The Impact of Oil Consumption Mechanisms on Diesel Exhaust Particle Size Distributions and Detailed Exhaust Chemical Composition

John Stetter, Nate Forster

Jaal Ghandhi, David Foster

University of Wisconsin-Madison

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Acknowledgements

- Army Research Office (ARO)
- Nippon-Mitsubishi Oil Co.
- BP-Amoco Co.
- Yanmar Co.
- Cummins Engine Co.
- Lubrizol Co.

Strategies for Reducing PM

Aftertreatment Systems

- Catalytic Diesel Particulate Traps
- ***Particulate oxidation rate depends on its composition and history***

Fuel Composition

- Ultra Low Sulfur Diesel Fuel
- Synthetic Diesel Fuel (i.e. Fischer-Tropsch Fuel)
- ***Impact on EC, OC, trace metals, sulfates***

Lubrication Oil Composition and Variables

- Viscosity, Volatility, and Sulfur Content

Engine Design

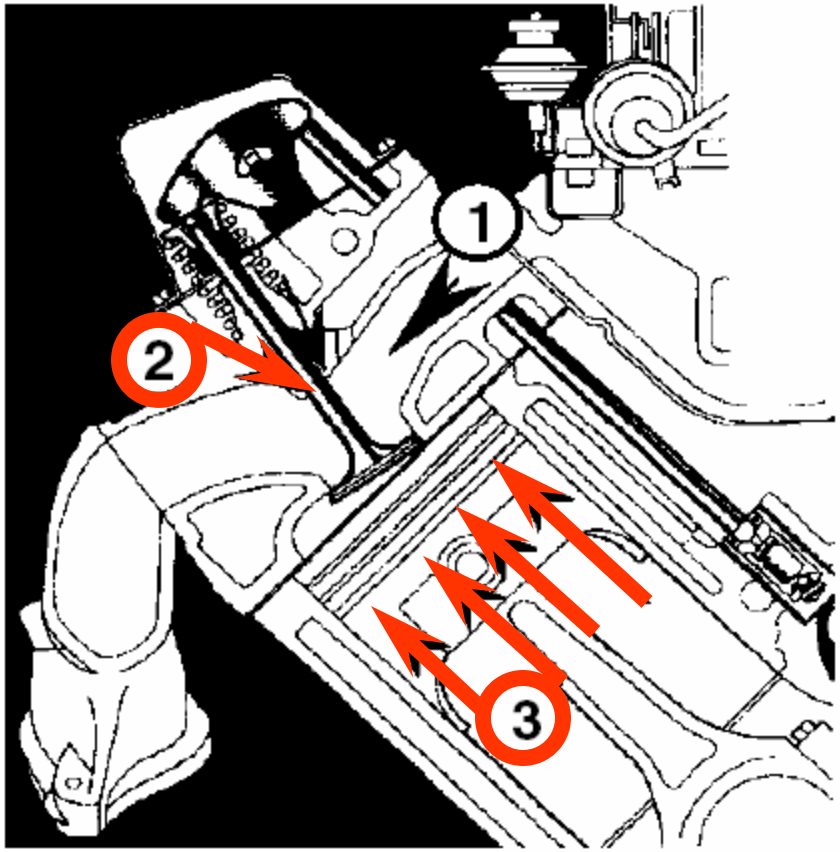
- Electronic Engine Control
- Fuel Injection System
- Intake Air System (Turbo-charging, etc.)
- Combustion Chamber Modification
- Lubrication Oil Consumption Reduction

Studies on the impact of engine operating conditions on particulate characteristics are underway

This study

Oil Consumption Mechanisms

1. Blowby Return – PCV (Effect not studied)
2. **Migration of oil past valve stem seals**
3. **Migration of oil past piston rings**
4. Turbocharger leakage (Effect not studied)

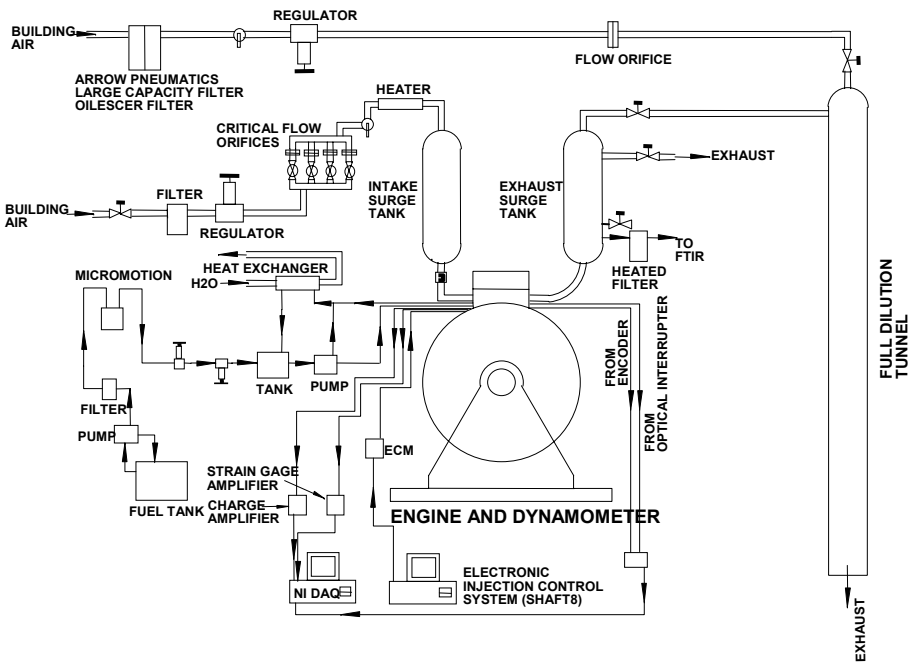


Adapted from SAE1999-01-3460.

Experimental Setup

Test Engine

Engine Bench Setup



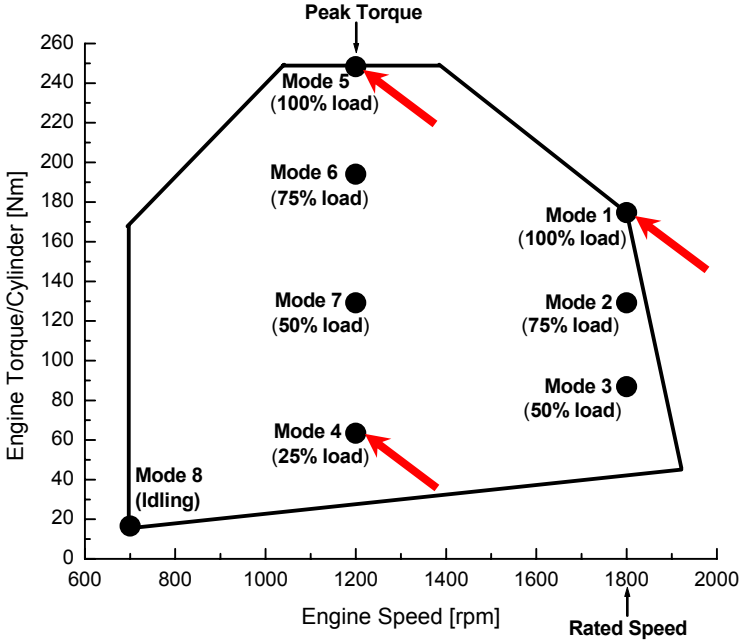
Engine Specification

Engine Type	Cummins N14 Single Cylinder Diesel
Cycle	4-stroke
Combustion Chamber	Quiescent
Piston Chamber	Shallow Dish
Number of Intake Valves	2
Number of Exhaust Valves	2
Compression Ratio	13.1:1
Swirl Ratio	1.4
Displacement	2336 cc
Bore	139.7 mm
Stroke	152.4 mm
Combustion Chamber Diameter	97.8 mm
Connection Rod Length	304.8 mm
Piston Pin Offset	None
Injection System	Unit Injector, Direct Injection (DI)
Nozzle Dimension	$8 \times \Phi 0.2$ mm
Length/Diameter of holes (l/d)	4.1
Spray Angle	152°

Experimental Operating Conditions

CARB 8-Mode Test Points
Steady-State Operation

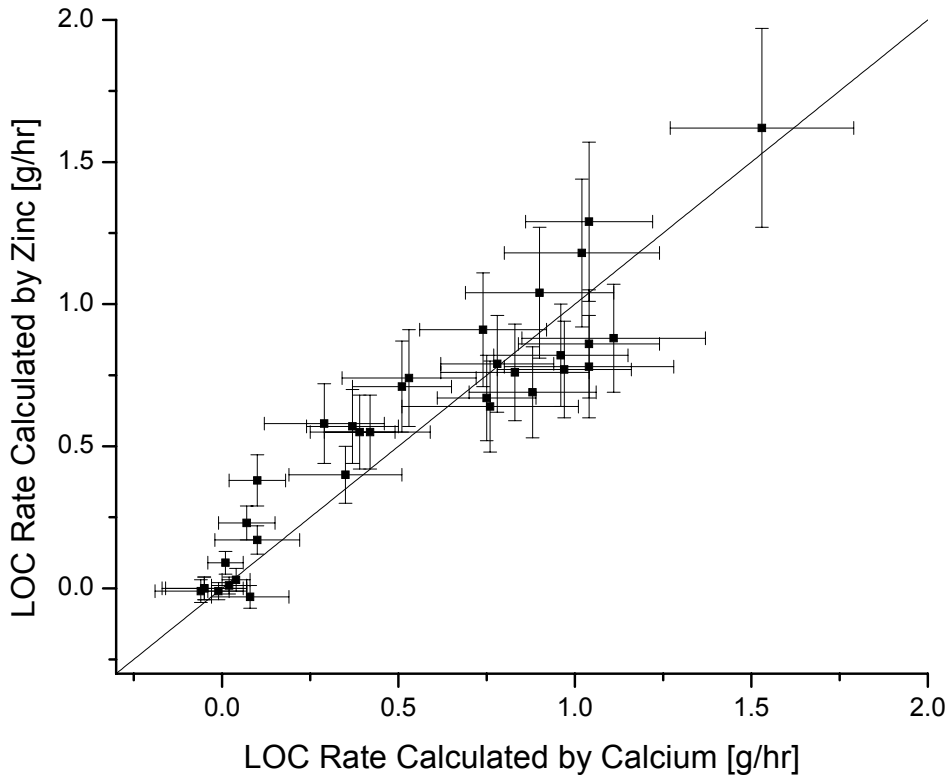
Fuel was a 2006 EPA low sulfur fuel, 14 PPM



