NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Collaborative Lubricating Oil Study on Emissions (CLOSE Project)

Vehicle Technologies Program Merit Review
Washington, DC

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May 12, 2011

Project ID: ACE046

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This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview/Collaboration/Coordination

Timeline

- Start Date: April 2007
- End Date: May 2011
- Percent Complete: 100%

Budget

- Total Project Funding $1.44 MM
  - $792K FY06-FY10 DOE; none in FY11
  - $322K CRC
  - $210K SCAQMD/CARB/CEC thru CRADA with NREL
  - $100K NREL Strategic Initiative Funds
  - $5K Lubrizol
  - All lubricants provided by American Chemistry Council Product Approval Protocols Task Group (PAPTG)

Project Team

- CLOSE Project Sponsors
- Southwest Research Institute
- Elemental Analysis Inc.
- Desert Research Institute

Barriers

VT Draft MYPP ACE R&D Goals

- Improve engine efficiency while meeting future federal and state emissions regulations
- Lack of data regarding fuel and lubricant interactions on emissions from pre-commercial, future, and in-use combustion engines, especially with alternative fuels
- Public understanding/knowledge of potential health impacts of new vehicle technologies, if there are any

Partners/Acknowledgments

- South Coast AQMD
- California Air Resources Board
- California Energy Commission
- Coordinating Research Council, AVFL-14 Project
- Lubrizol
- American Chemistry Council PAPTG
- VIA Metropolitan Transit (San Antonio) and Foothills Transit (Southern California) provided HD test vehicles

Relevance

Collaborative Lubricating Oil Study on Emissions (CLOSE) Project

Objective

Quantify the relative contributions of fuel and engine lubricating oil to motor vehicle particulate matter (PM) and semivolatile organic compound (SVOC) emissions through extensive chemical and physical characterization of emissions under a variety of engine operating conditions

Does the CLOSE Project Pass the "So What" Test?

- PM from light-duty vehicle "normal" emitter's tailpipe = <1-2 mg/mile
- PM from new 2007-compliant heavy-duty diesel trucks = 1-4 mg/mile
- PM from Amy Winehouse's open window at 60 mph = 5 mg/mile

But Source Apportionment Studies in urban areas suggest that a large fraction of $PM_{2.5}$ comes from mobile sources, especially LD vehicles – Why??

CLOSE Project Milestones

- Funding for project began at $250K from DOE Office of Vehicle Technologies and we grew it to ~$1.5MM from government and industry groups
- All vehicle testing completed in June 2010
- All fuel and lubricant (fresh and aged) chemical analyses completed in August 2010
- All chemical analyses of exhaust samples completed in October 2010
- Last project review meeting was held at SwRI in September 2010 to review analyses of all vehicle emissions data and apportionment results
- First draft final report sent to CLOSE Project sponsors for review in December 2010
- Revised final draft report received by sponsors in April; final report released by end of May 2011

Vehicle, Fuel, Lube, and Temp Test Matrix

Test Temperature	72°F				20°F			
Test Lubricant	Fresh		Aged		Fresh		Aged	
Sample Number	1	2	1	2	1	2	1	2
LD E0 gasoline (normal PM emitter)	✓	✓	✓	✓	✓	✓	✓	✓
LD E0 gasoline (high PM emitter)	✓	✓	✓	✓	✓	✓	✓	✓
LD E10 (normal PM emitter)	✓	✓	✓	✓	✓	✓	✓	✓
LD E10 (high PM emitter)	✓	✓	✓	✓	✓	✓	✓	✓
MD TxLED diesel (normal PM emitter)	✓	✓	✓	✓	✓	✓	✓	✓
MD TxLED diesel (high PM emitter)	✓	✓	✓	✓	✓	✓	✓	✓
MD B20 biodiesel (normal PM emitter)	✓	✓	✓	✓	✓	✓	✓	✓
MD B20 biodiesel (high PM emitter)	✓	✓	✓	✓	✓	✓	✓	✓
HD CNG (normal PM emitter bus)	✓	✓	✓	✓				
HD CNG (high mileage bus)	✓	✓	✓	✓				
HD TxLED diesel (normal PM emitter bus)	✓	✓	✓	✓				
HD TxLED diesel (high mileage bus)	✓	✓	✓	✓				

