

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



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# Acknowledgements

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

## *Introduction*

# 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

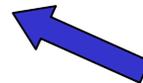
Intake Air System (Turbo-charging, etc.)

Combustion Chamber Modification

Lubrication Oil Consumption Reduction



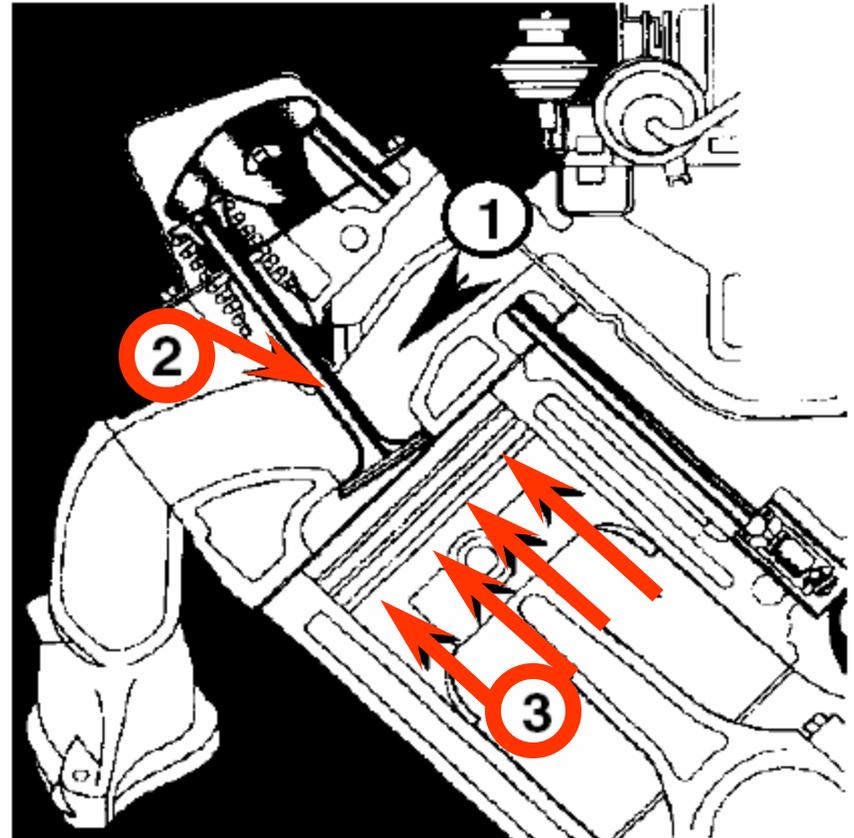
*Studies on the impact of engine operating conditions on particulate characteristics are underway*



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)

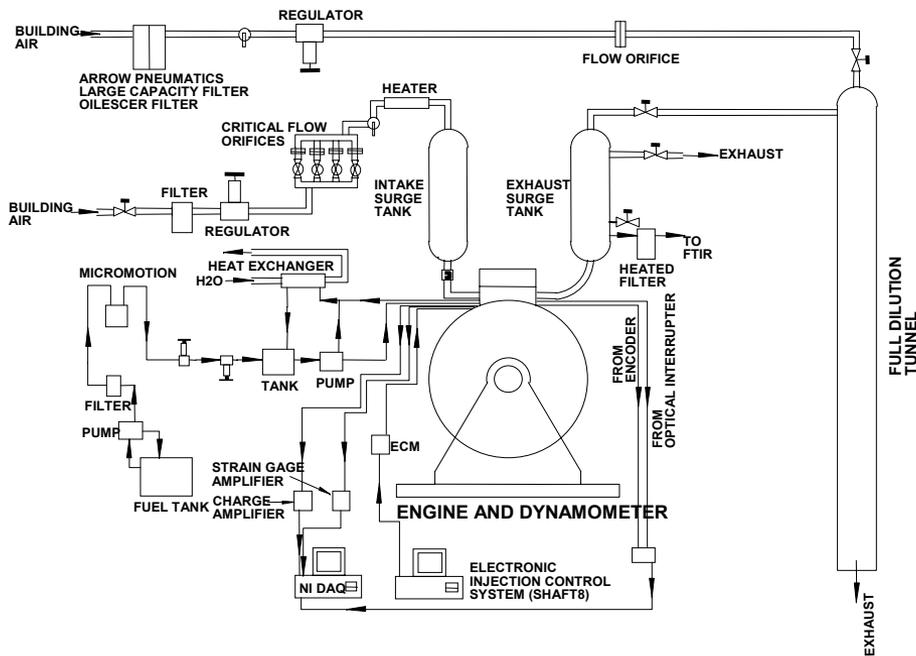


Adapted from SAE1999-01-3460.

# Experimental Setup

## Test Engine

### Engine Bench Setup



### Engine Specification

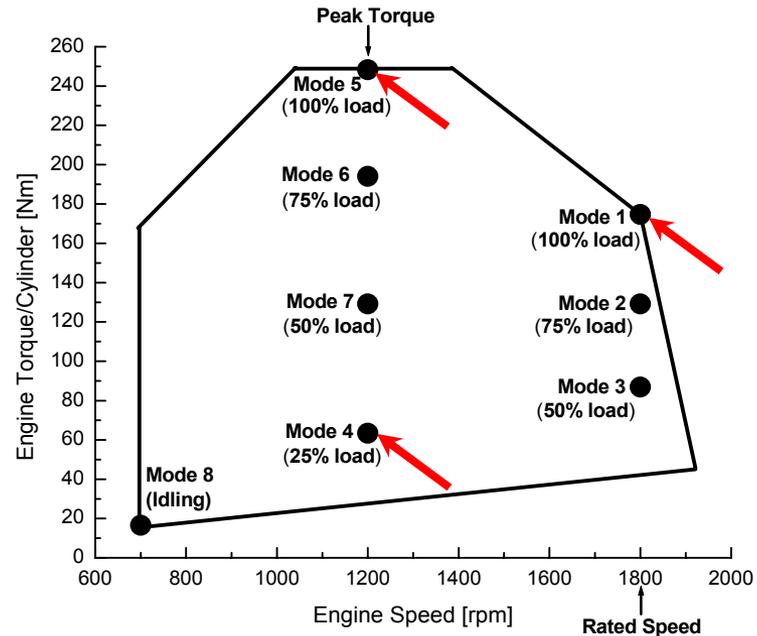
Engine Type	Cummins N14 Single Cylinder Diesel
Cycle	4-stroke
Combustion Chamber	Quiescent
Piston Chamber	Shallow Dish
Number of Intake Valves	2
Number of Exhaust Valves	2
Compression Ratio	13.1:1
Swirl Ratio	1.4
Displacement	2336 cc
Bore	139.7 mm
Stroke	152.4 mm
Combustion Chamber Diameter	97.8 mm
Connection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

# Experimental Design

## Experimental Operating Conditions

CARB 8-Mode Test Points  
Steady-State Operation

Fuel was a 2006 EPA low sulfur fuel, 14 PPM

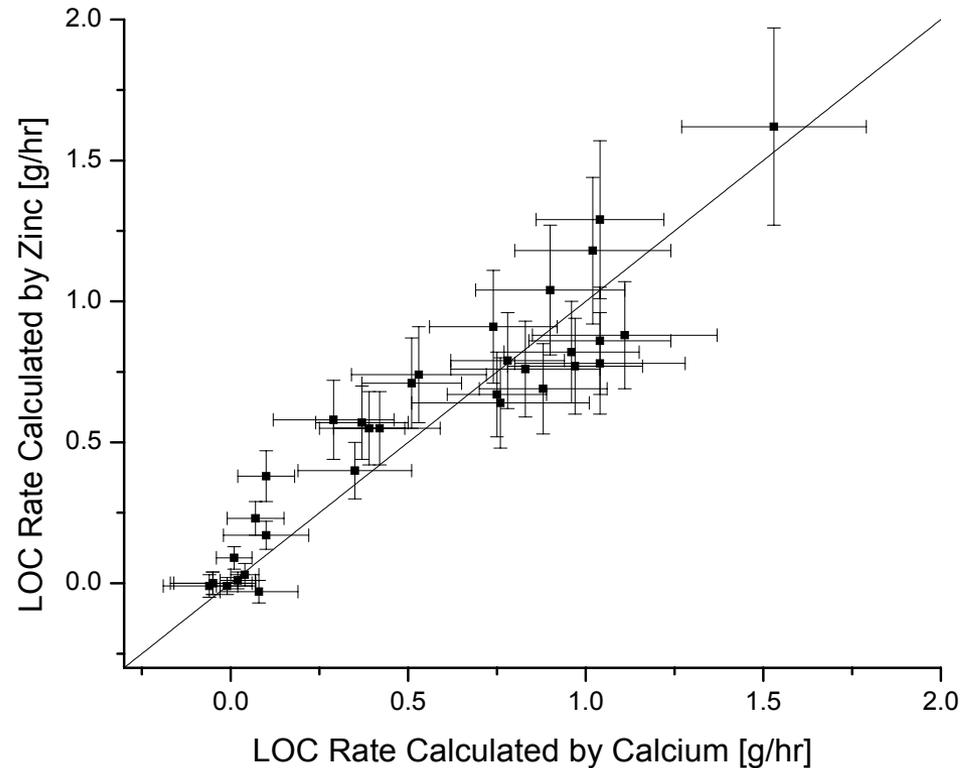


	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 6	Mode 7	Mode 8
Speed [rpm]	1800	1800	1800	1200	1200	1200	1200	700
Load [%]	100	75	50	25	100	75	50	10 (idle)
Remark	Rated speed				Peak torque			
Intake T [°C]	46.48	46.48	46.48	46.11	45.93	45.74	46.30	45.74
Intake P [kPa]	148.05	148.97	143.00	160.46	152.87	157.01	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

