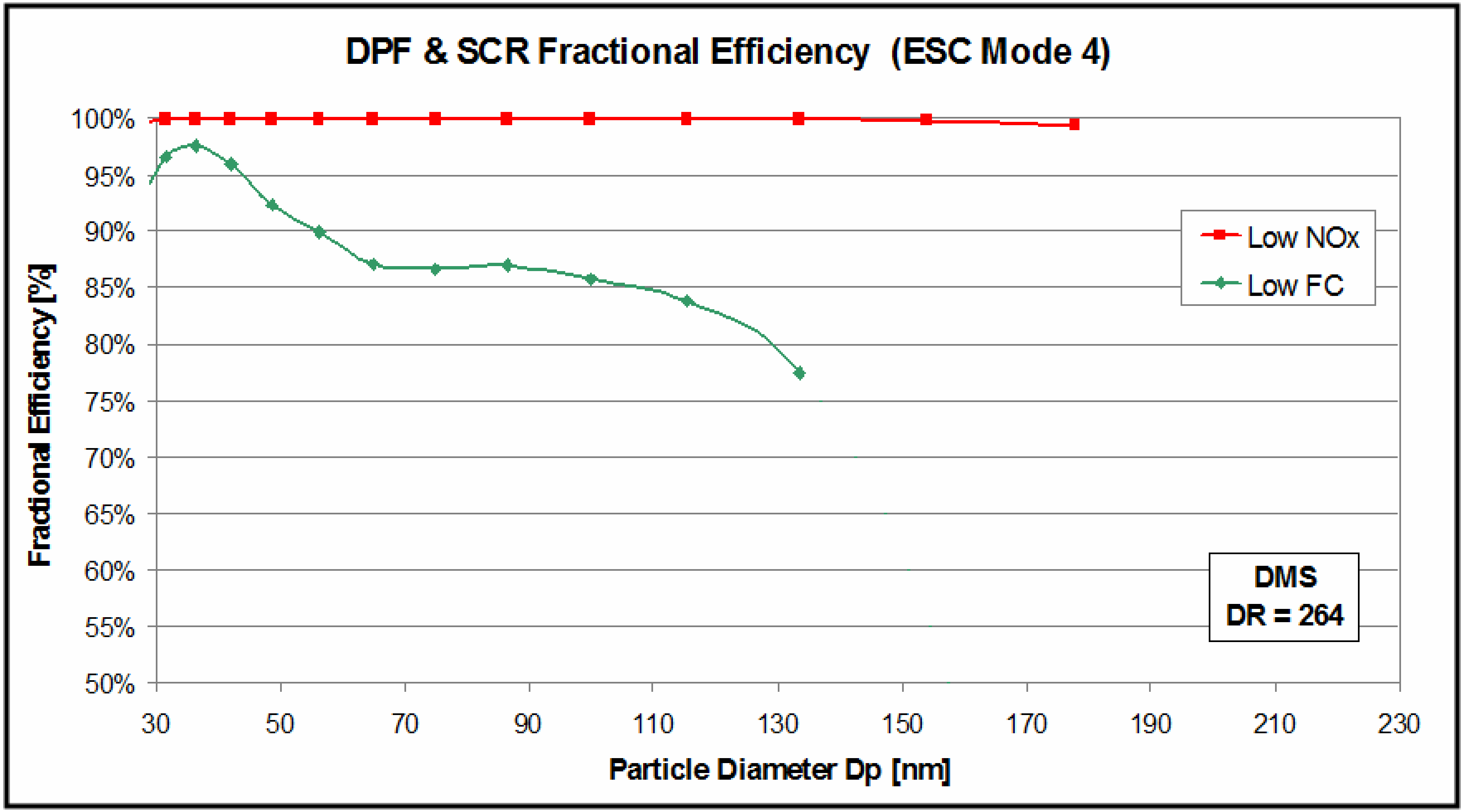
Results: DPF Fractional Efficiency - Steady State