	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
Speed [rpm]	1800	1800	1800	1200	1200	1200	1200	700
Load [%]	100	75	50	25	100	75	50	10 (idle)
Remark	Rated speed				Peak torque			
Intake T [°C]	46.48	46.48	46.48	46.11	45.93	45.74	46.30	45.74
Intake P [kPa]	148.05	148.97	143.00	160.46	152.87	157.01	162.07	164.37
Exhaust P [kPa]	181.91	195.54	160.23	162.41	152.94	202.67	182.18	151.52
SOI, CA aTDC [degrees]	-5.0	-5.0	-5.0	-2.0	-11.0	-2.0	-2.0	-2.0

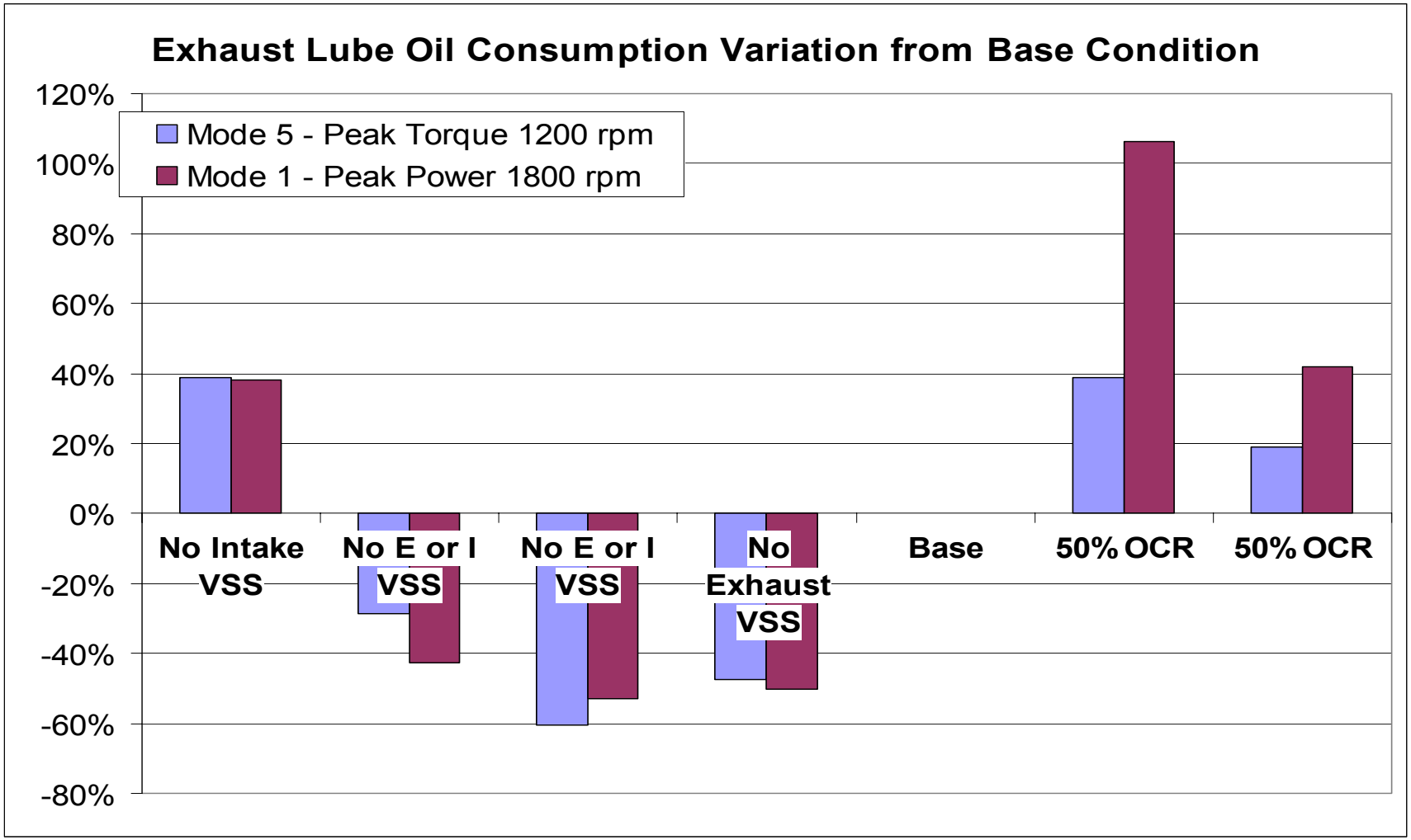
LOC Rate Measurement Method

- Calcium: a viable LOC tracer
  (SAE 980523 and SAE 2003-01-0076)
- Calcium compounds are common additives
- Other metals in oil (Fe, Al, Cu, etc.) can also be attributed to engine wear.
- Ca and Zn show good agreement.



Experimental Results

Lube Oil Consumption



Lube Oil Consumption

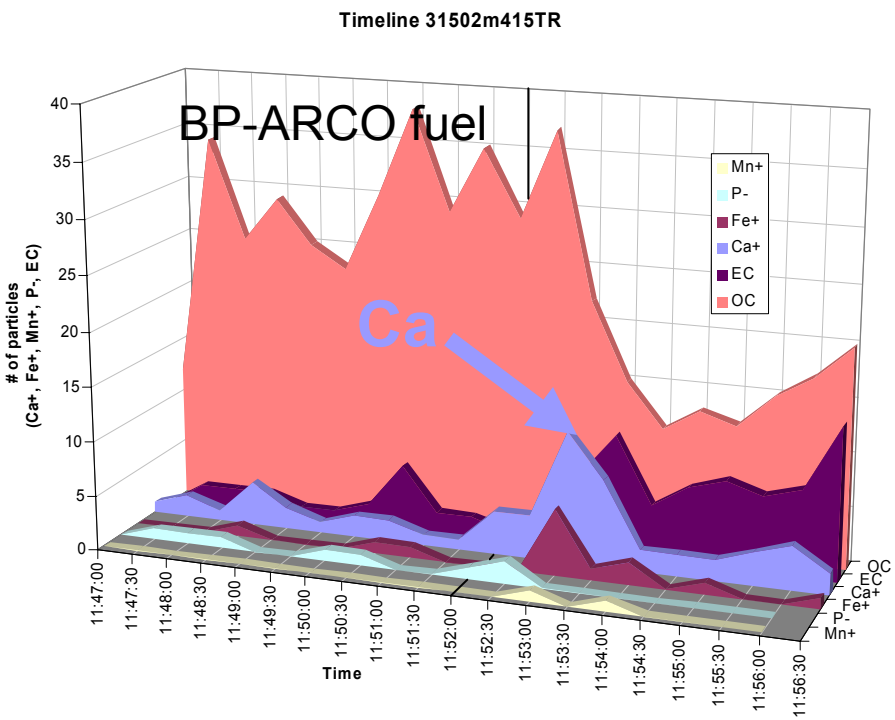
- Measured LOC rates: 0.3 – 1.5 g/hr

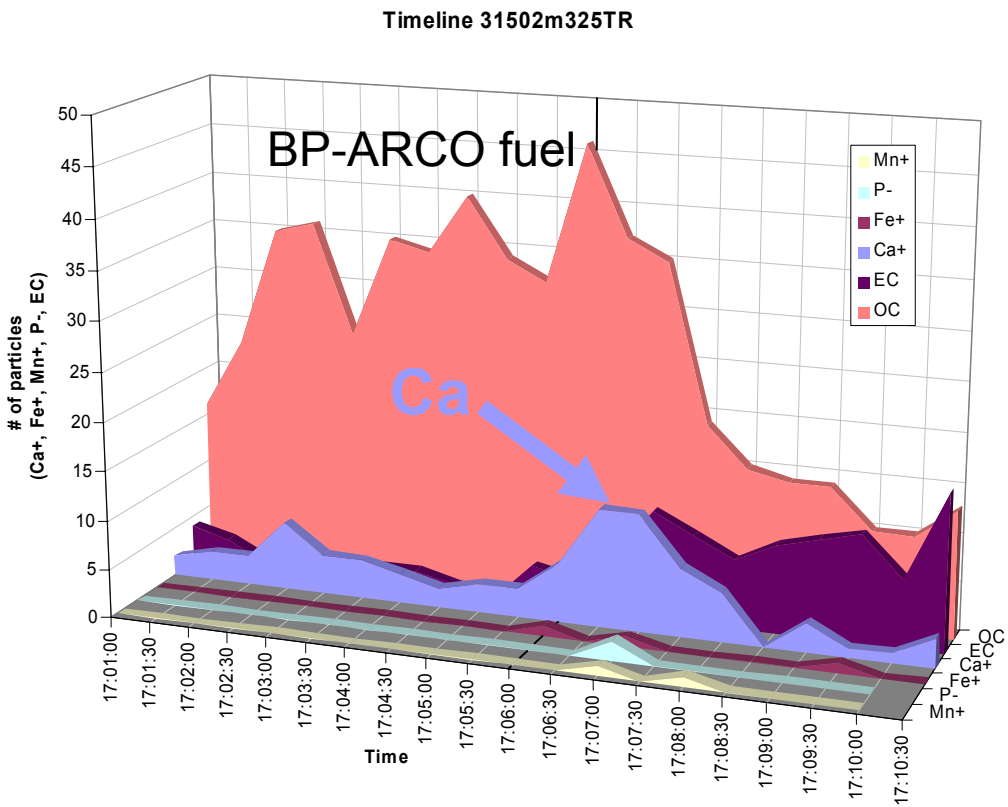
  (Mode 4 LOC < 0.1 g/hr)
- Typical LOC (High Speed Diesels): 0.1-0.5% of full load fuel which would correspond to 7 – 40 g/hr
- Test points are steady state conditions

Experimental Results

Transient Lube Oil Consumption

- "Transient" calcium spikes on order of 10x steady state operation from *raw* ATOFMS data