## Experimental Results

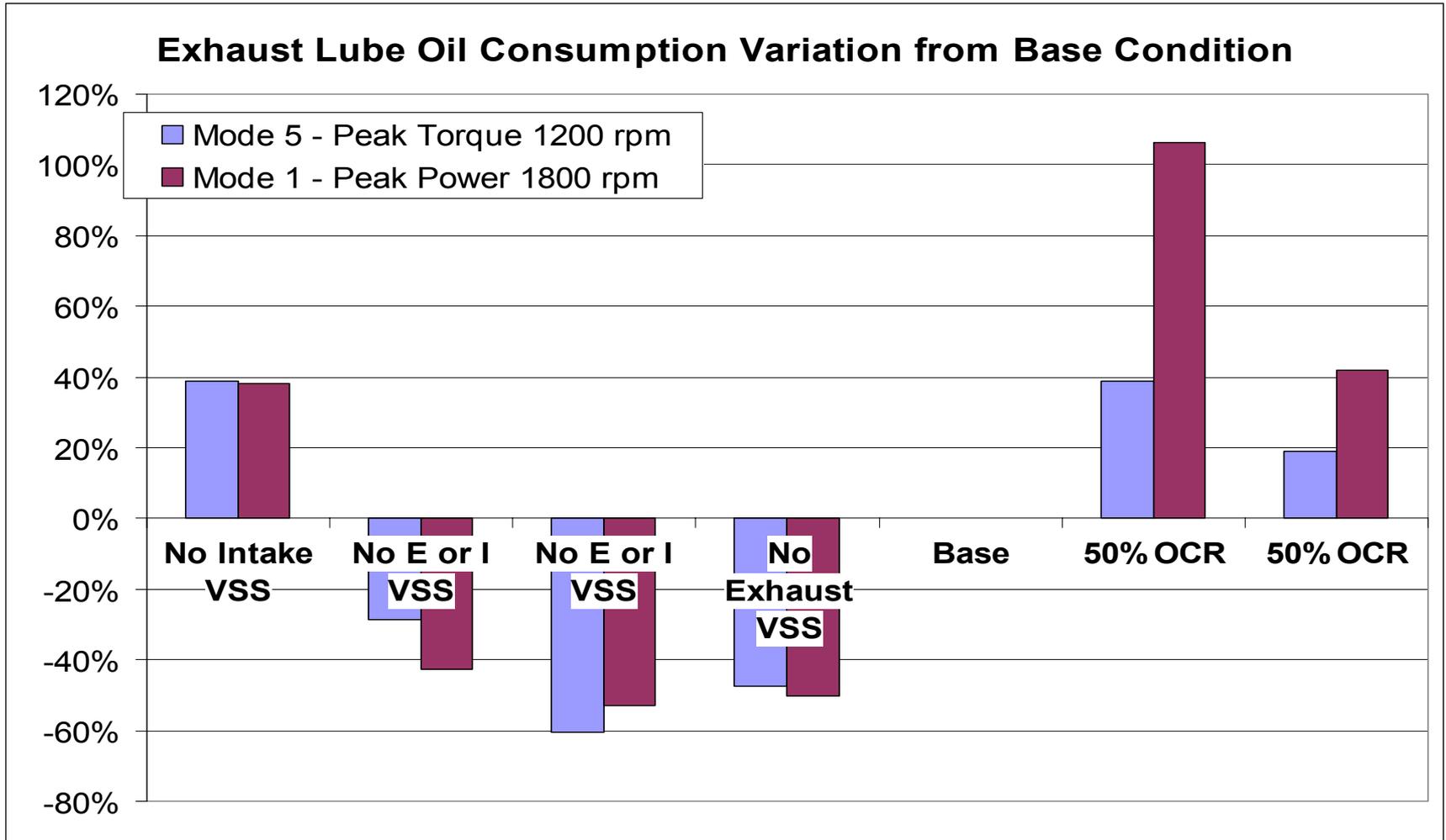
# LOC Rate Measurement Method

- 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



## *Experimental Results*

# 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

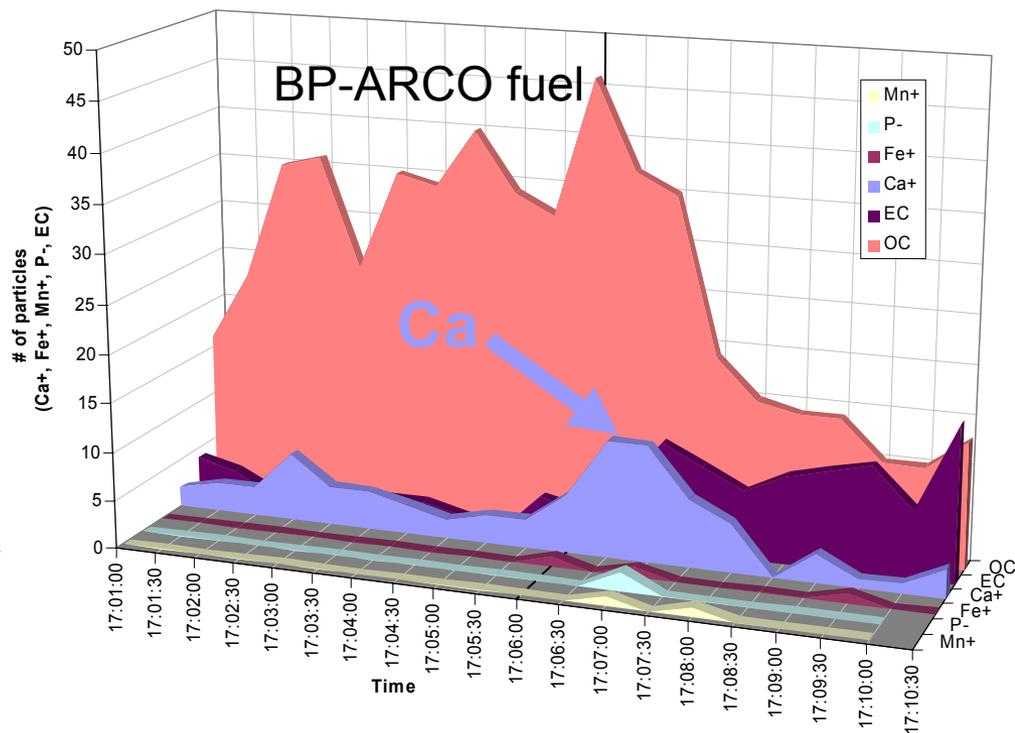
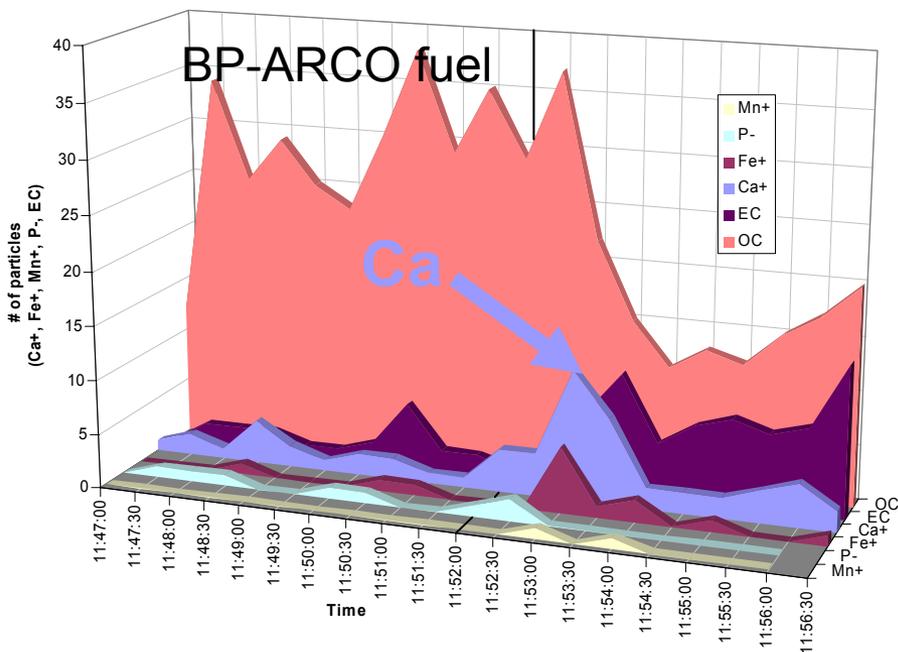
# Experimental Results