⇐ Today's Presentation

LD and MD Driving Cycle: California Unified Cycle (LA-92)
HD Driving Cycle: EPA HD Urban Dynamometer Driving Schedule (heavy duty chassis cycle)

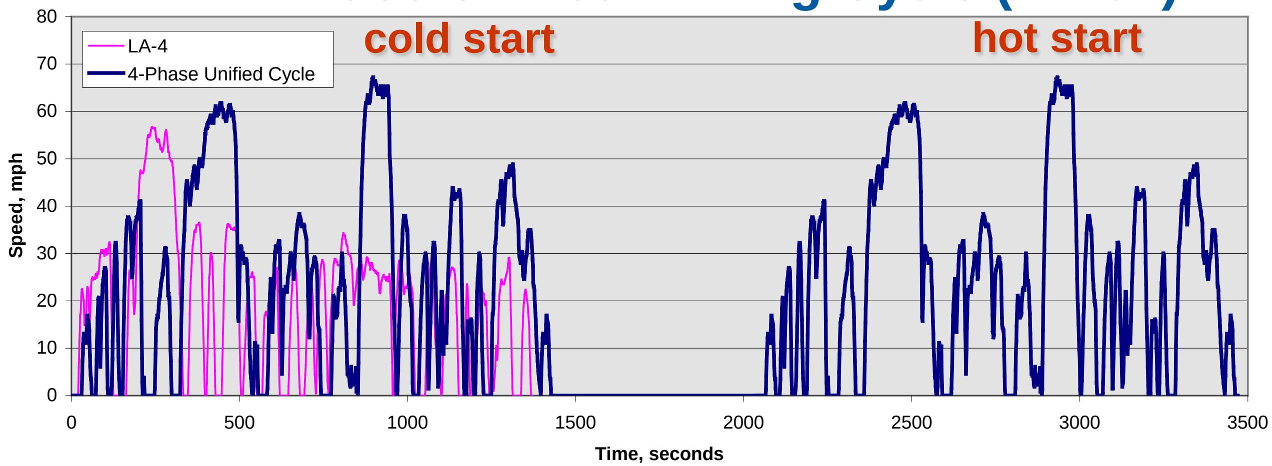
Test Vehicles

	Fuel	Category	MY	Brand	Model	Engine	Starting Odometer	Comments
MD	diesel	Normal PM Emitter	2007	Ford	F-250	6.0L V8	57,665	oxidation catalyst and EGR
		High PM Emitter	1989	Ford	F-250	7.3L V8	498,446	naturally aspirated, indirect fuel injection, ~2000 miles/quart of oil
HD	diesel	Normal PM Emitter	2001	NABI	40 LFW	8.3L Cummins I6	461,403	145 miles/quart of oil
		High ~~PM Emitter~~ Mileage	2001	NABI	40 LFW	8.3L Cummins I6	569,240	971 miles/quart of oil (high blowby)
	natural gas	Normal PM Emitter	2006	NABI	40 LFW	8.3L Cummins I6	162,366	catalytic muffler
		High ~~PM Emitter~~ Mileage	2003	Orion	VII	DDC S-50G	335,064	catalytic muffler

- **NABI – North American Bus Industries**
- **Diesel buses provided by VIA Metropolitan Transit**
- **CNG buses Provided by Foothills Transit; arrangements and shipment by SCAQMD**

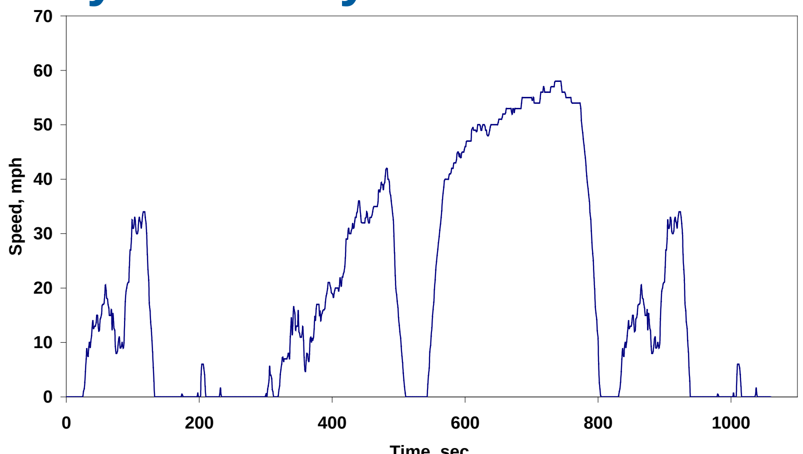
Driving Cycles for MD and HD Vehicles

MD: 4-Phase Unified Driving Cycle (LA-92)