Accumulation Mode PM



Results: Overall fractional efficiency - Steady State

Accumulation Mode PM



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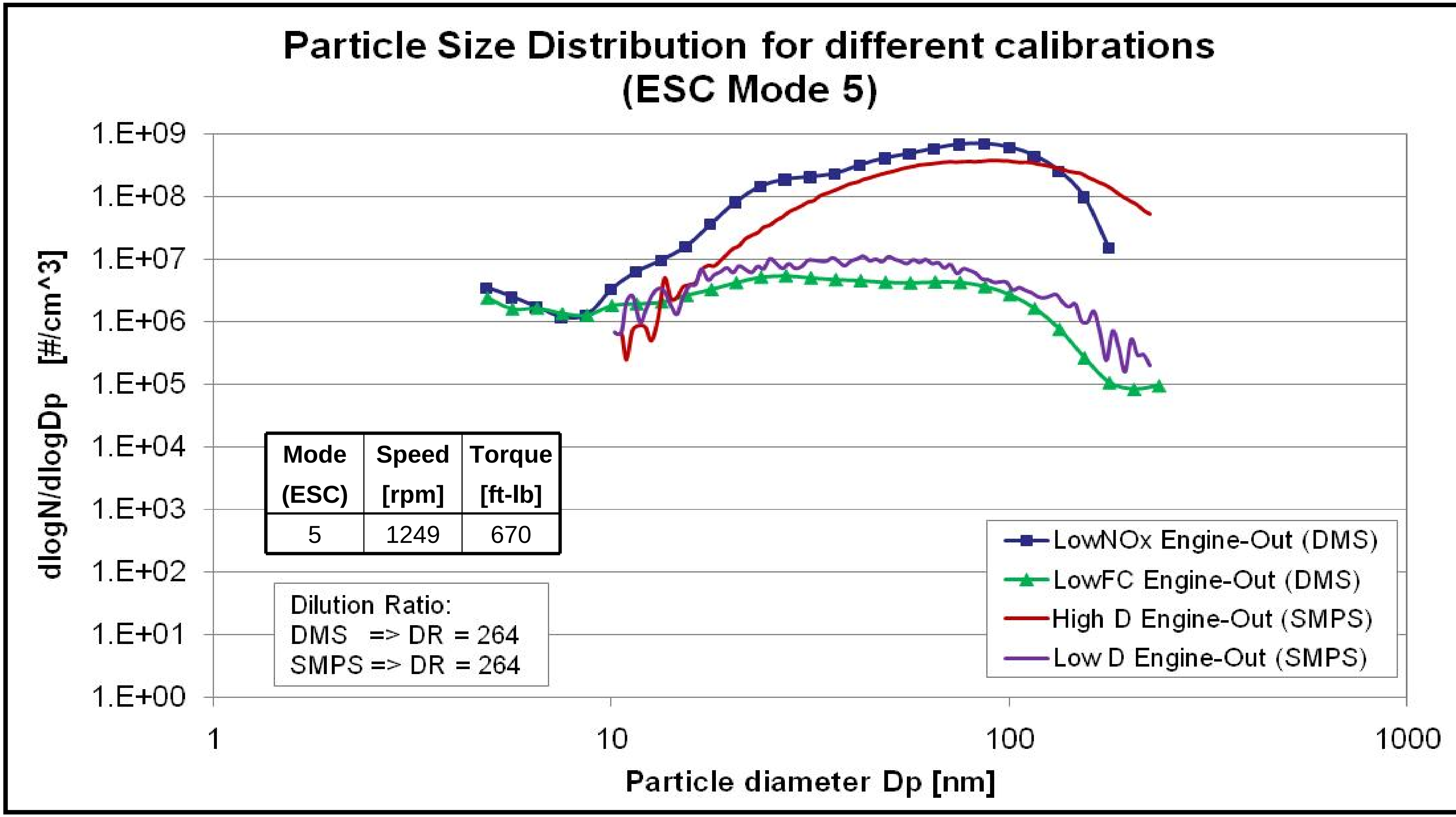
Results: Correlation between Engine-out Distribution