## Transient Lube Oil Consumption

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

Timeline 31502m325TR

Timeline 31502m415TR

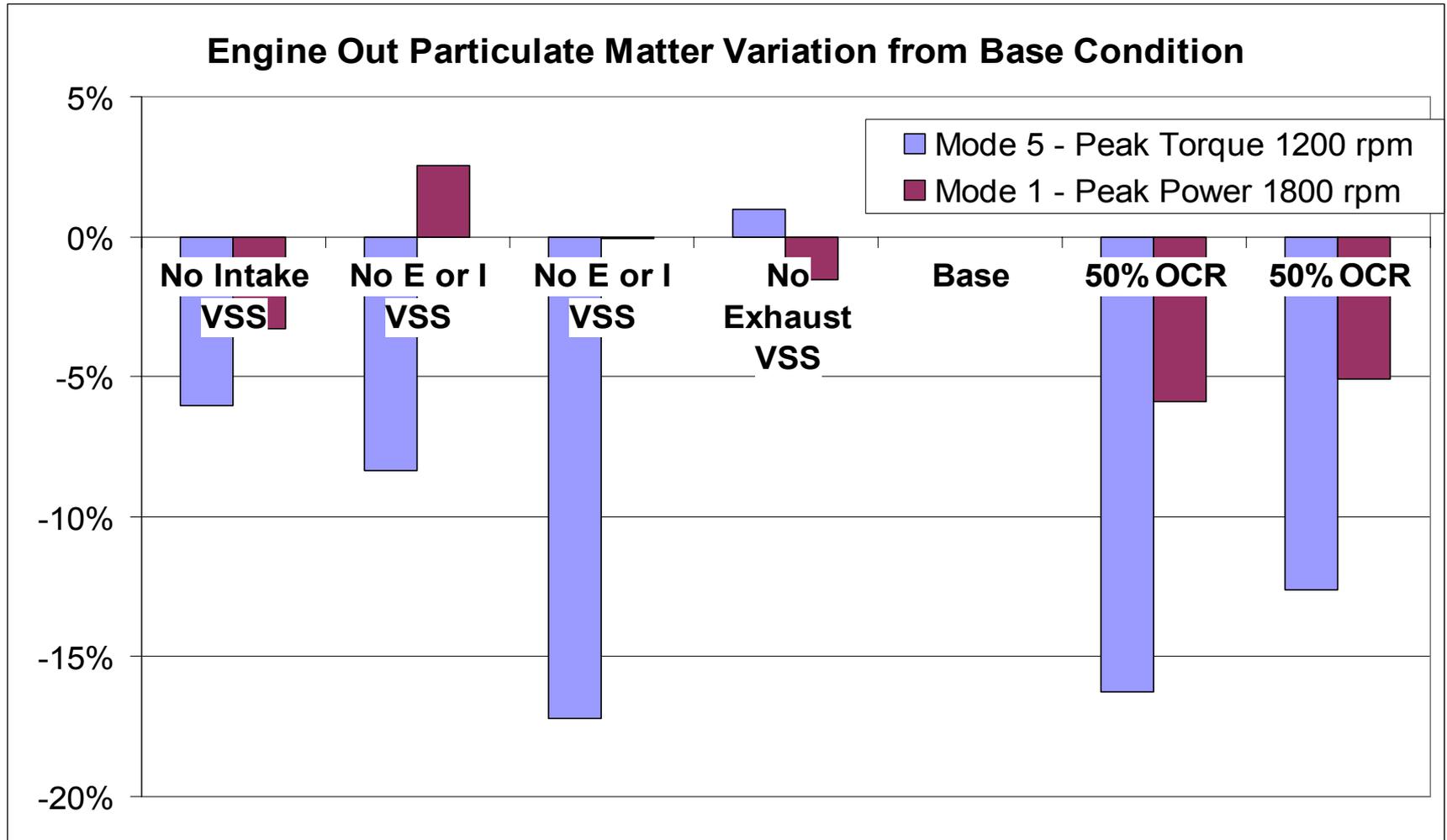


## Lube Oil Consumption

- 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

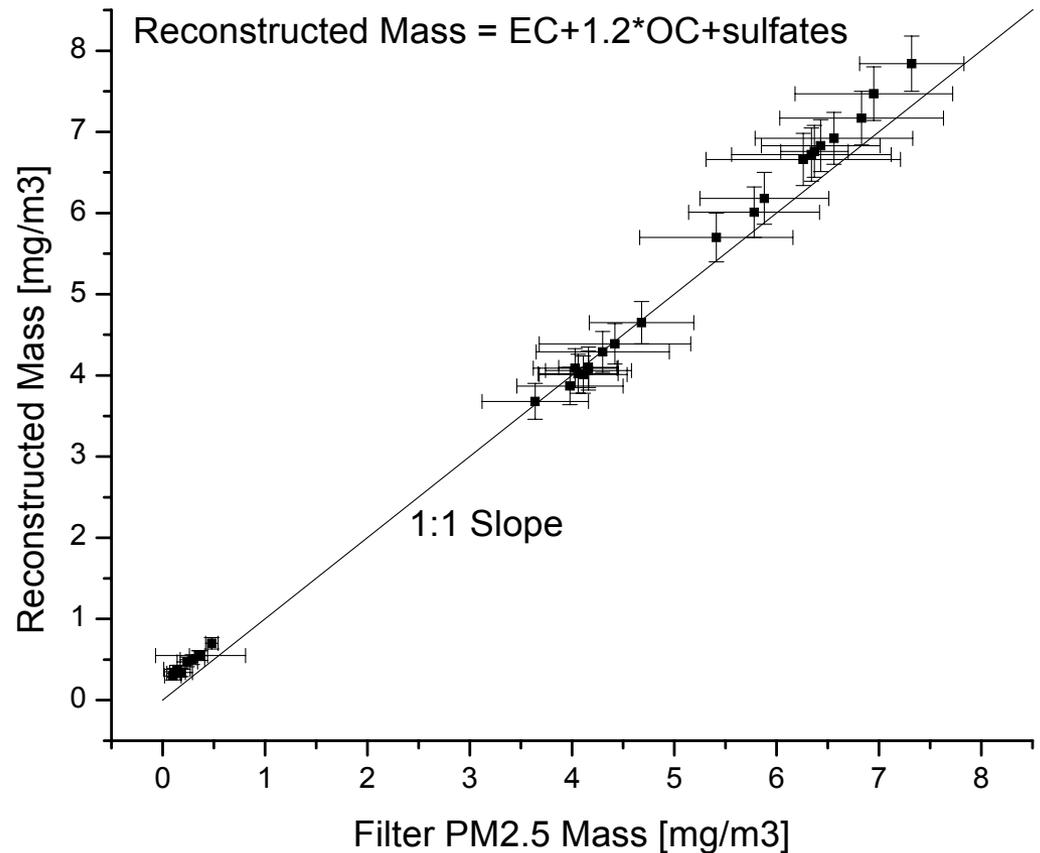
## Engine Out PM



## Experimental Results

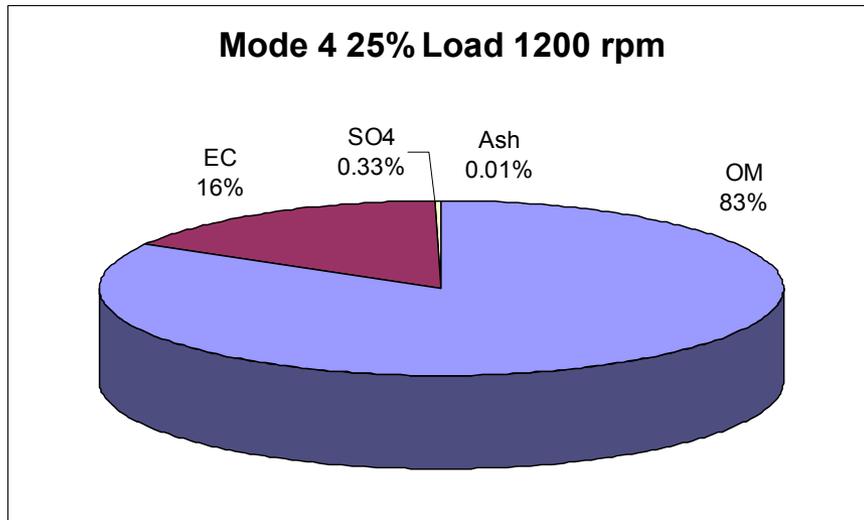
# Reconstructed Mass vs. PM2.5 Mass

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

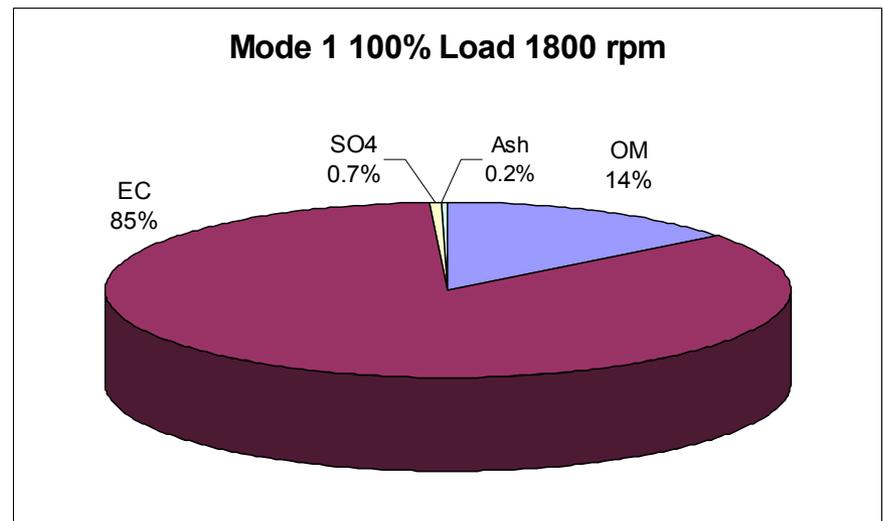
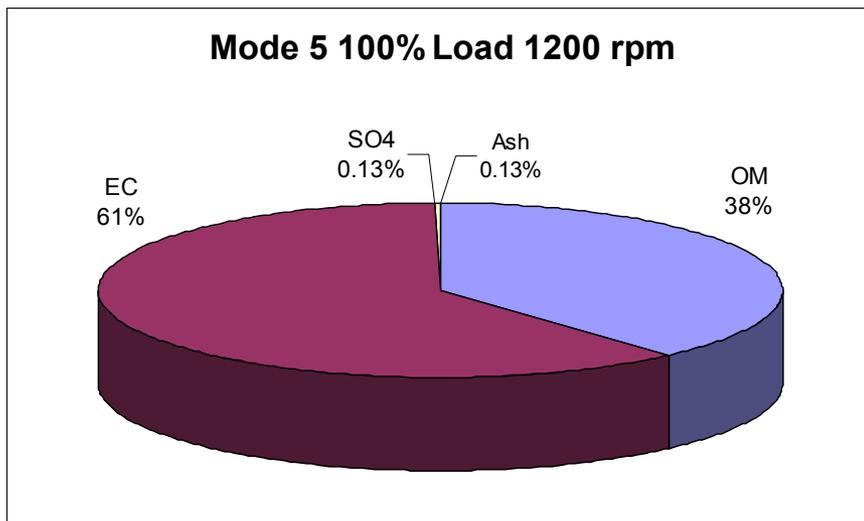