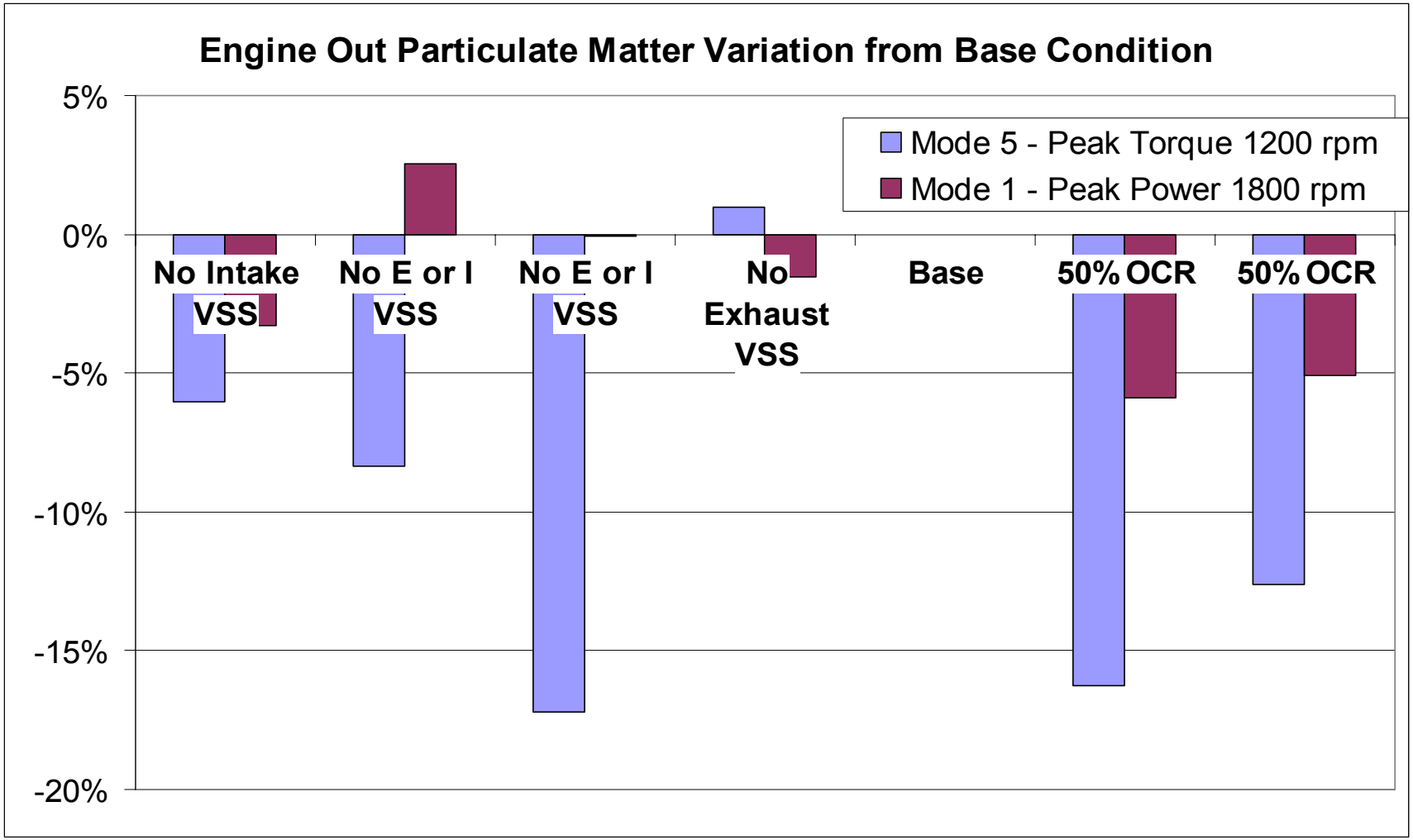


Lube Oil Consumption

- Measured LOC rates: 0.3 – 1.5 g/hr
- Typical LOC (High Speed Diesels): 0.1 – 0.5% of full load fuel which would correspond to 7 – 40 g/hr
- Test points are steady state conditions
- Transient operation critical to understanding overall LOC, but…
- What can be learned from less complex, fundamental steady state operation?

Experimental Results

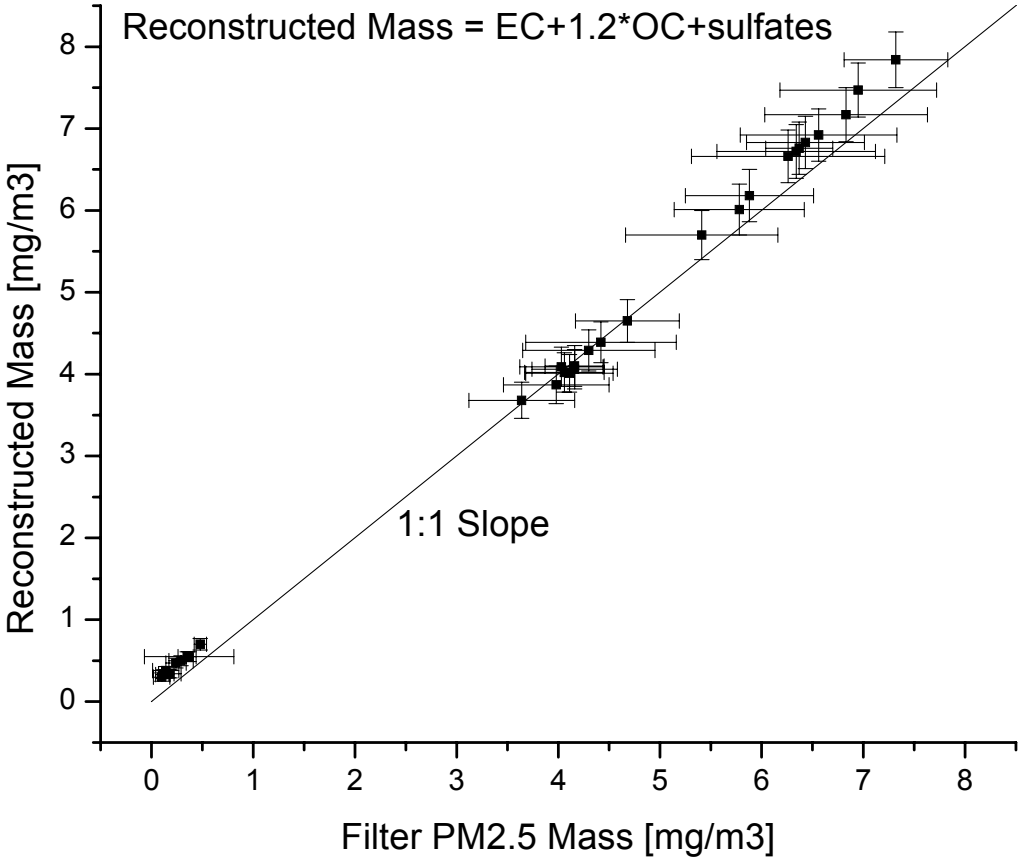
Engine Out PM



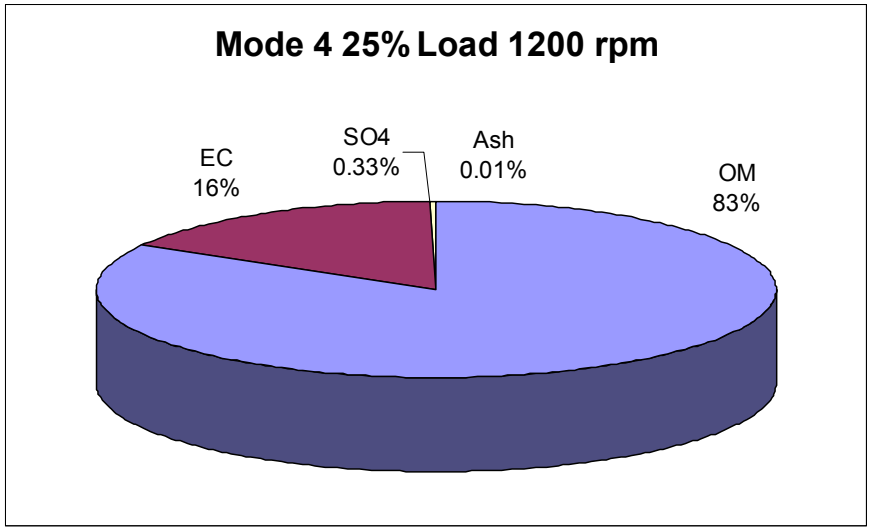
Experimental Results

Reconstructed Mass vs. PM2.5 Mass

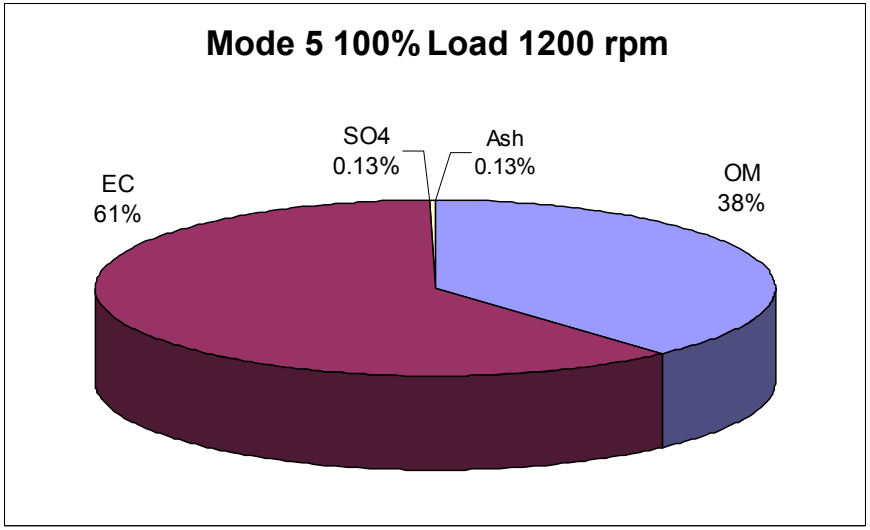
- Very Good Agreement
- Recon > Measured for low loading
- This may be due to sorption of semi-volatile gas-phase organic compounds to the filter.