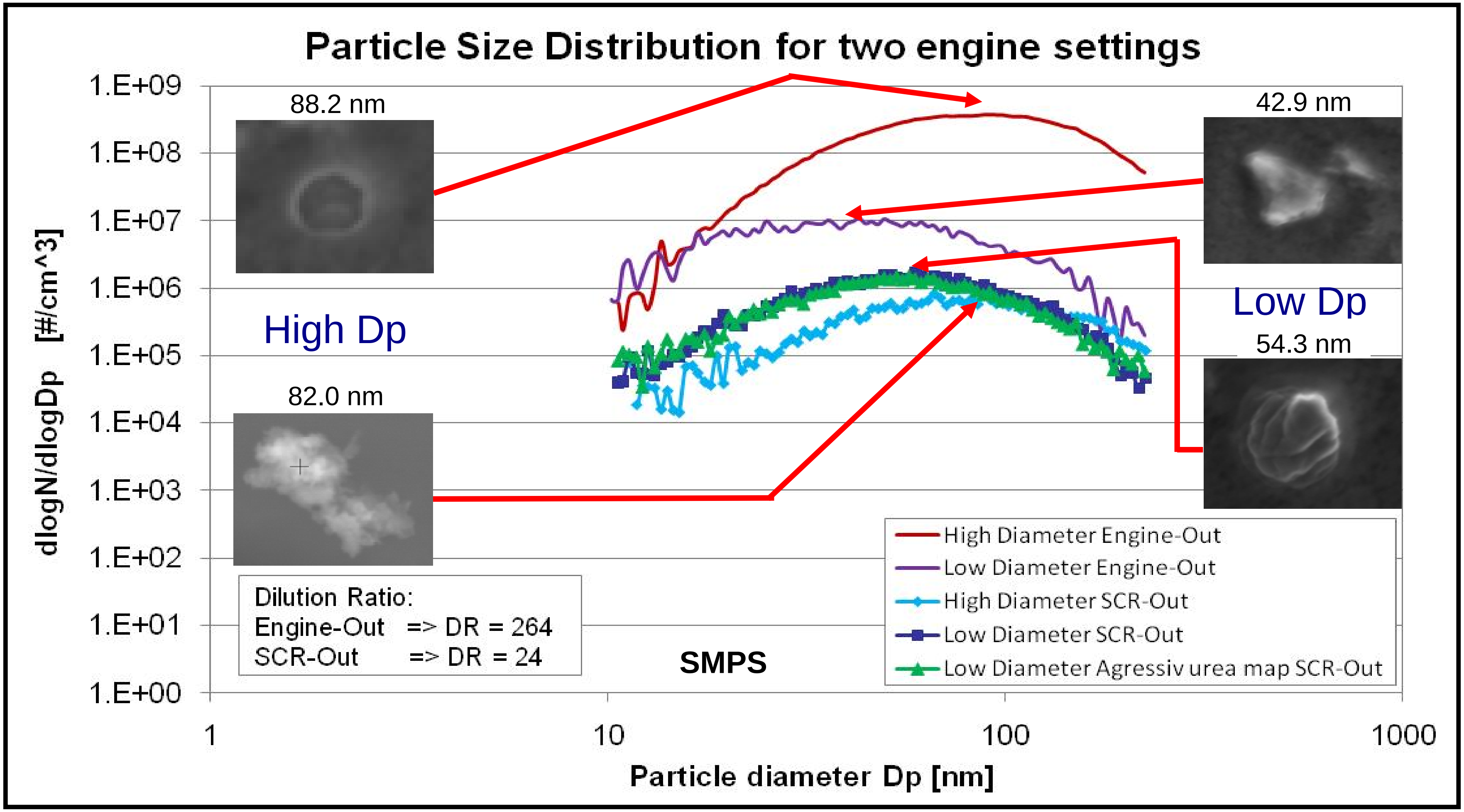
Single Mode - Accumulation Mode PM



Mode (ESC)	Speed [rpm]	Torque [ft-lb]
5	1249	670

Results: Engine-out / SCR-out Correlation

Single Mode - Accumulation Mode PM



Results: Chemical Analysis of Gravimetric Filter