- **Normal Emitter: 2 cold-start tests composited per sample**
- **High Emitter: 1 cold-start test per sample**

HD: Heavy-Duty Urban Dynamometer Driving Schedule



- **NG buses: One cold start cycle and five hot-start cycles composited per sample**
- **Diesel buses: One cold start and one hot-start cycle composited per sample**

Oil and Fuel Properties

	Medium-Duty Diesel	Heavy-Duty Natural Gas	Heavy-Duty Diesel
Performance Level	**API CJ-4**	**Cummins CES20074 / DDC 7SE272**	**API CJ-4/SM**
Viscosity Grade	**15W40**	**15W40**	**15W40**
How Aged Oil was Generated	**Heavy-Duty Class 8 trucks over the road 80,000 lb max. Drain intervals 20,000 - 30,000 miles.**	**Natural Gas City Bus Service, approx. 60,000 miles/yr. 6,000 mile drain interval.**	**HD diesel line service running 50% of the time at 80,000 pound GVW. Drain interval was 25,000 miles.**
Supplier	**Afton**	**Oronite**	**Lubrizol**

- **Fresh oil was same formulation as aged oil**
- **Fresh and aged oils blended with deuterated alkane hexatriacontane ($C_{36}D_{74}$) as a tracer**
- **Lubricants with tracer "degreened" in test vehicle over 150 highway miles with appropriate test fuel**

Medium-Duty Vehicle Fuel

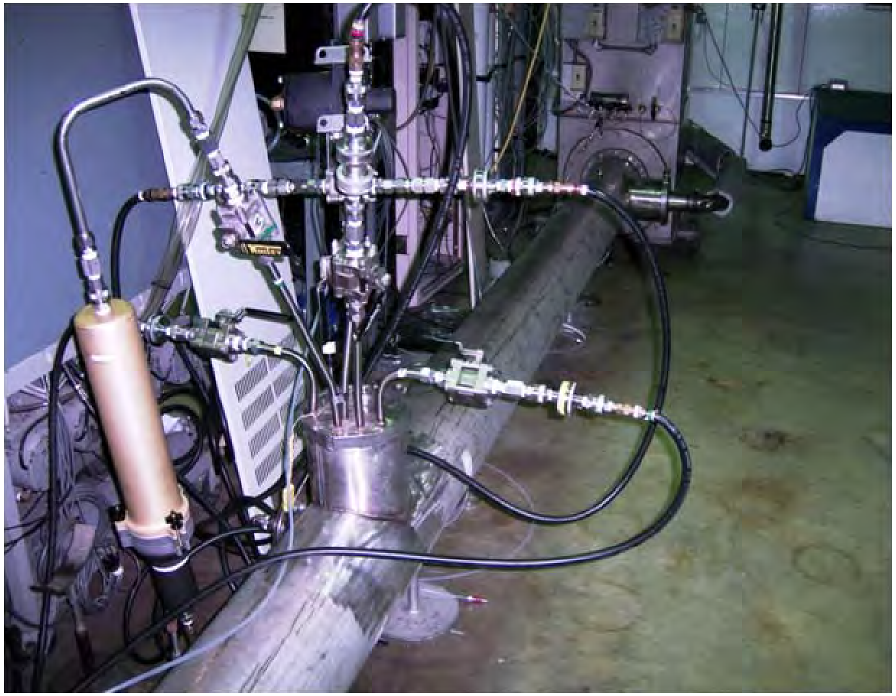
- **Texas low-sulfur (~6 ppm S) commercial diesel (TxLED)**
- **B20: biodiesel splash-blended with TxLED**