## Experimental Results

# Particulate Matter Composition

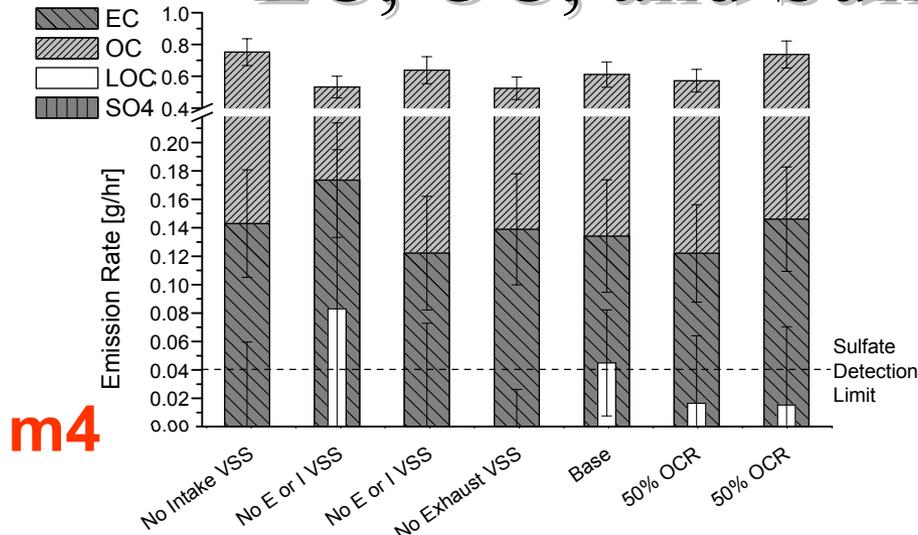


- Varying composition with engine mode
- Fairly consistent ( $\pm 5\%$ ) composition among variations in LOC for each engine mode

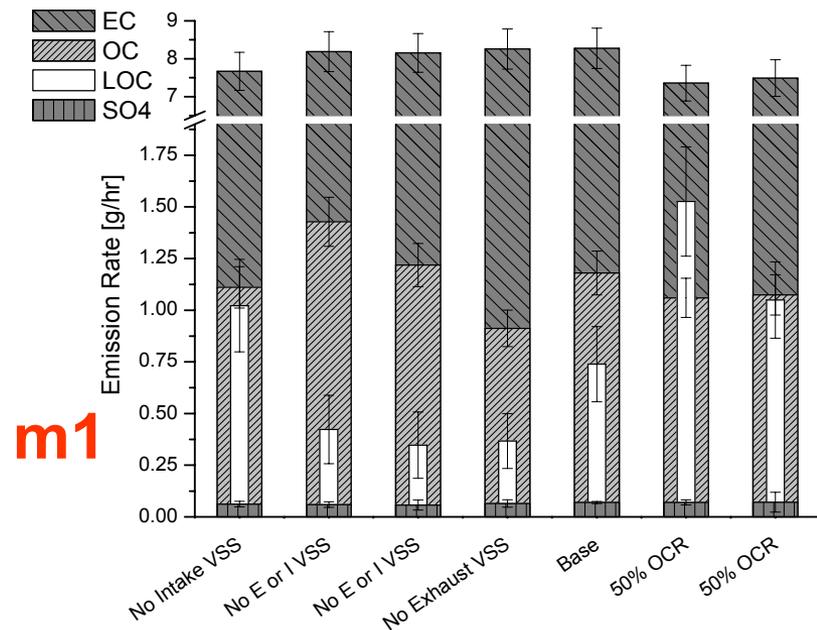
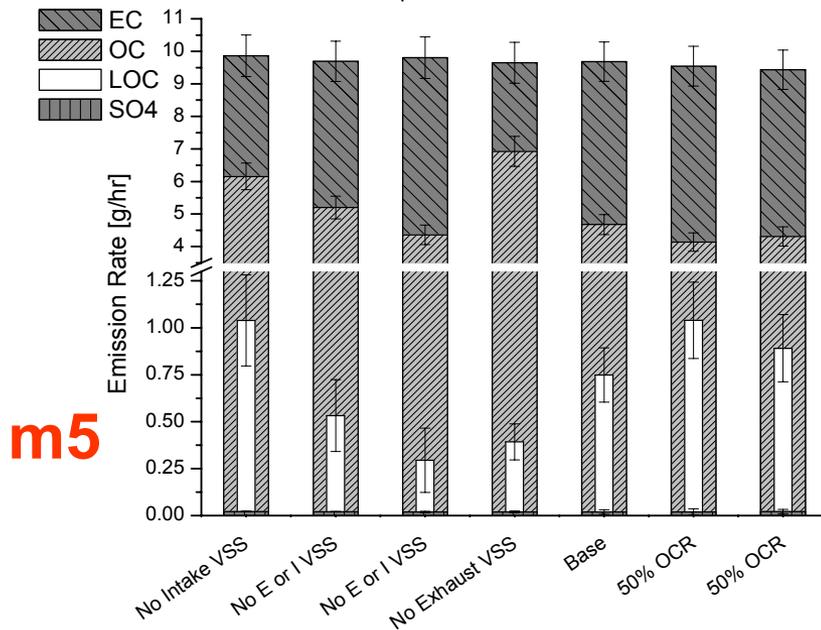


# Experimental Results

## EC, OC, and Sulfates with LOC

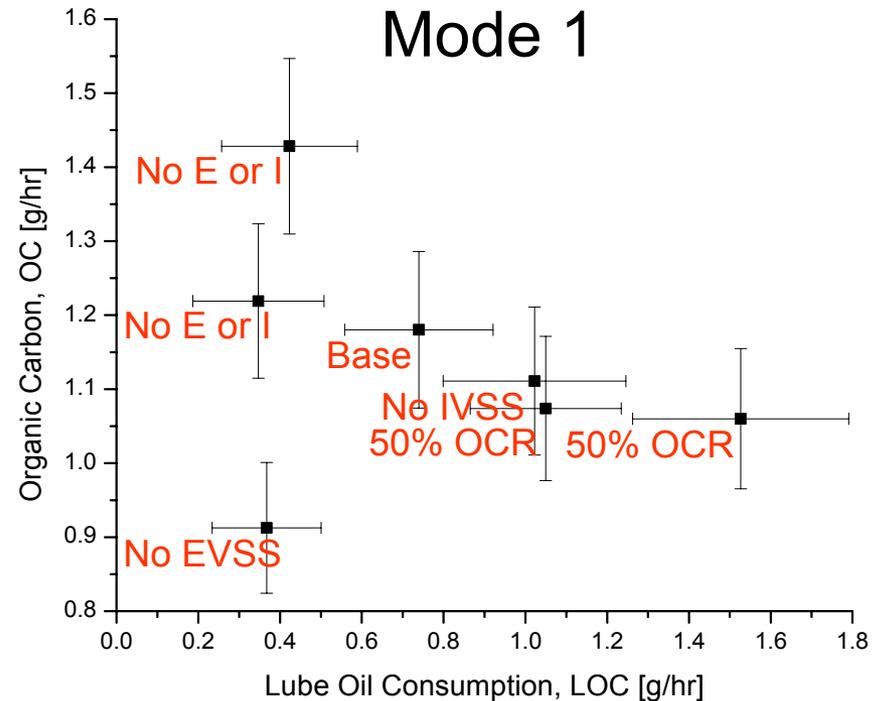
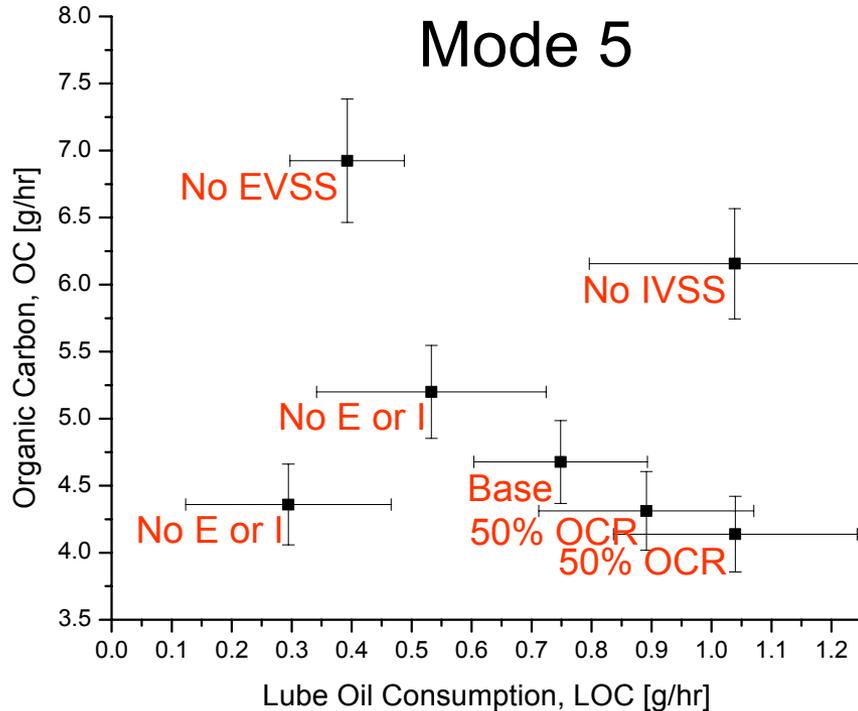


- Modes 5 and 1 show significant differences in OC emissions
- Differences do not correspond with variations in lube oil consumption