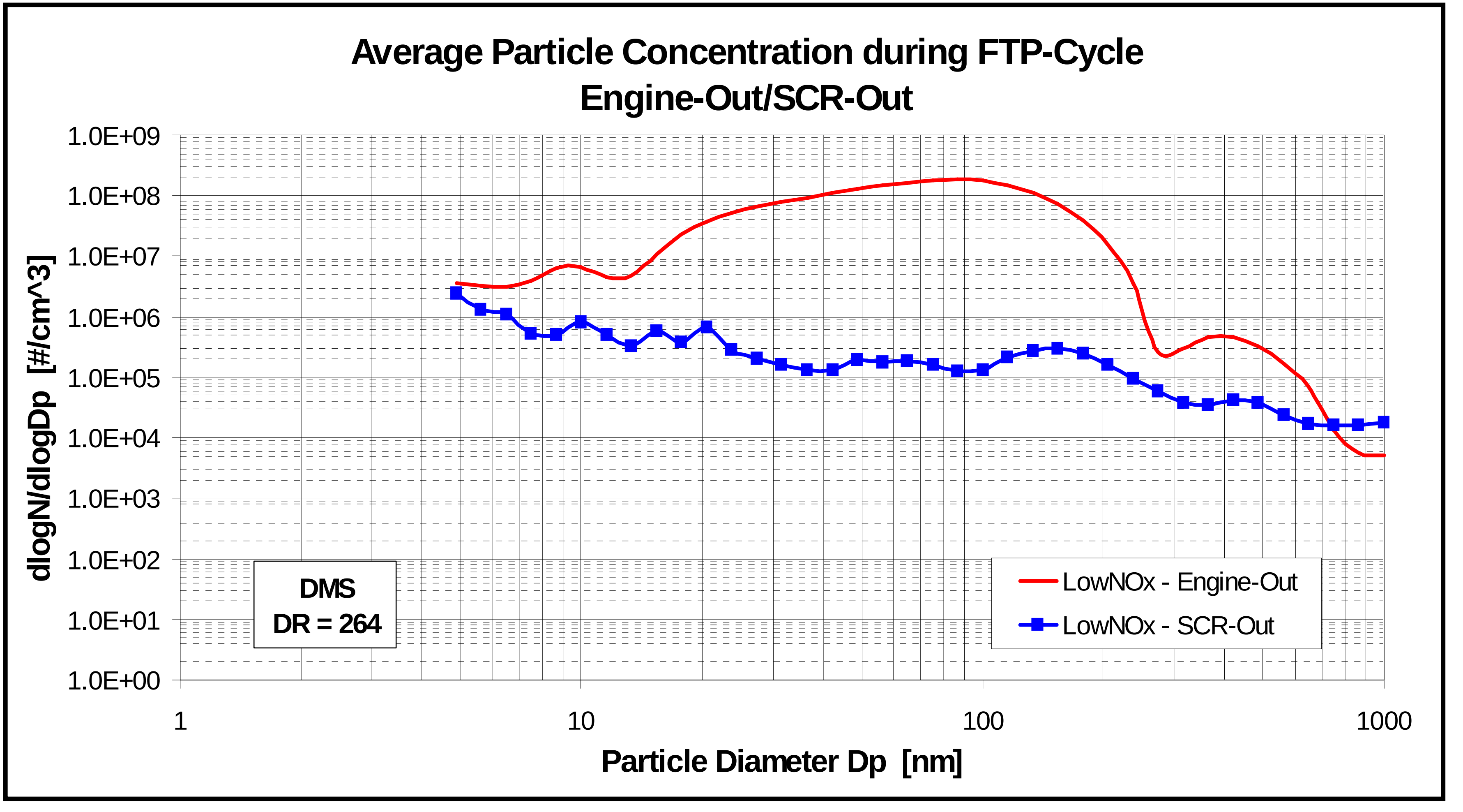
Steady State - Accumulation Mode PM

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

Sample position	Sulfates [µg/filter]	Nitrates [µg/filter]
Engine out	0.0	0.9
DPF out	0.0	0.0
SCR out	1.6	0.4
SCR out aggressive urea map	20.9	0.5