Heavy-Duty Vehicle Fuel

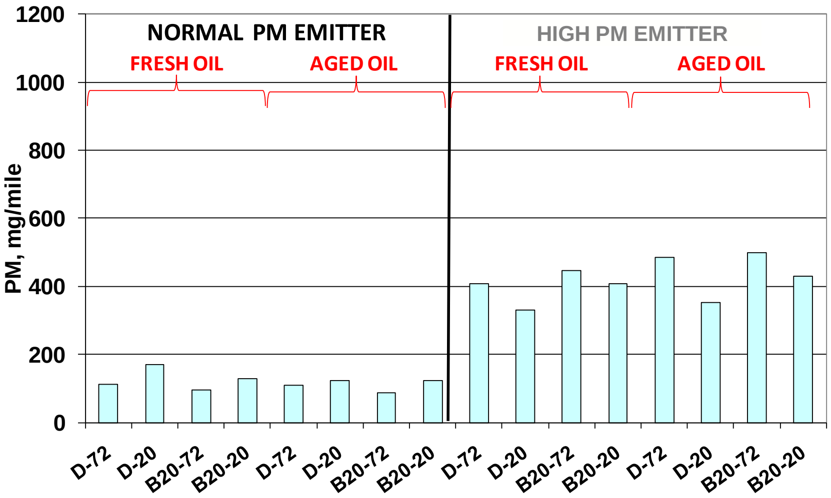
- **Texas low-sulfur (~8 ppm S) commercial diesel (TxLED)**
- **Natural gas blended at SwRI meets Federal and CARB certification test formulations**

Composite PM & SVOC Samples Collected for Analyses

- Mass – measured by two groups
- Elements
- (including lube oil markers)
- Hopanes and steranes
- "Elemental" and "organic" carbon
- PAHs
- C_{14} to C_{40} alkanes & cycloalkanes (Unresolved Complex Mixture (UCM)
- Soluble organic fraction
- Sulfate