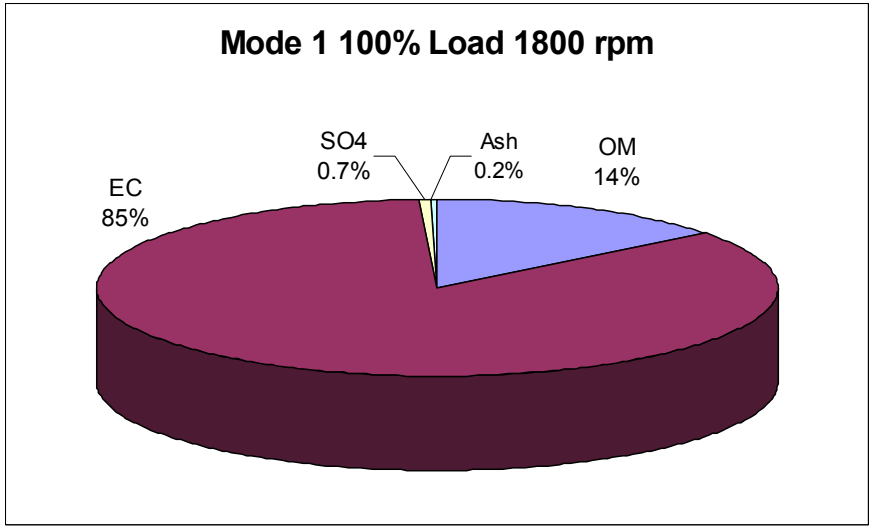


Particulate Matter Composition



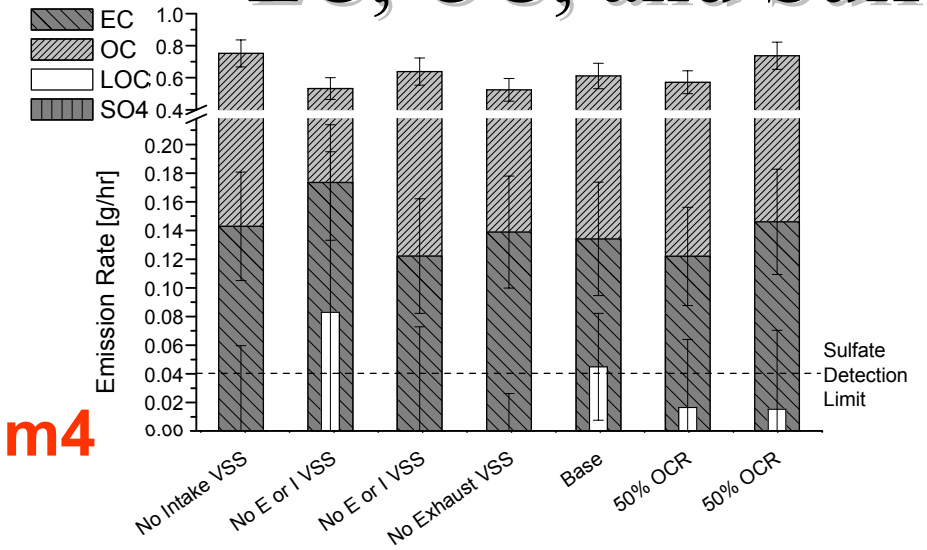
- Varying composition with engine mode
- Fairly consistent (±5%) composition among variations in LOC for each engine mode





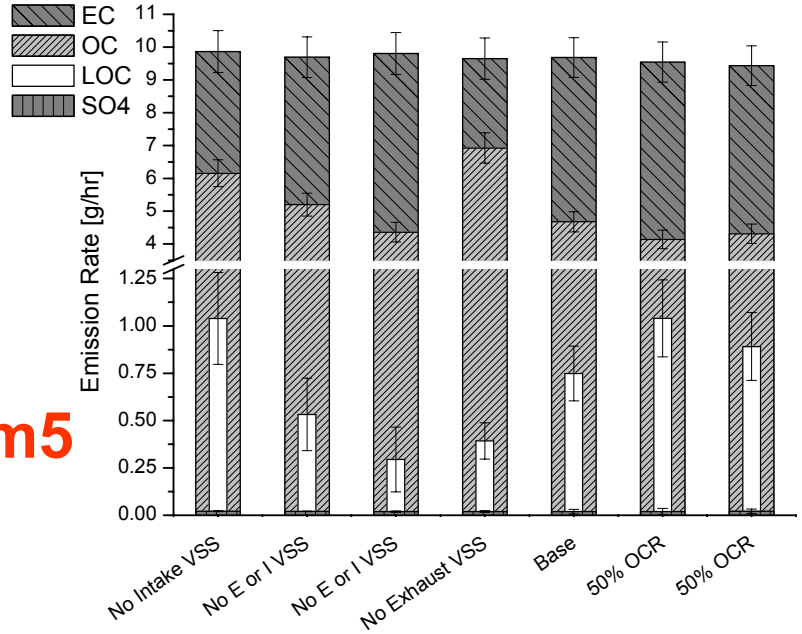
Experimental Results

EC, OC, and Sulfates with LOC

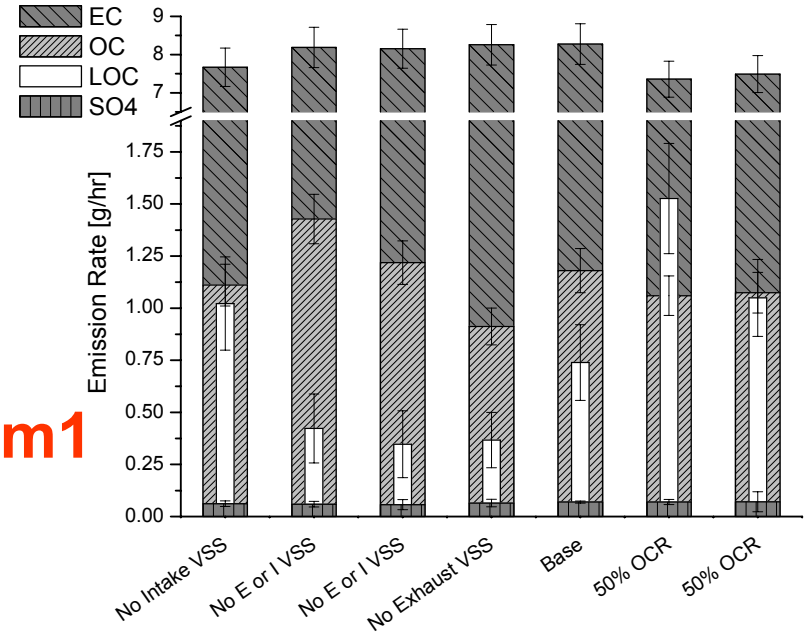


m4

- Modes 5 and 1 show significant differences in OC emissions
- Differences do not correspond with variations in lube oil consumption