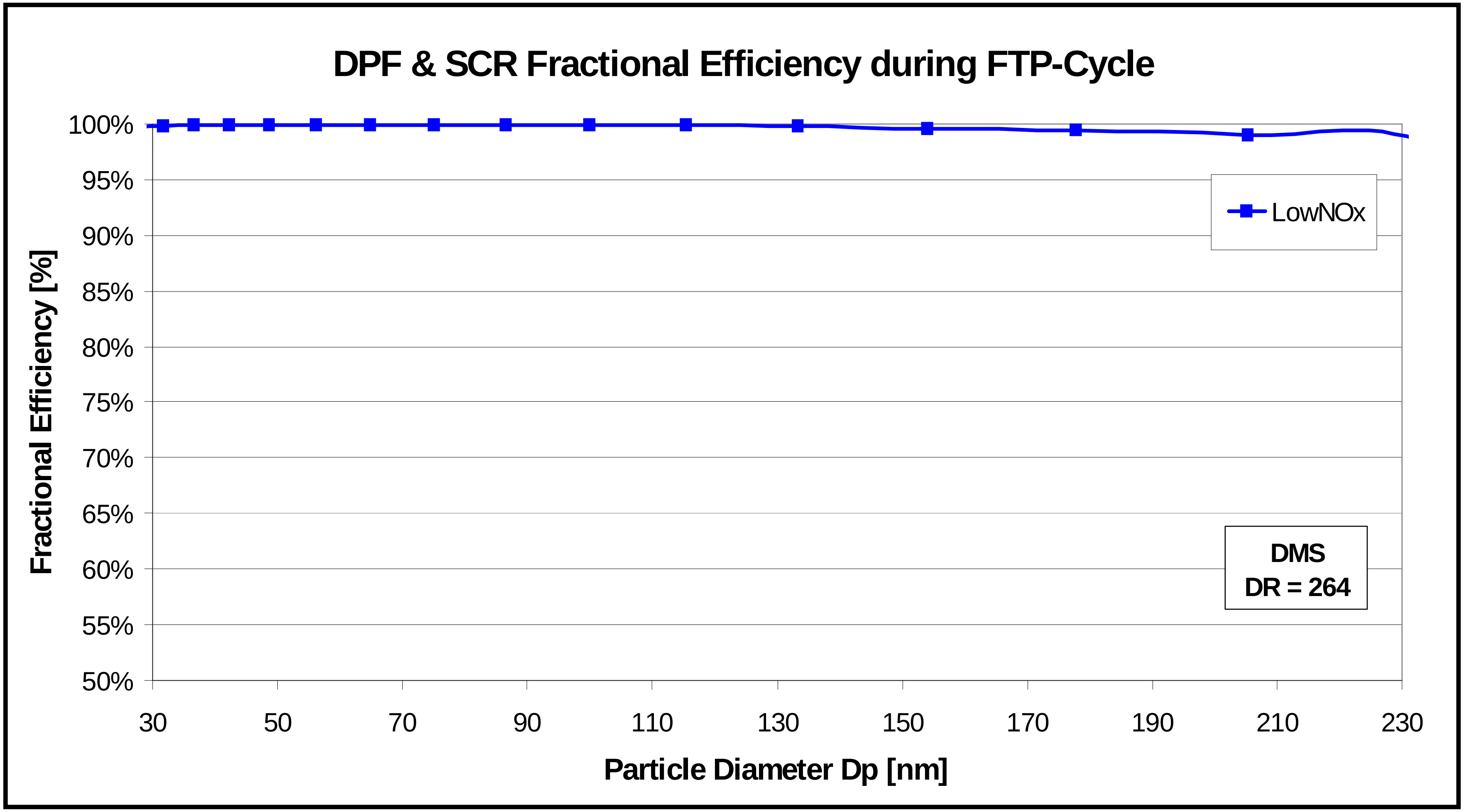
Results: Engine-out / SCR-out Correlation