## Experimental Results

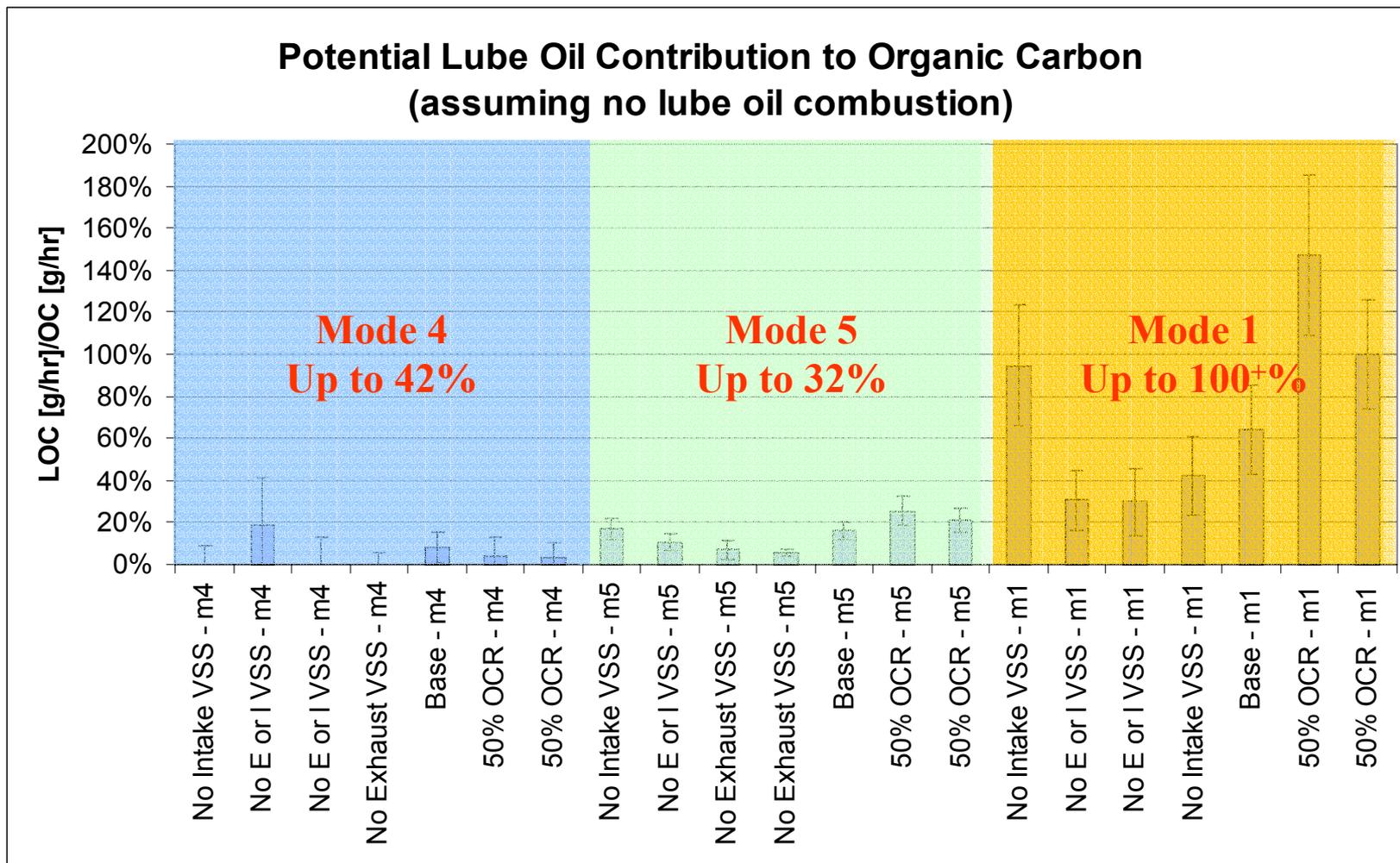
# OC vs. LOC for Mode 5 and Mode 1



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

# Experimental Results

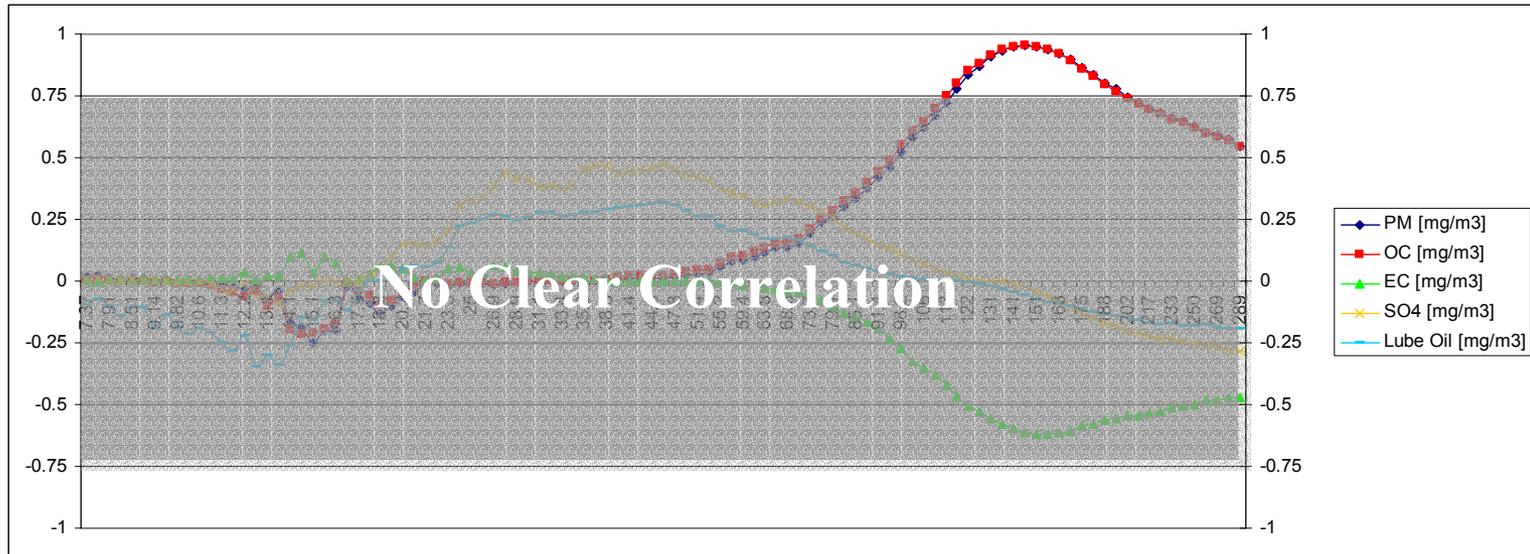
## Lube Oil Contribution to OC



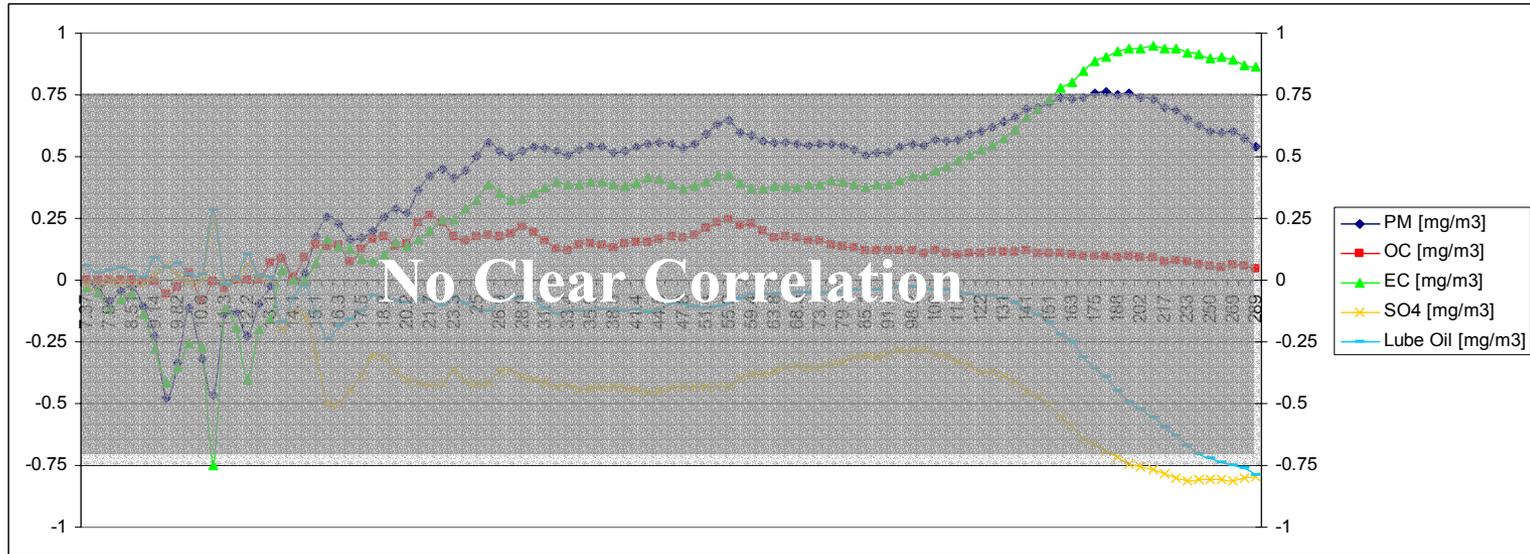
# Experimental Results

## Filter and SMPS Correlations

Mode 5