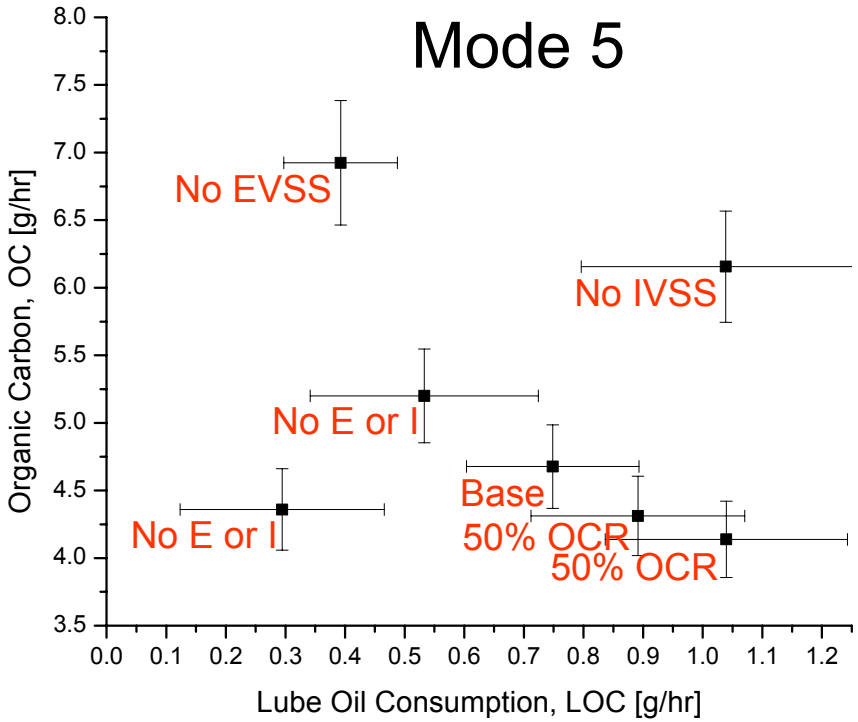
m5

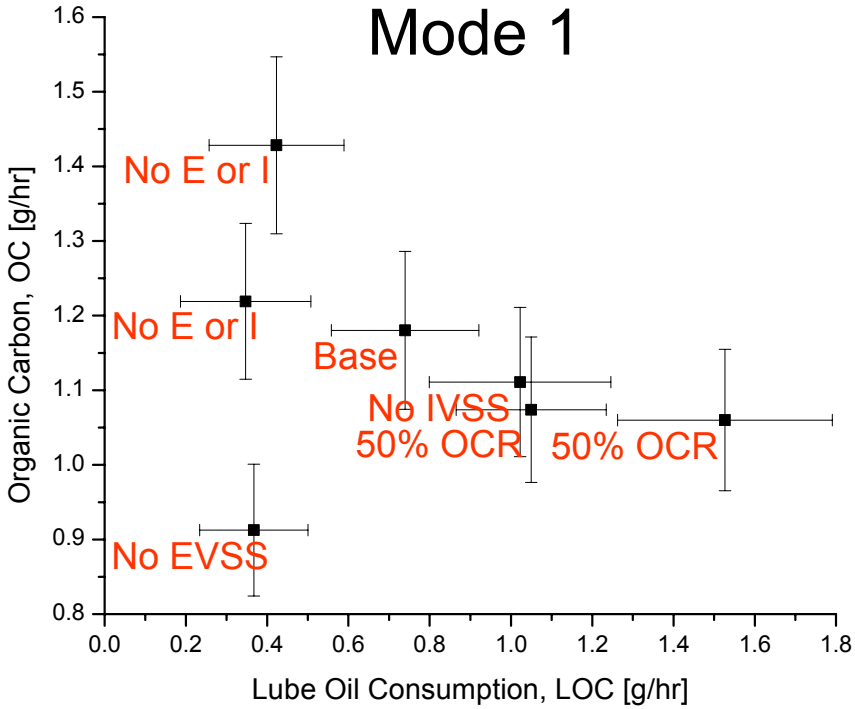


m1

Experimental Results

OC vs. LOC for Mode 5 and Mode 1

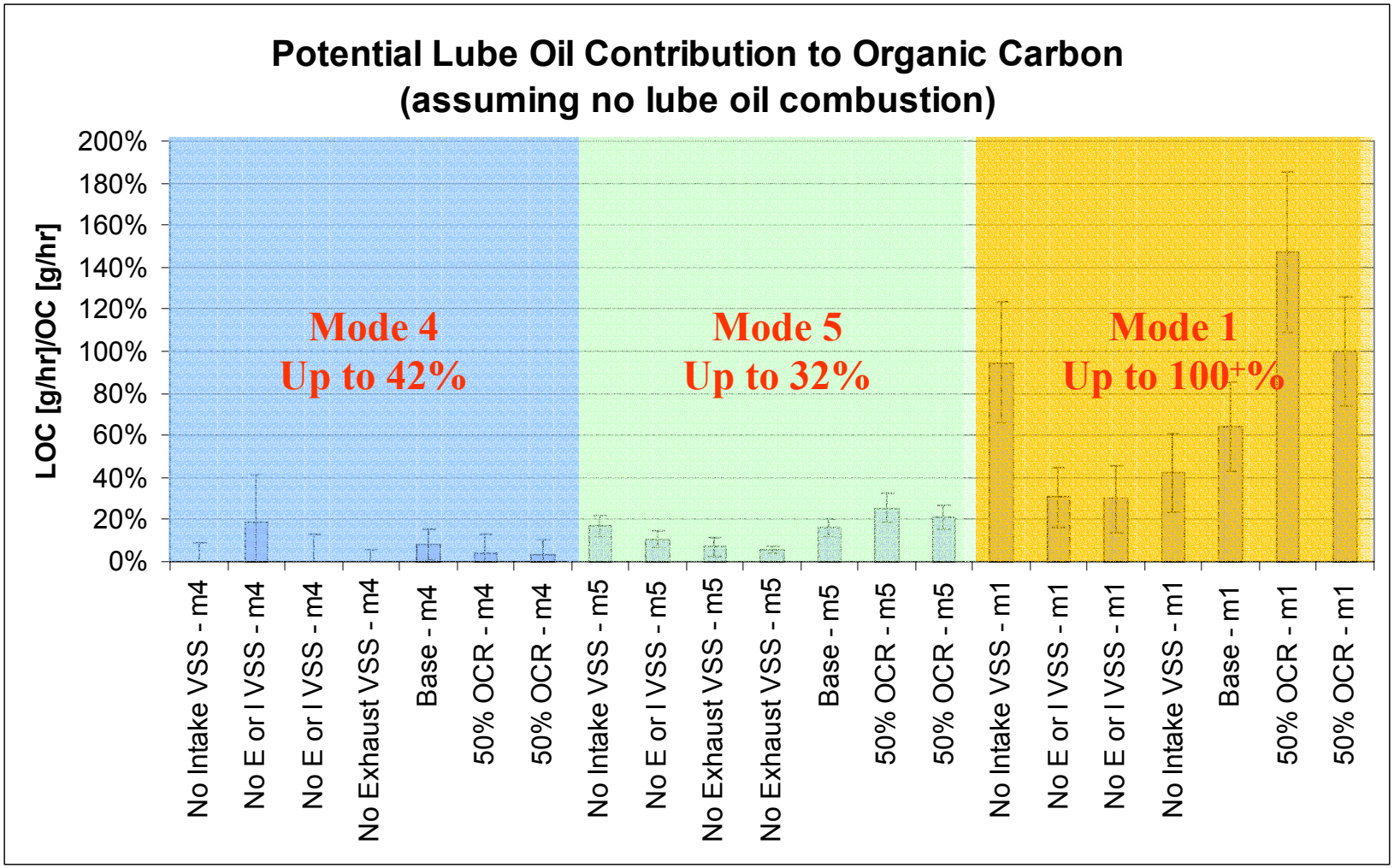




- No obvious relationship between Organic Carbon and Lube Oil Consumption for Modes 5 and 1