Transient Cycle - Accumulation Mode PM



Results: Overall Fractional Efficiency - Transient

Accumulation Mode PM



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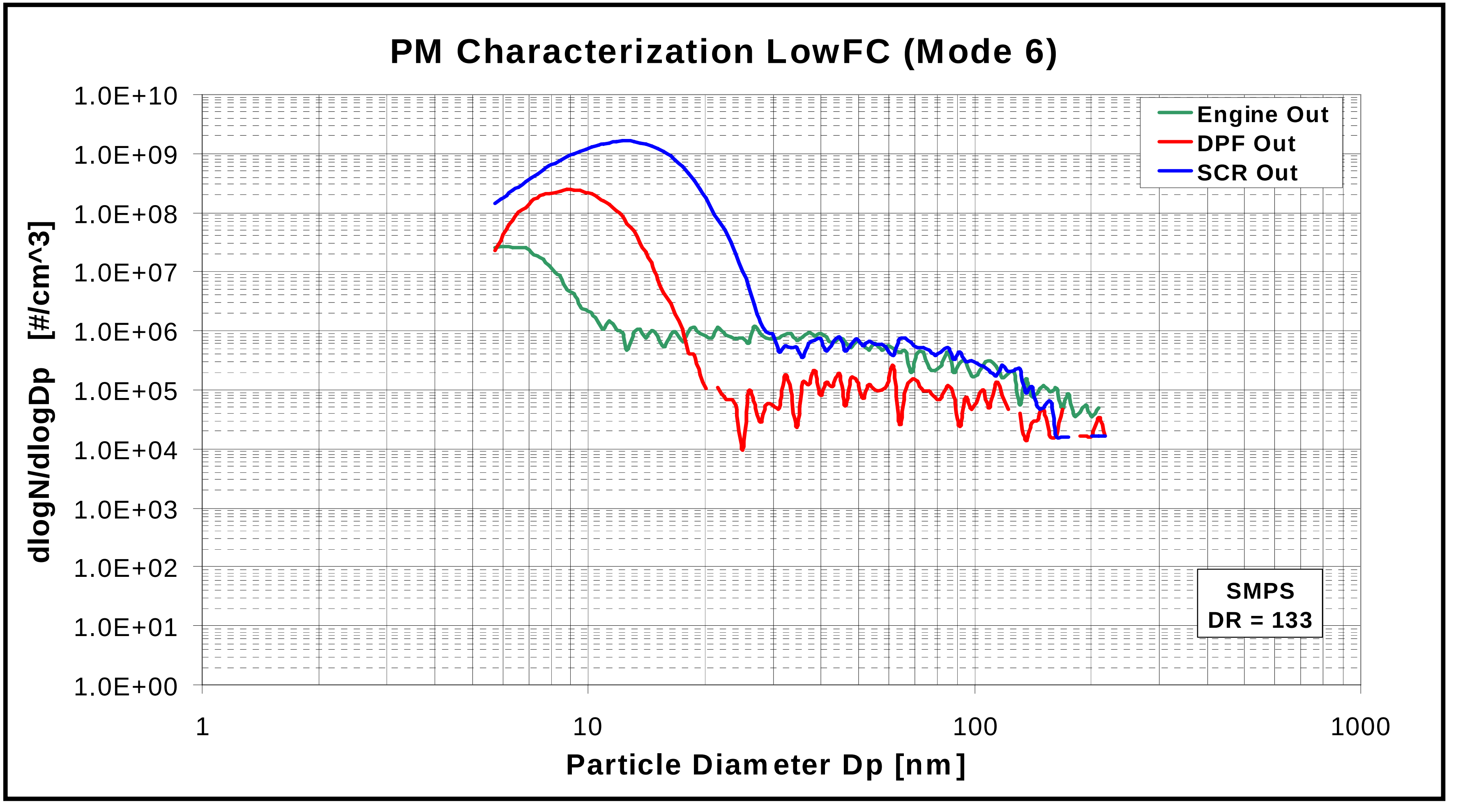
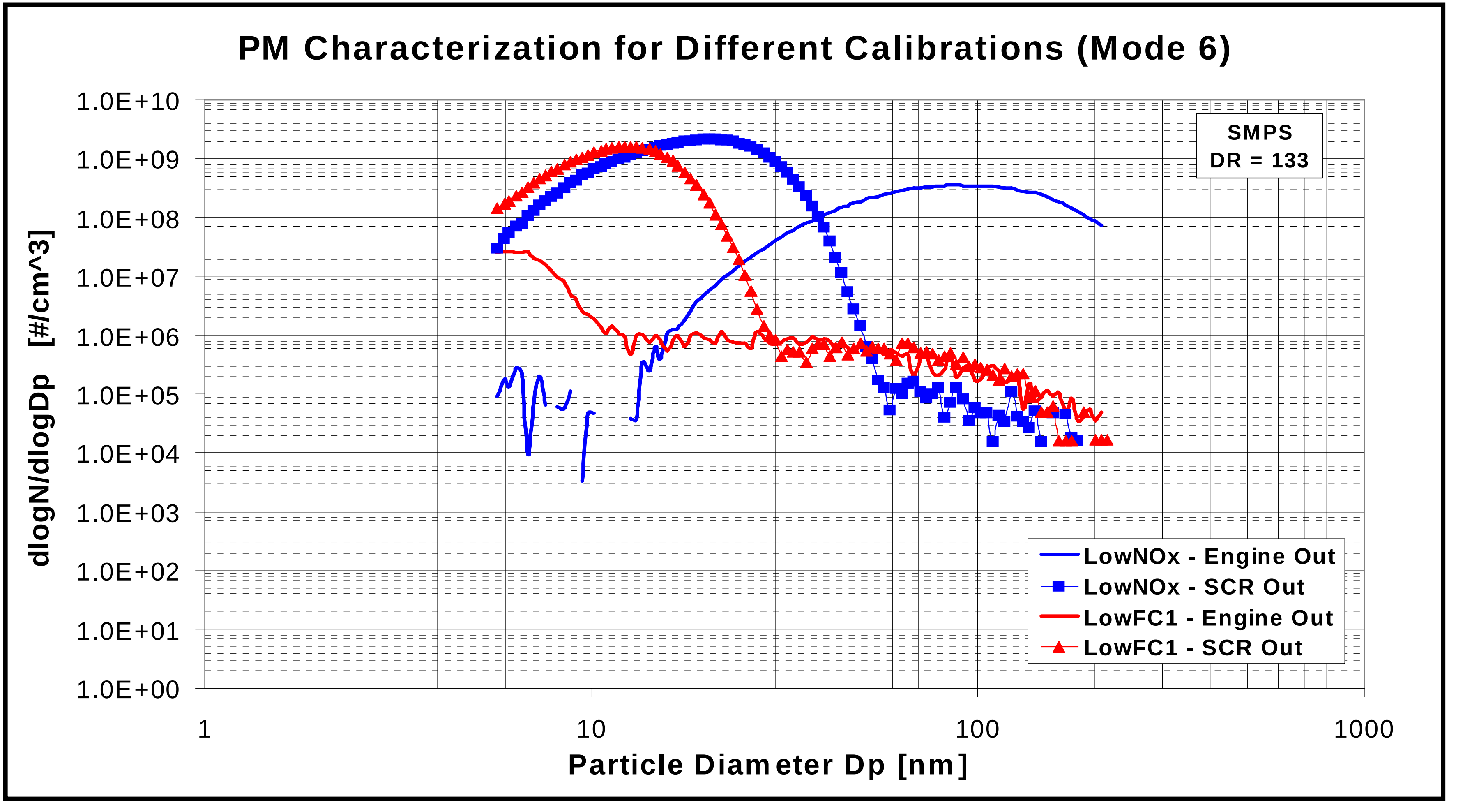
Results: Effect of Aftertreatment Components

Single Mode - Nucleation Mode PM



Results: Engine-out / SCR-out Correlation

Single Mode - Nucleation Mode PM



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 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 emisson 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