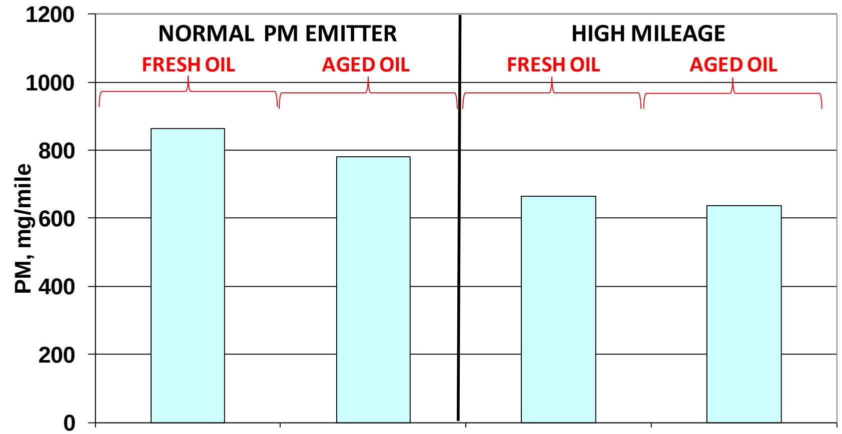


Average PM Emission Rates



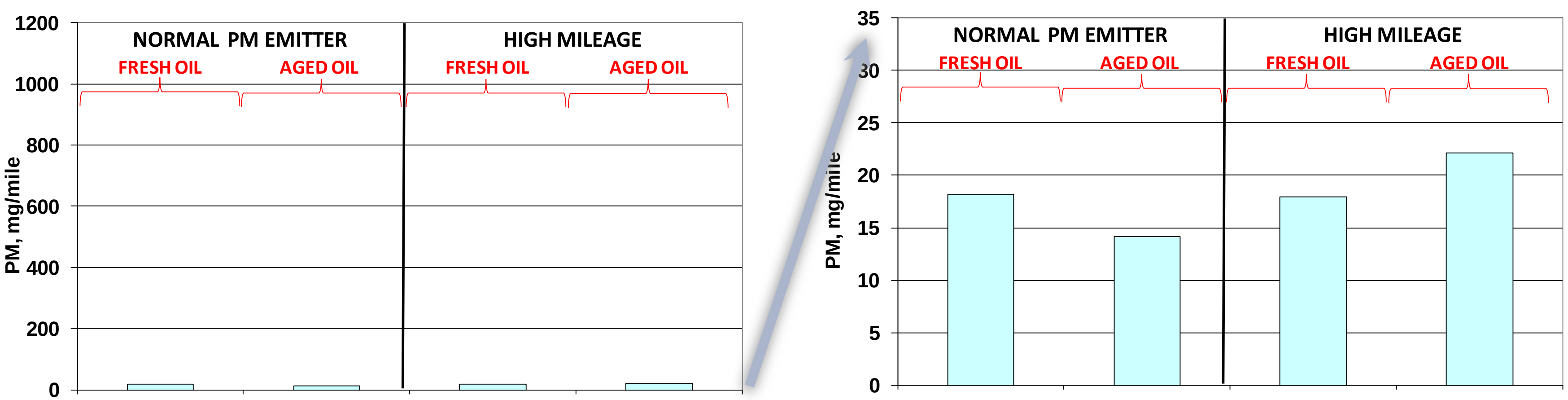
Medium Duty

(TxLED & B20 @ 72°F and 20°F)



Heavy-Duty Diesel

(TxLED Diesel only)



Heavy-Duty Natural Gas

Determination of Unburned Oil Content in PM

- **Utilized averages and sums when appropriate to reduce variability in data**

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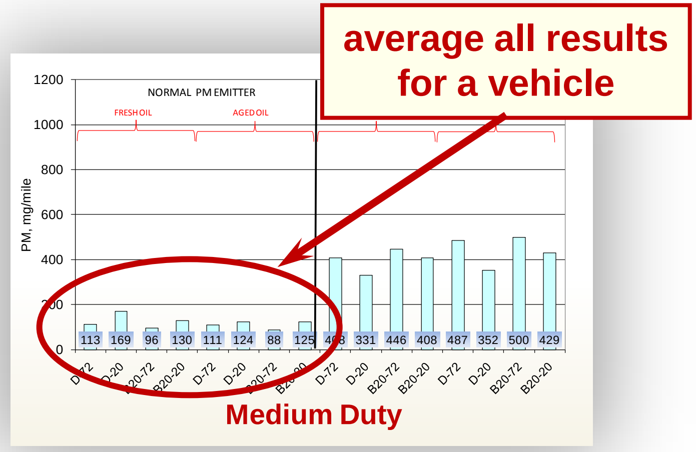
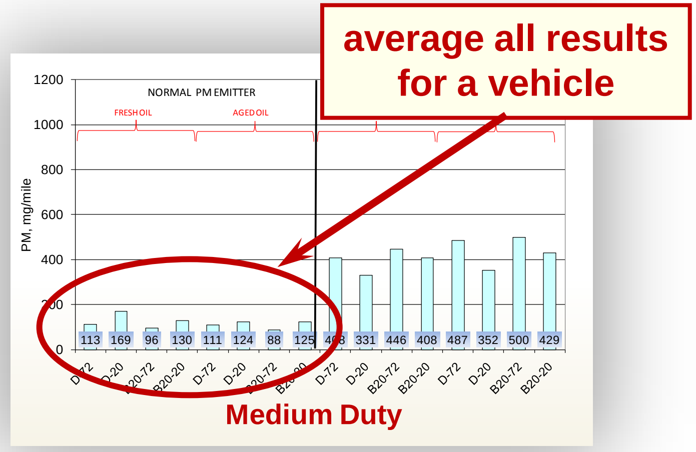


Determination of Unburned Oil Content in PM

- **Utilized averages and sums when appropriate to reduce variability in data**



- **Used Ca in PM to estimate oil consumption rate**
  - Assumed all Ca in consumed oil was collected as PM
- **Used unique oil tracers to determine unburned oil contribution to PM**
  - **hexatriacontane-d74 ($C_{36}D_{74}$)**
  - **sum of 11 hopanes and 12 steranes**
  - **sum unresolved complex mixture (UCM) of C_{20} to C_{35} alkanes and cycloalkanes**
  - **Assumed tracer mass concentration was the same in oil and PM**
- **Compared unburned oil estimates to OC and total PM**