Experimental Results

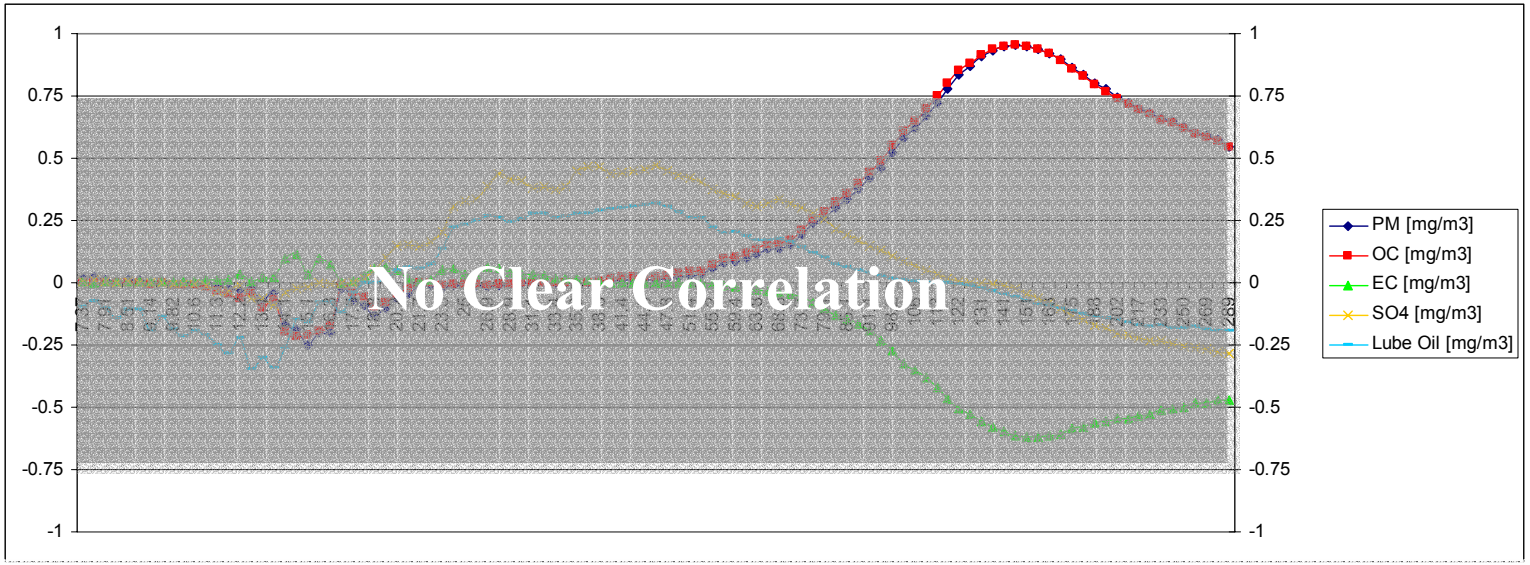
Lube Oil Contribution to OC



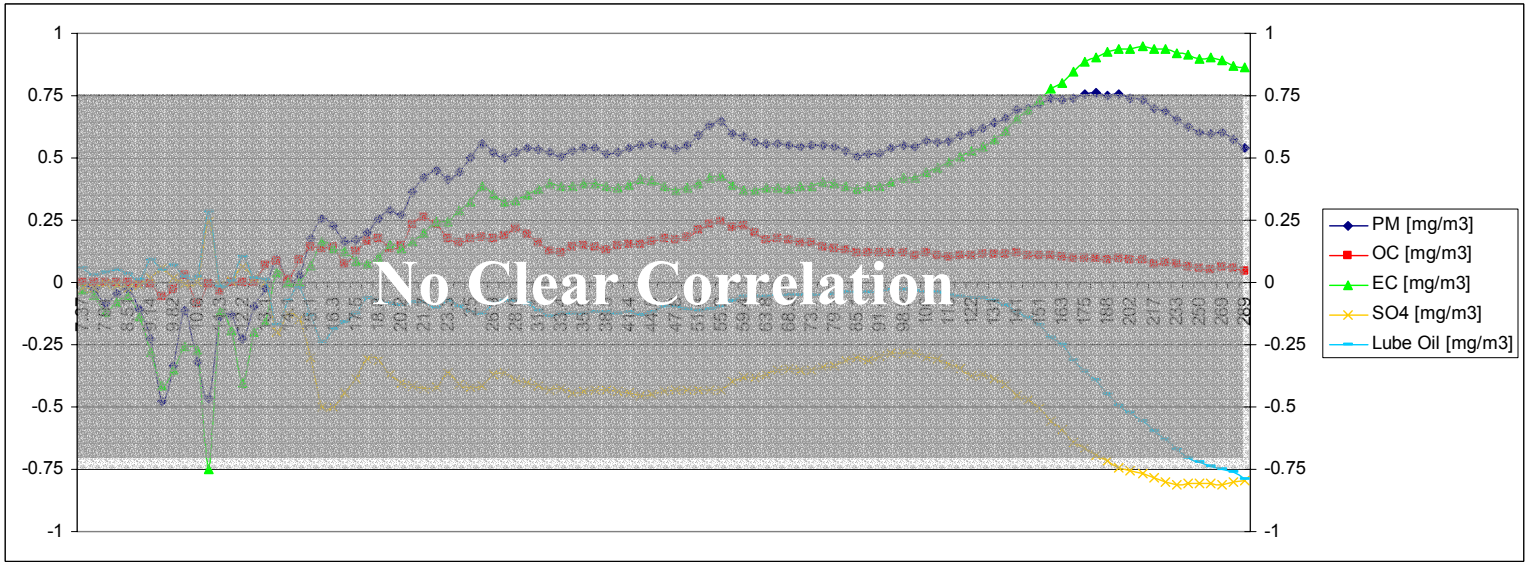
Experimental Results

Filter and SMPS Correlations

Mode 5



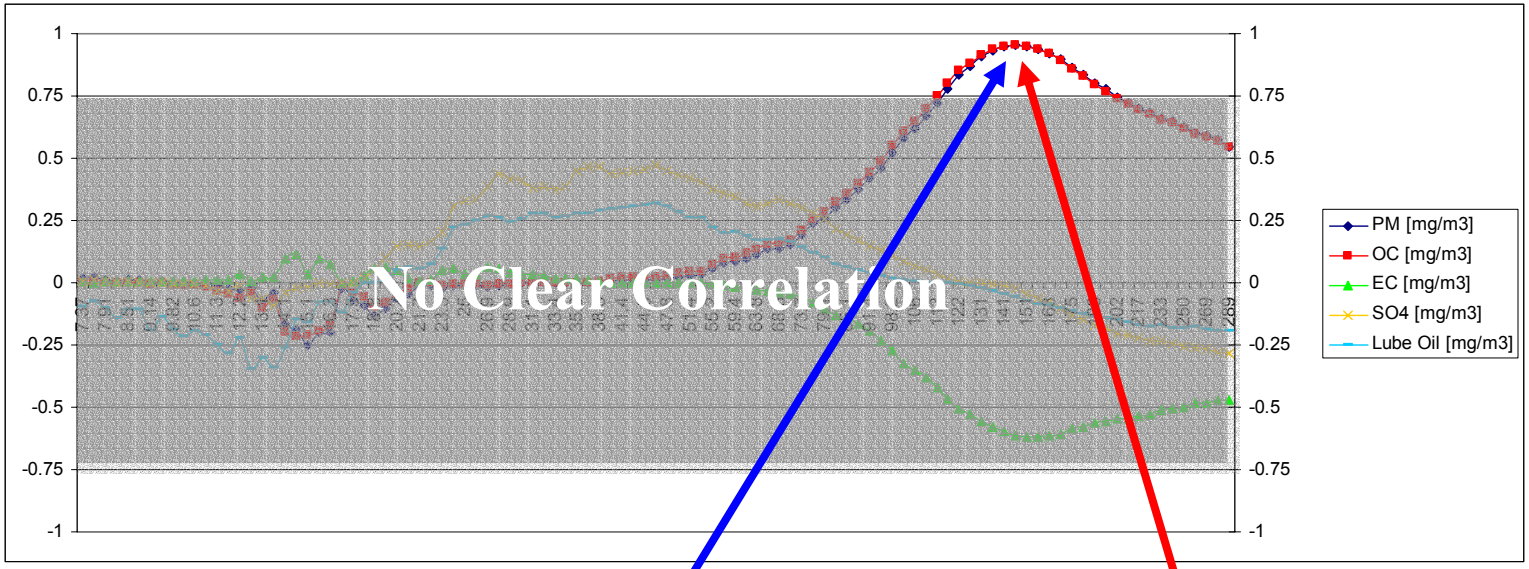
Mode 1

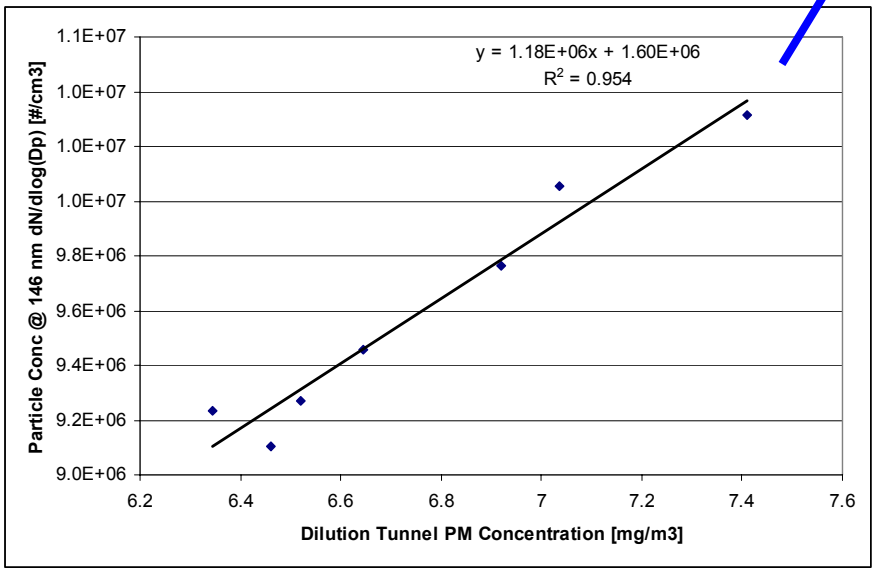


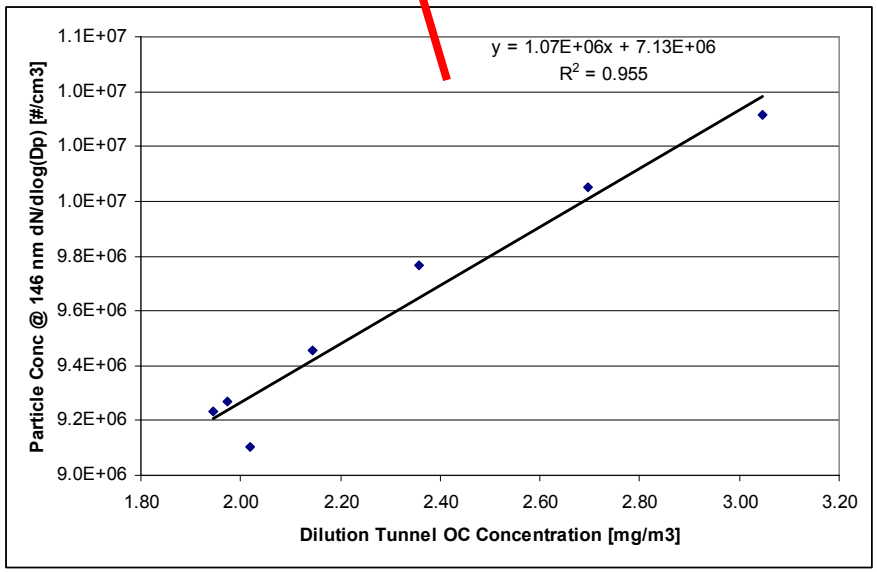
Experimental Results

Filter and SMPS Correlations

Mode 5



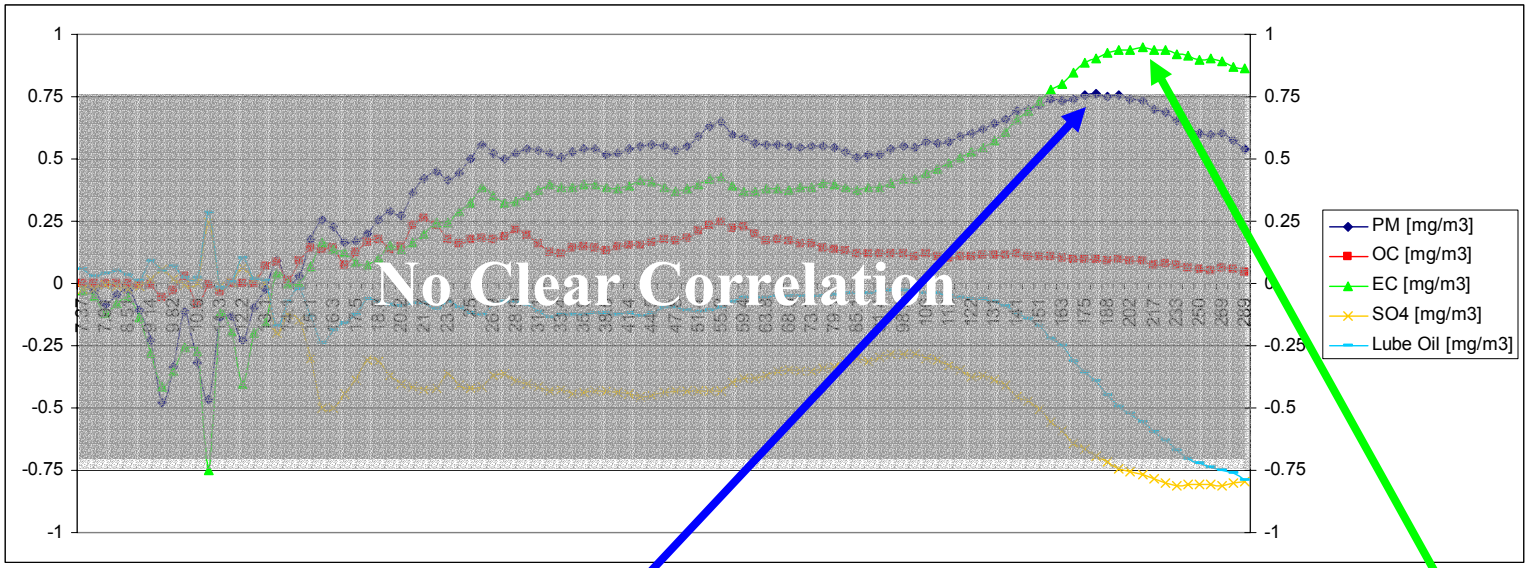


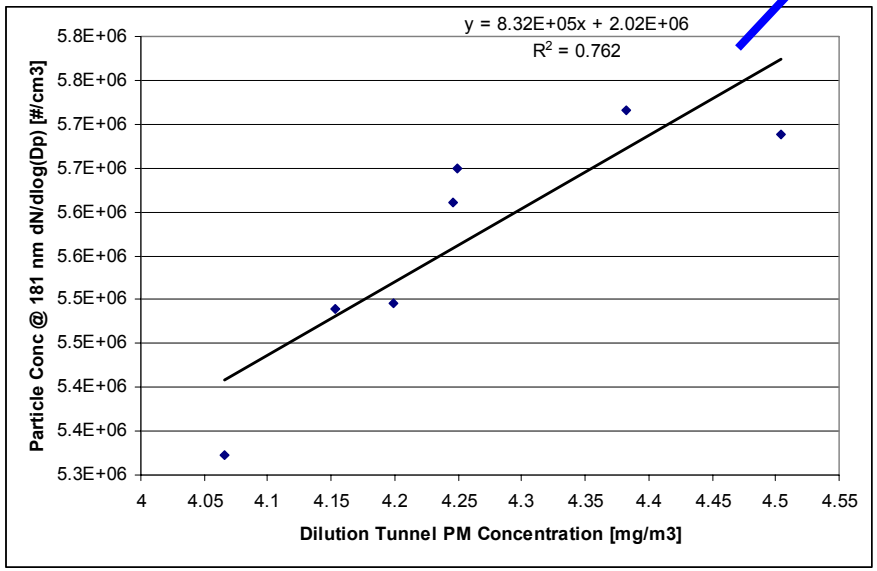


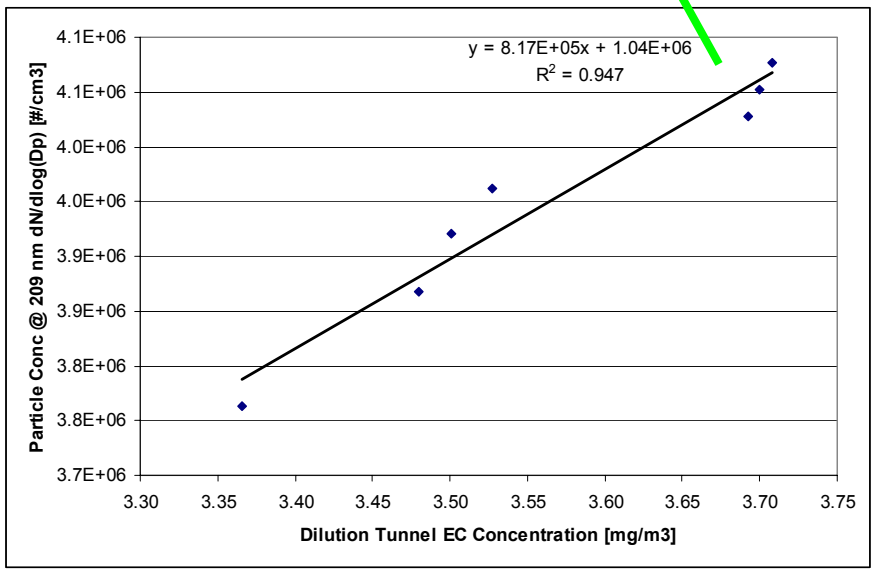
Experimental Results

Filter and SMPS Correlations

Mode 1



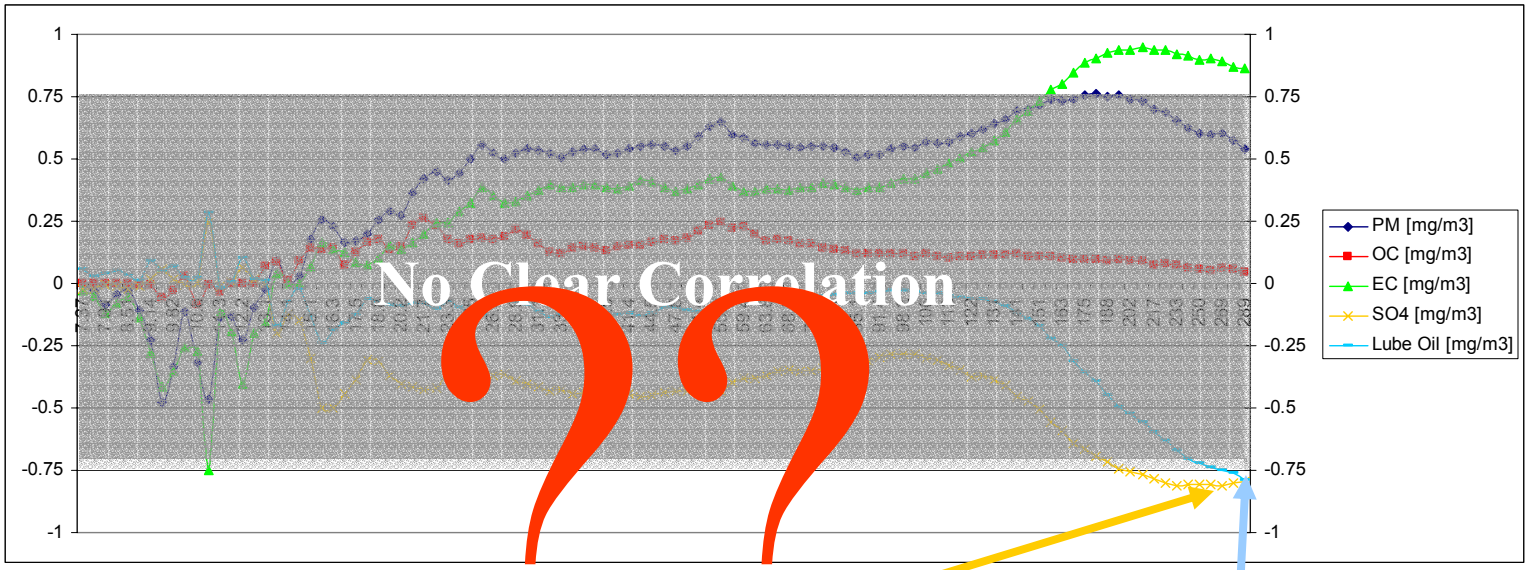


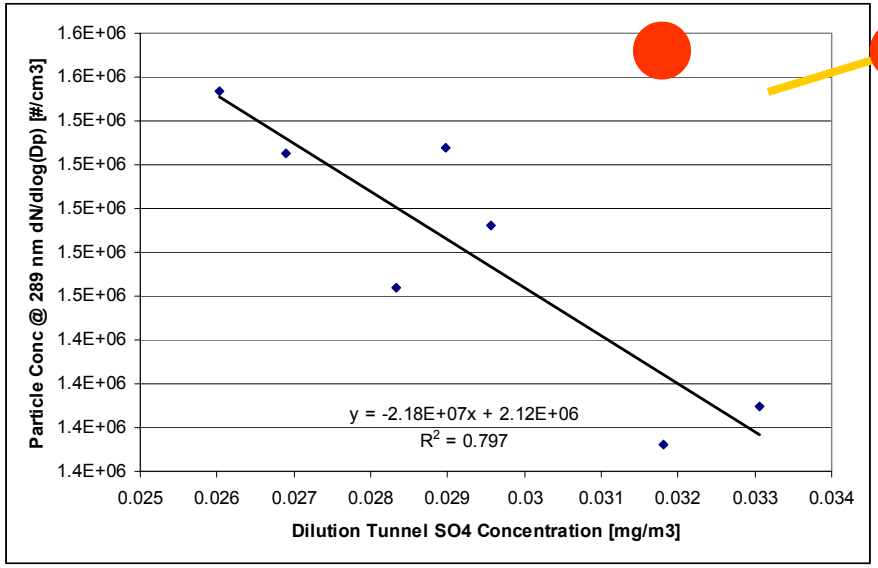


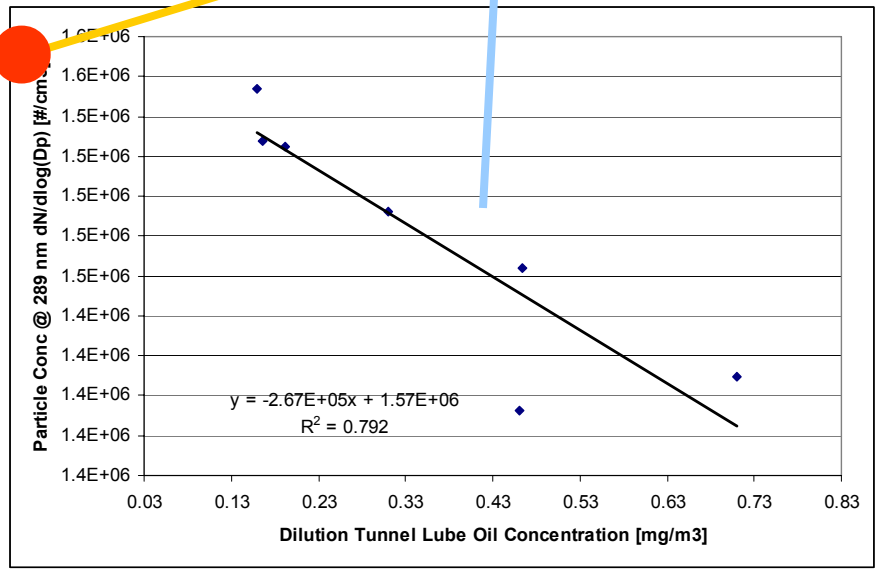
Experimental Results