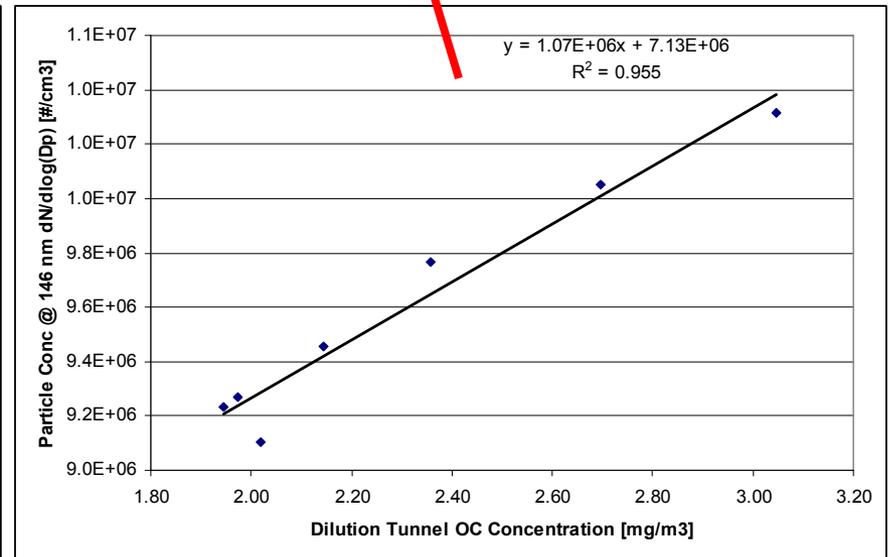
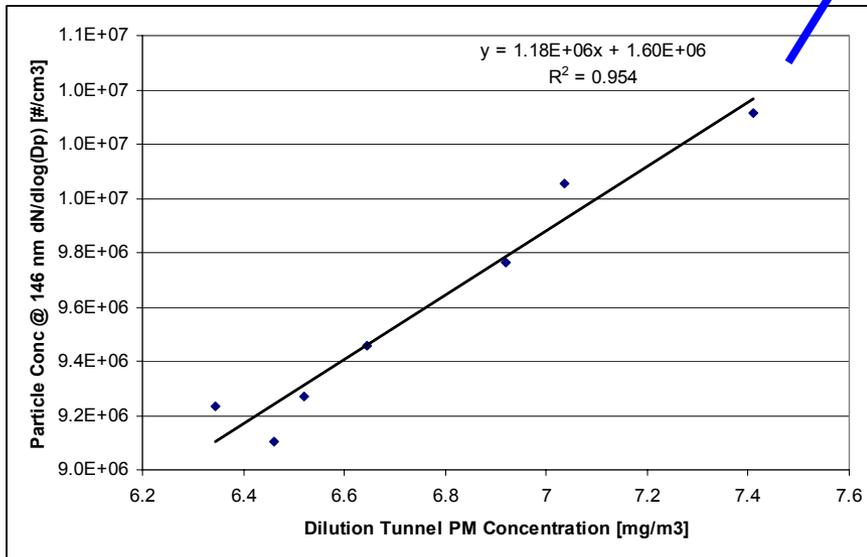
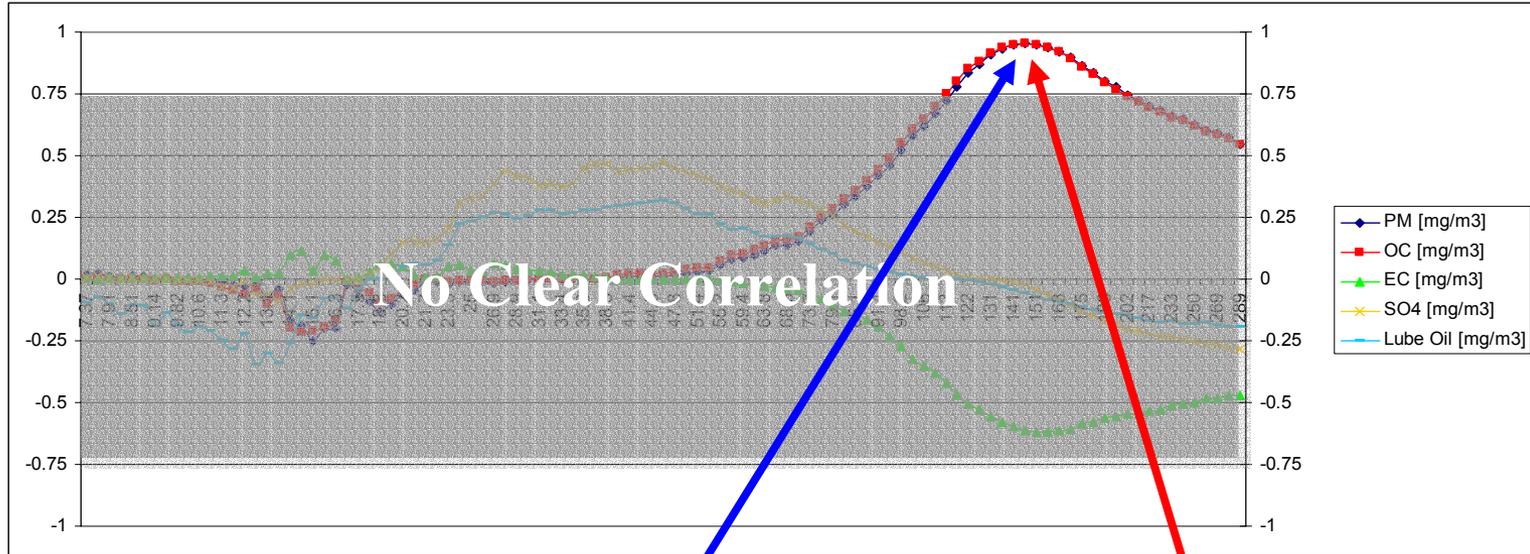
Mode 1



# Experimental Results

## Filter and SMPS Correlations

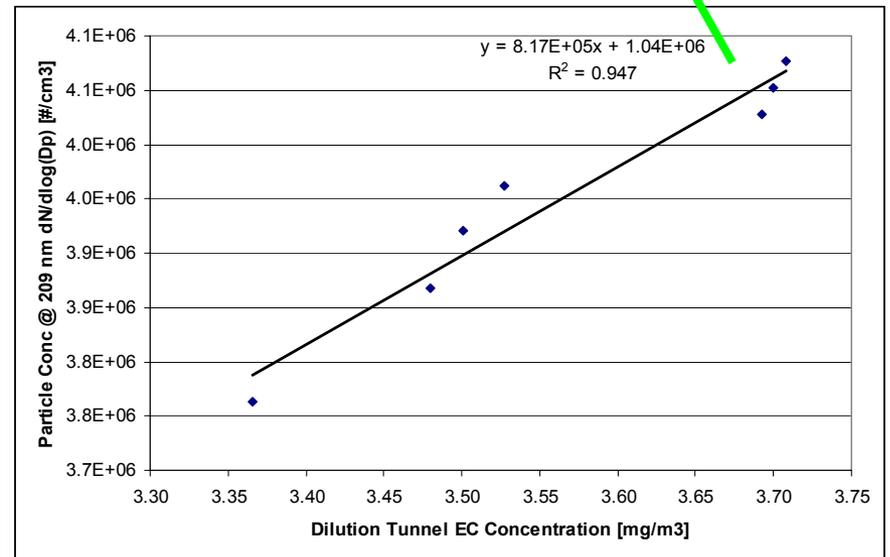
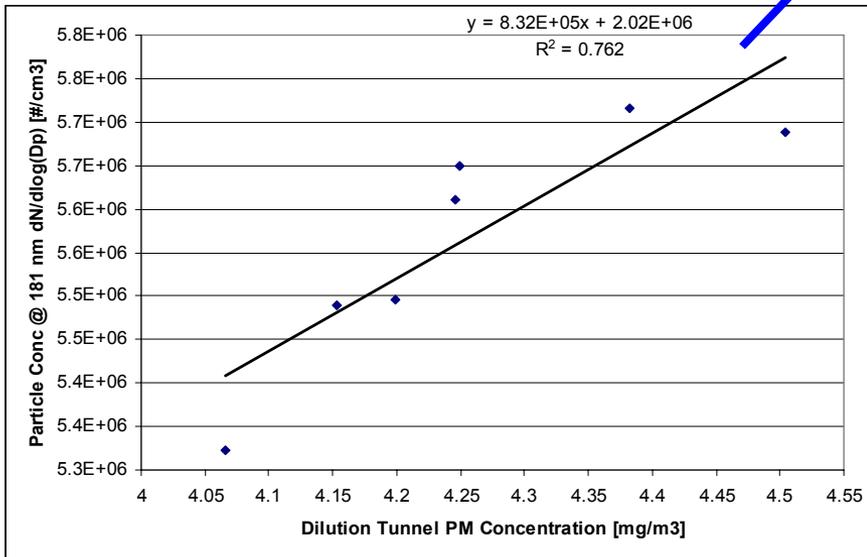
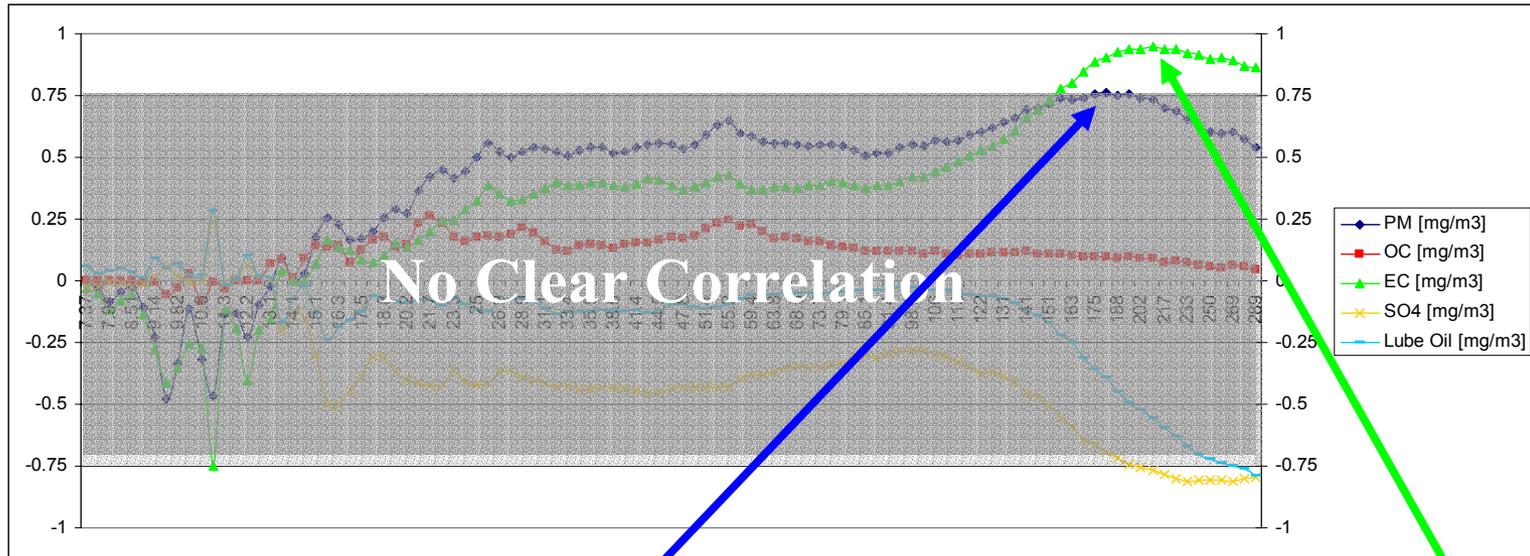
Mode 5