Filter and SMPS Correlations

Mode 1

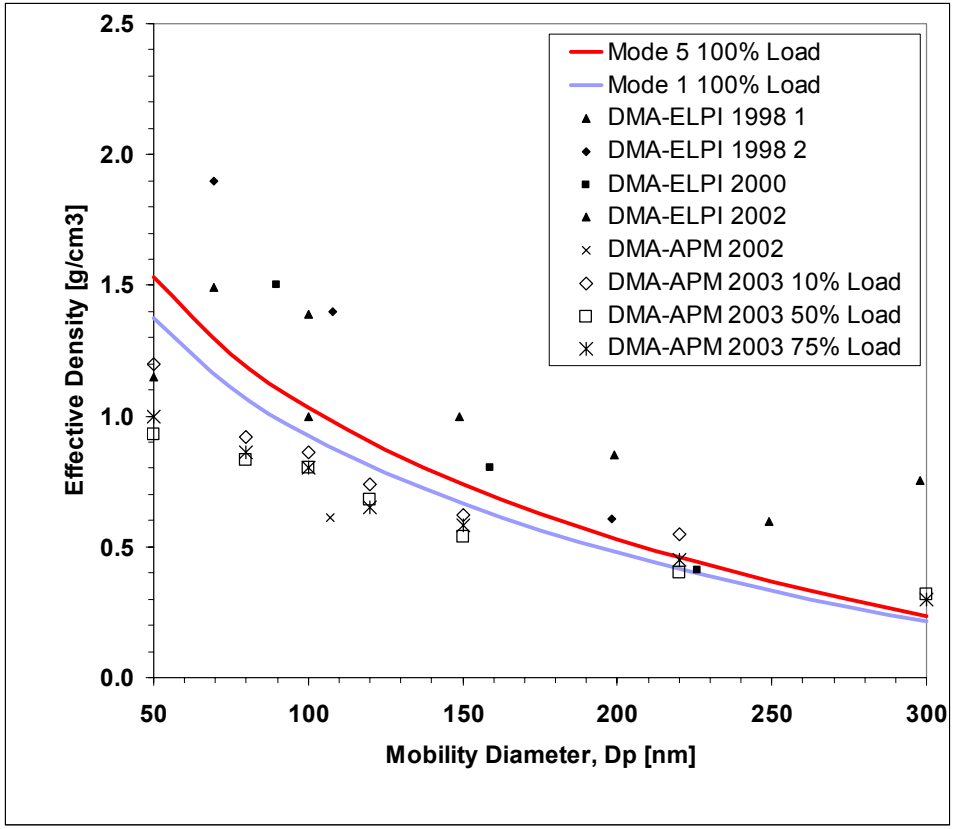






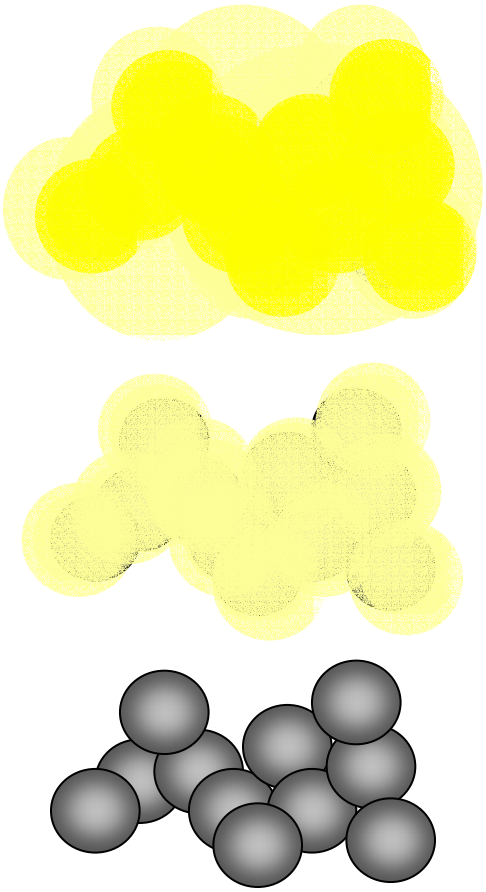
Particulate Matter Effective Density

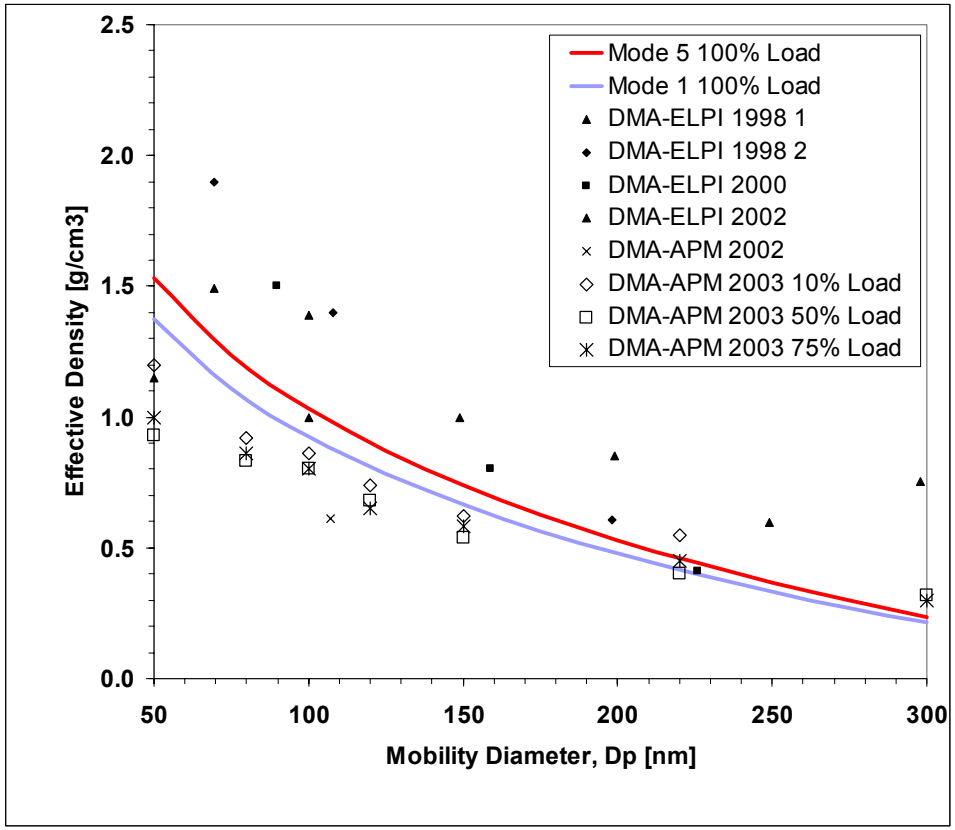
- Some effective density data available from various instruments
- Assume empirical density function of the similar functional form
- Spherical particles
- PM = Conc * Vol * ρ_{eff}

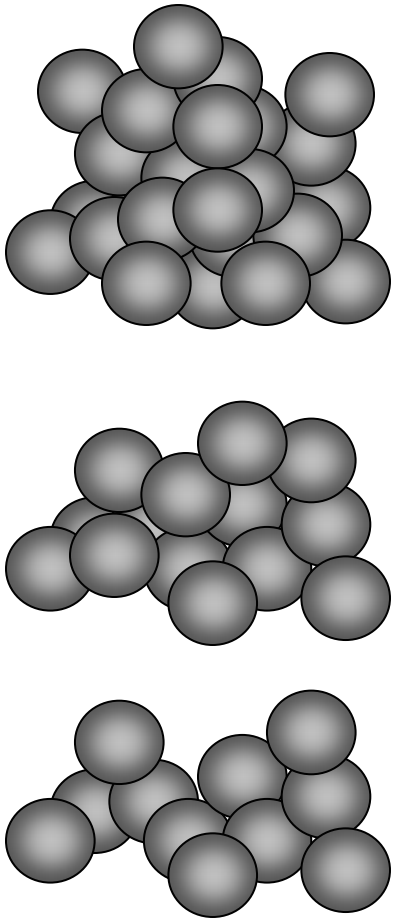


Experimental Results

Particulate Matter Effective Density



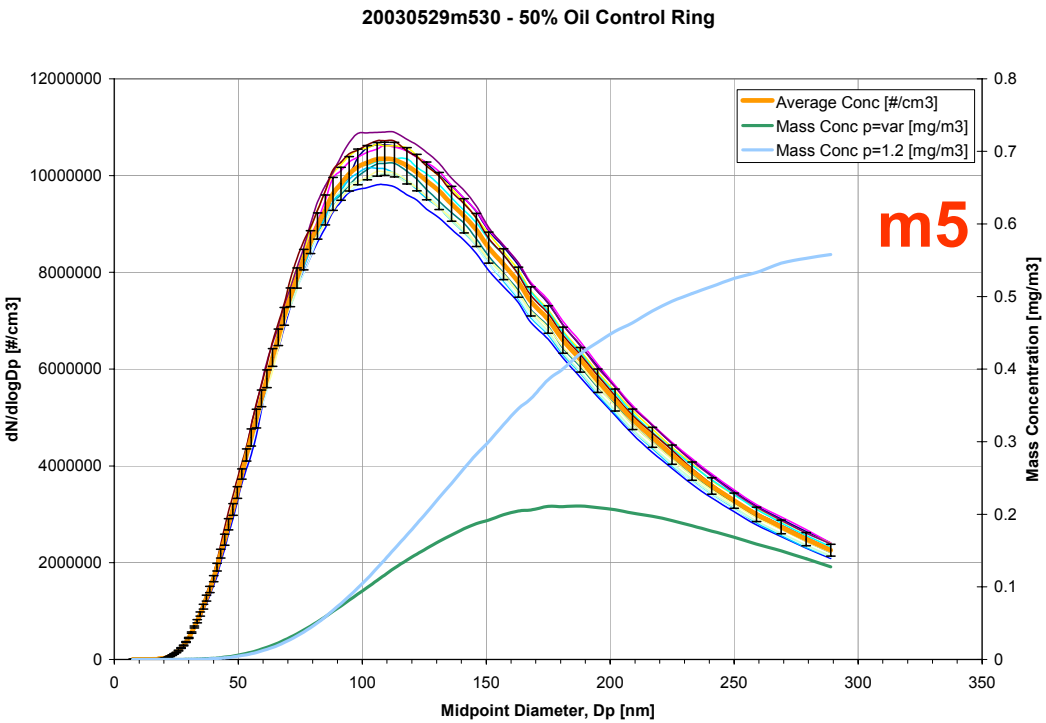




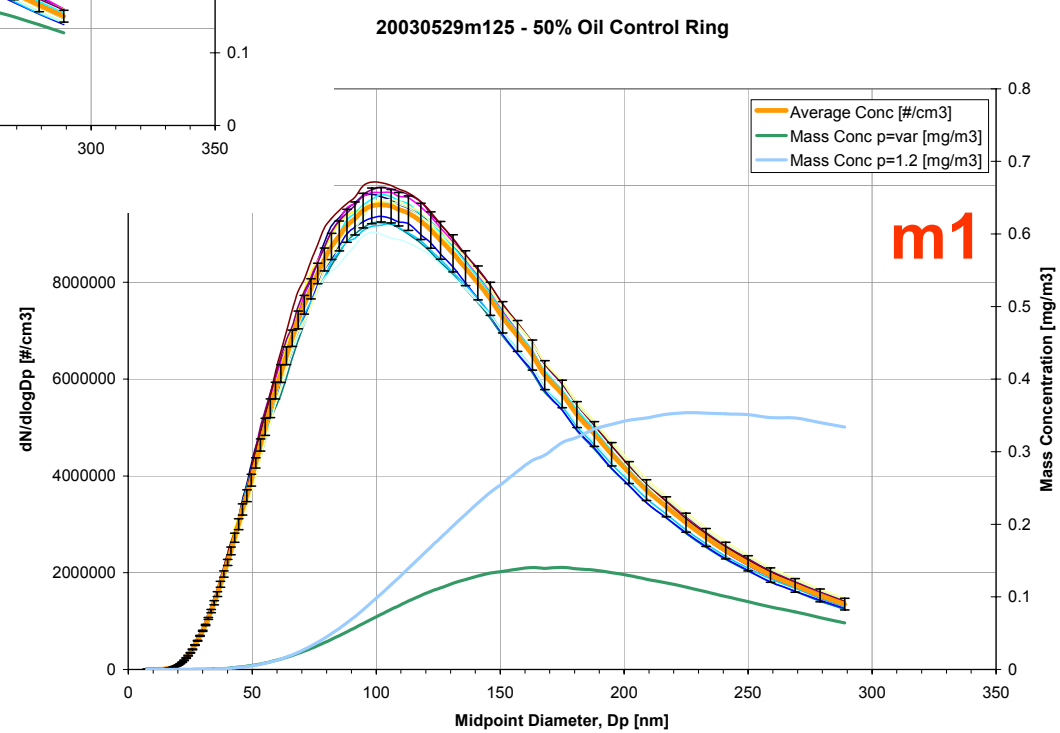
200 nm

200 nm

Experimental Results – SMPS Size Distributions



- Highest LOC but no significant nanoparticle formation (nuclei mode)
- Constant density (SMPS) overestimates filter mass



- 12 samples shown for each hour test with average and 1 standard deviation shown
- Data for comparison to gravimetric filters

Conclusions (Stead State Operation)

- Lube oil consumption for steady state operation has insignificant effect on diesel particulate matter
- Engine operating conditions have significant effects on the detailed particulate matter composition
- Lube oil has a small contribution to overall organic carbon for some operating conditions
- Effective density calculations provide additional insight in understanding the details of diesel PM.
- No apparent changes in particle size distributions with changes in oil consumption

Questions?

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