# Experimental Results

## Filter and SMPS Correlations

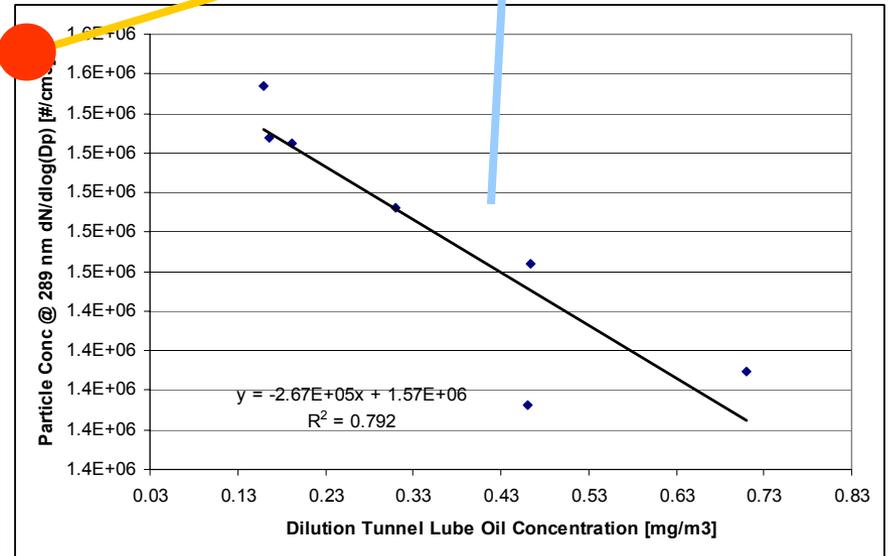
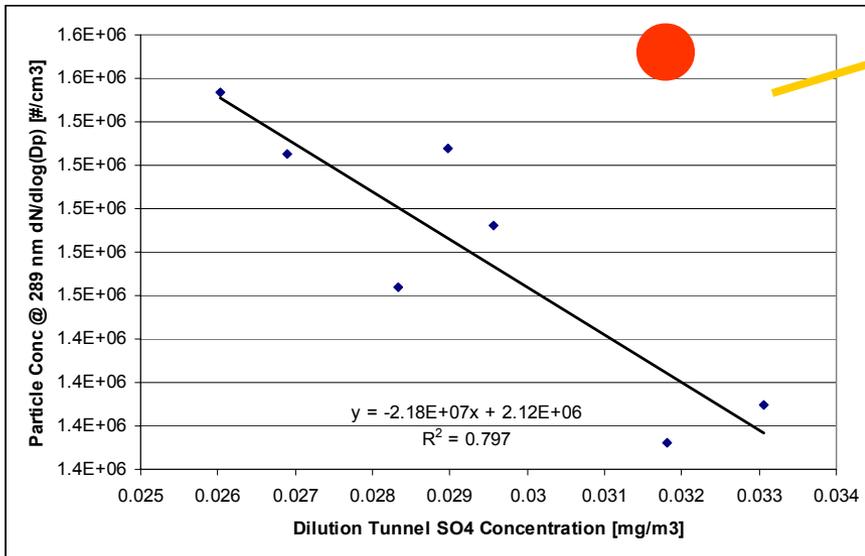
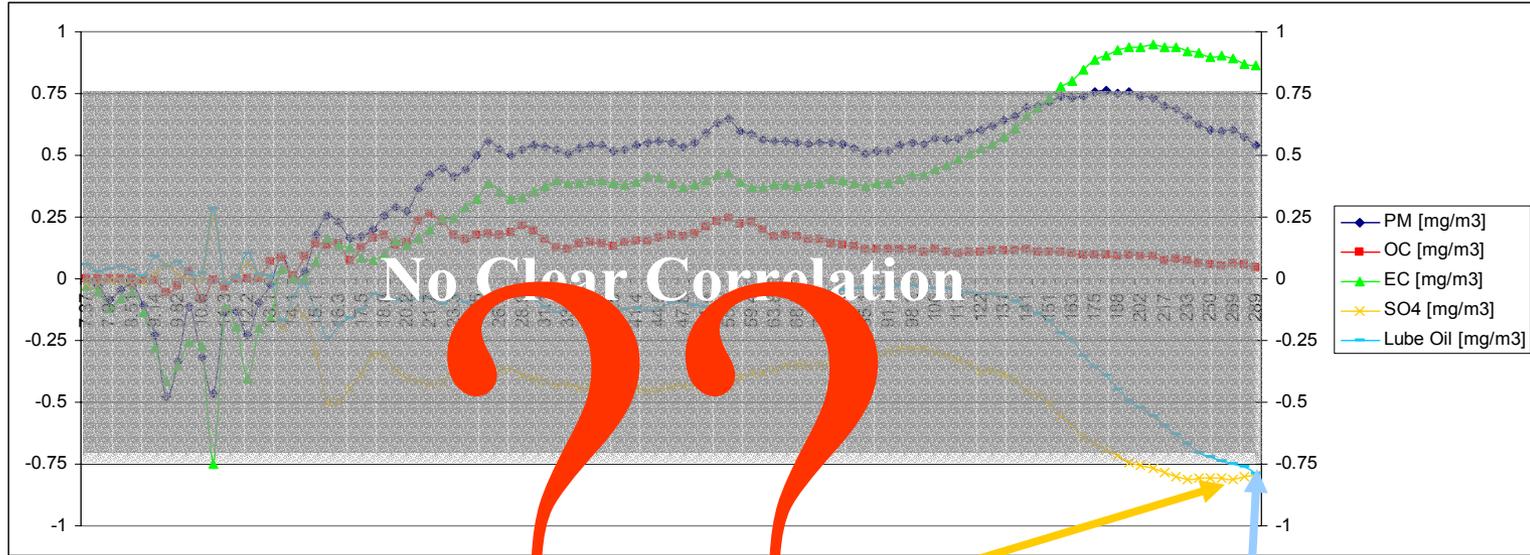
Mode 1



# Experimental Results

## Filter and SMPS Correlations

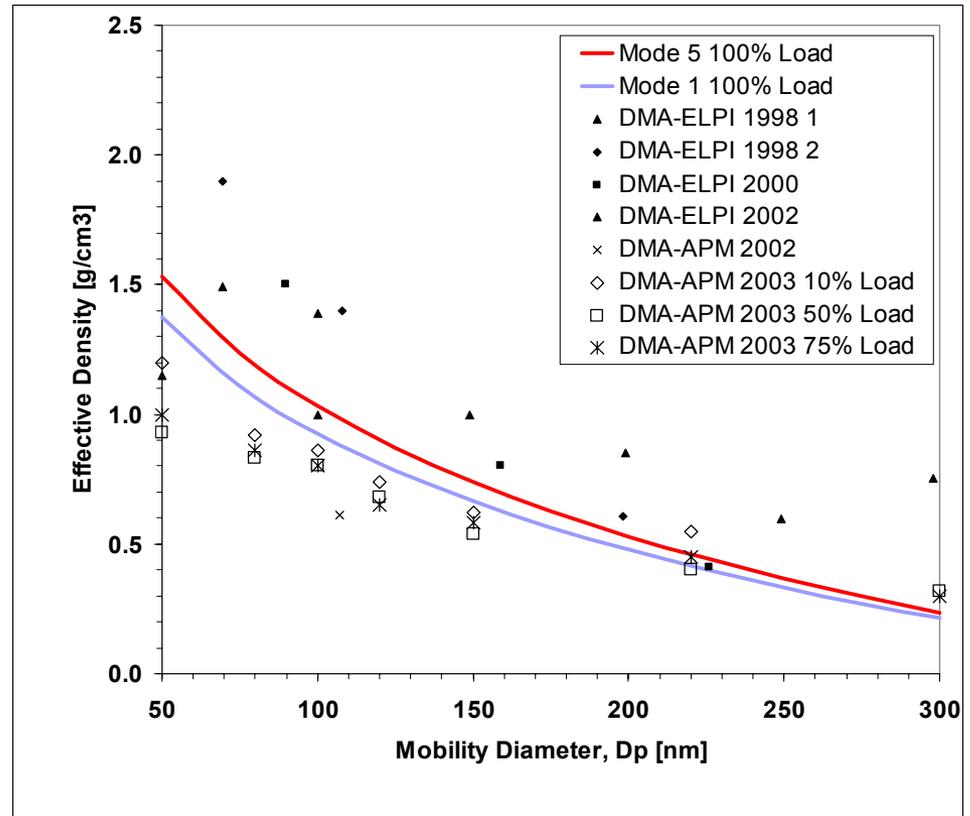
Mode 1



## Experimental Results

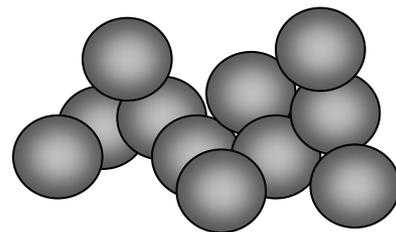
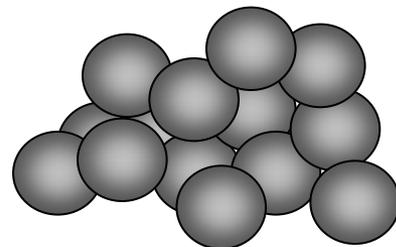
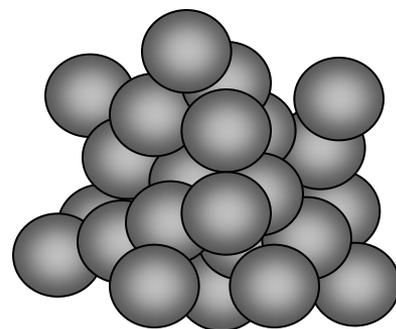
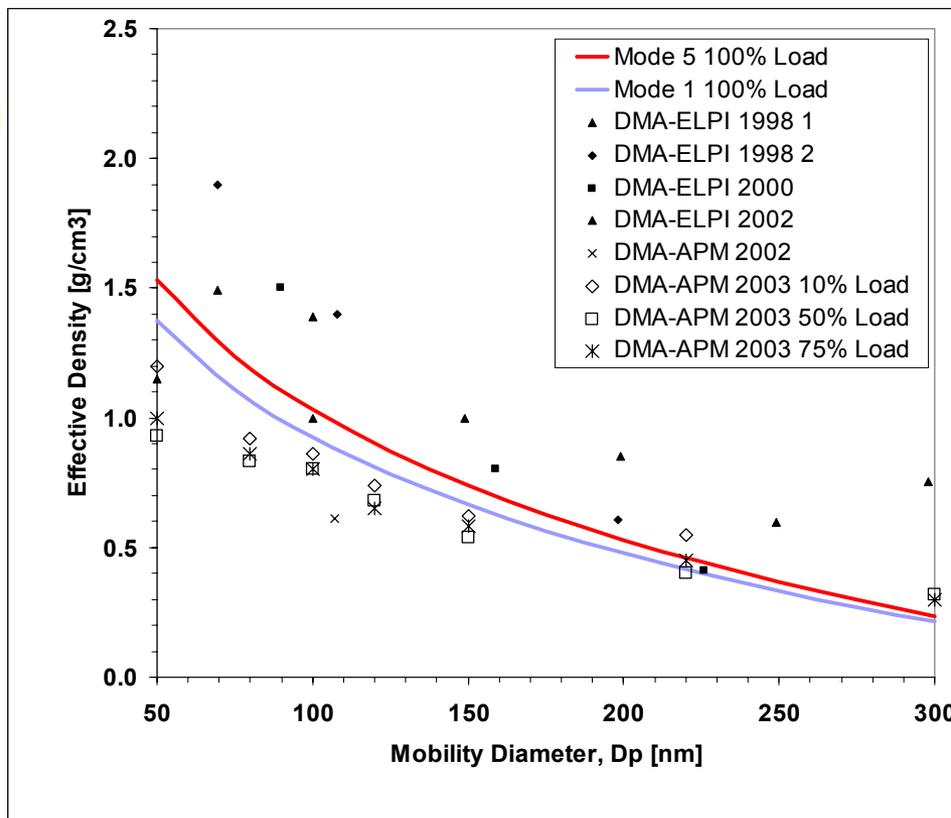
# Particulate Matter Effective Density

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

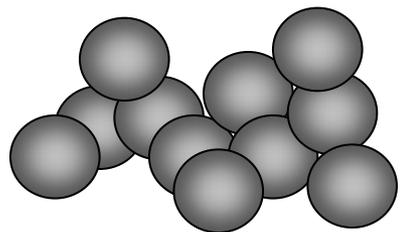
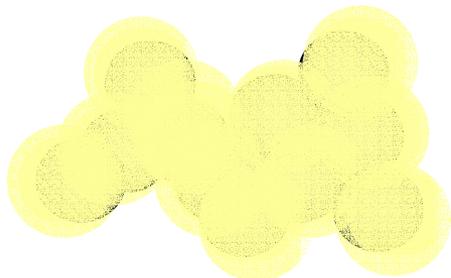
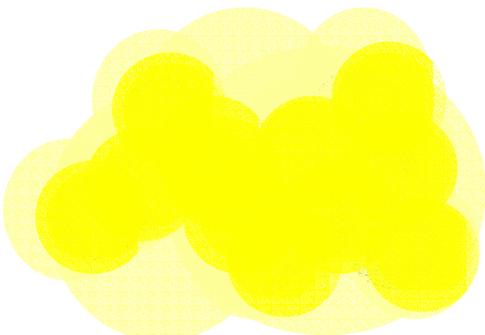


# Experimental Results

## Particulate Matter Effective Density



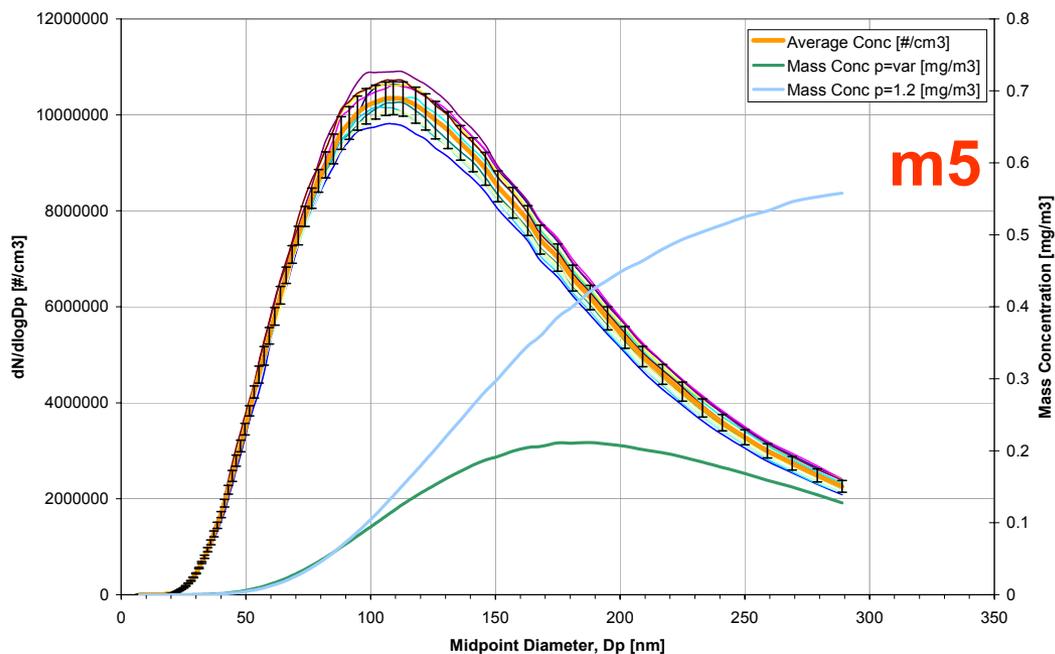
← 200 nm →



← 200 nm →

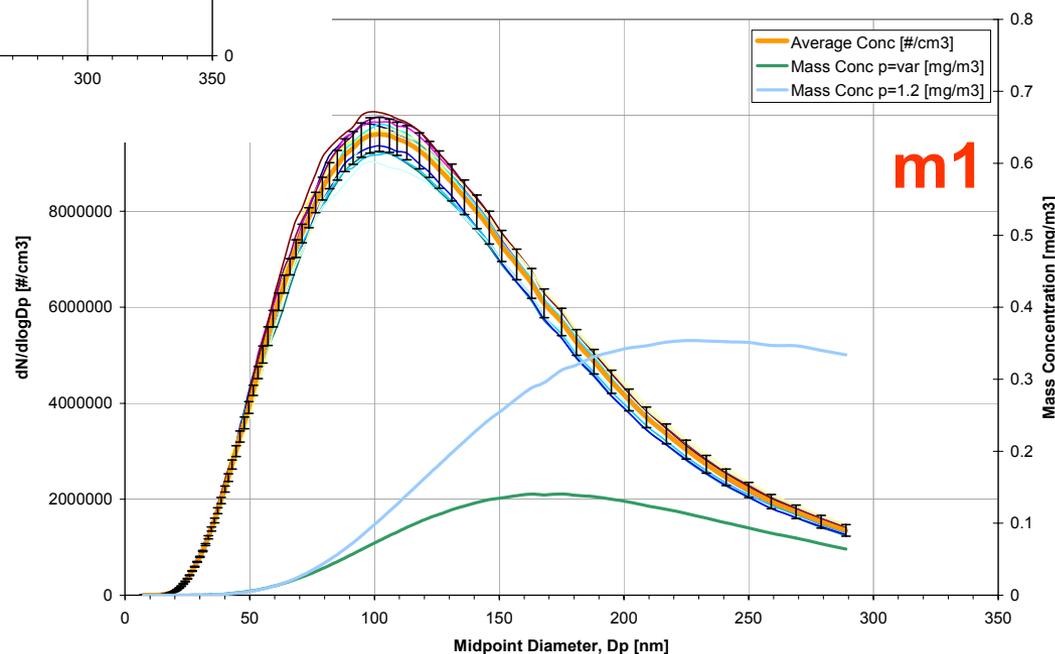
# Experimental Results – SMPS Size Distributions

20030529m530 - 50% Oil Control Ring



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

20030529m125 - 50% Oil Control Ring



- 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?