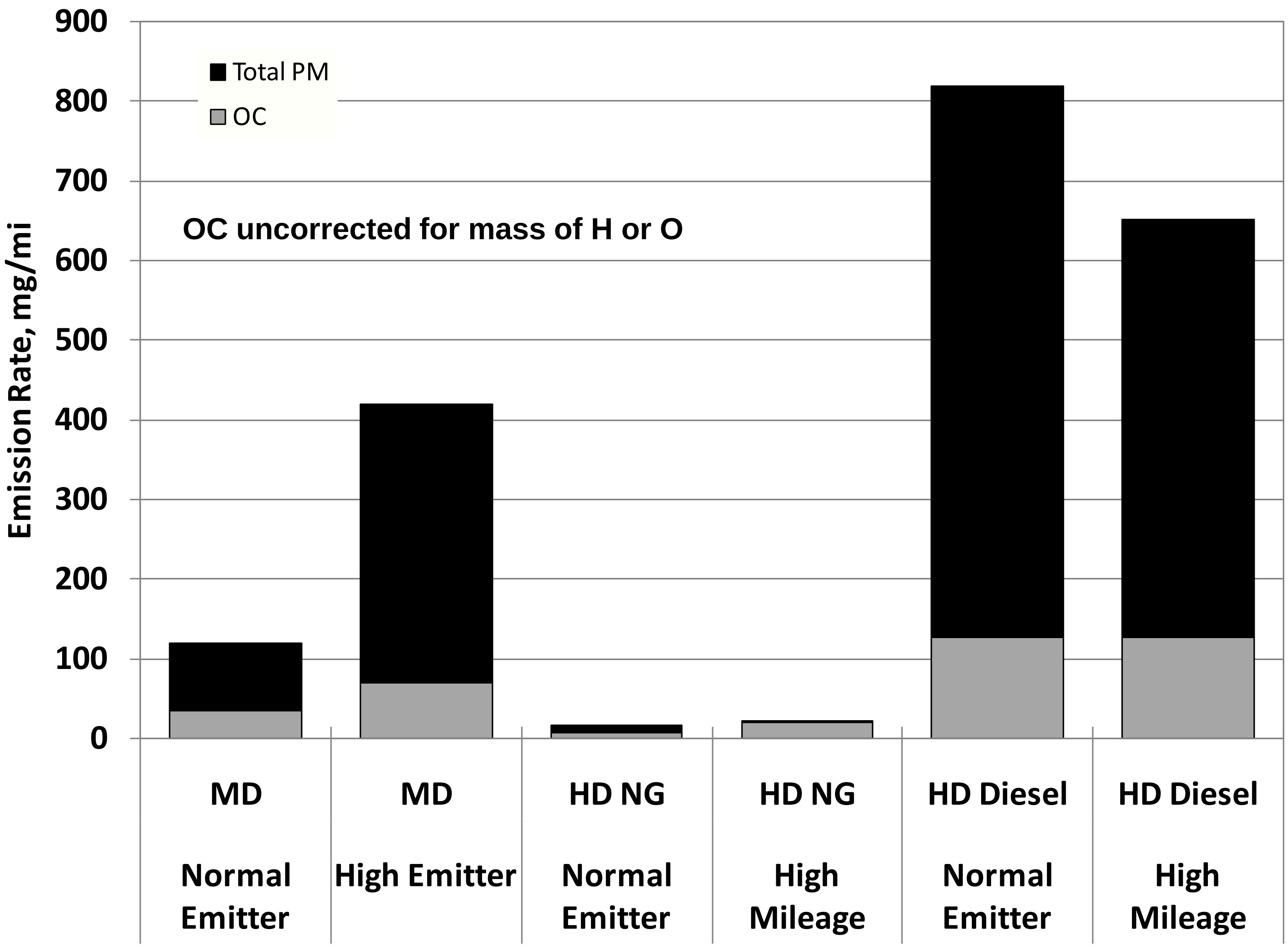
Lubricating Oil Consumption (LOC) Rate Estimates Using Oil Tracers

$$LOC_{estimated}(g/mi) = \frac{T_{Exh}(\mu g/mi)}{T_{Oil}(\mu g/g)} = A * LOC_{actual}$$

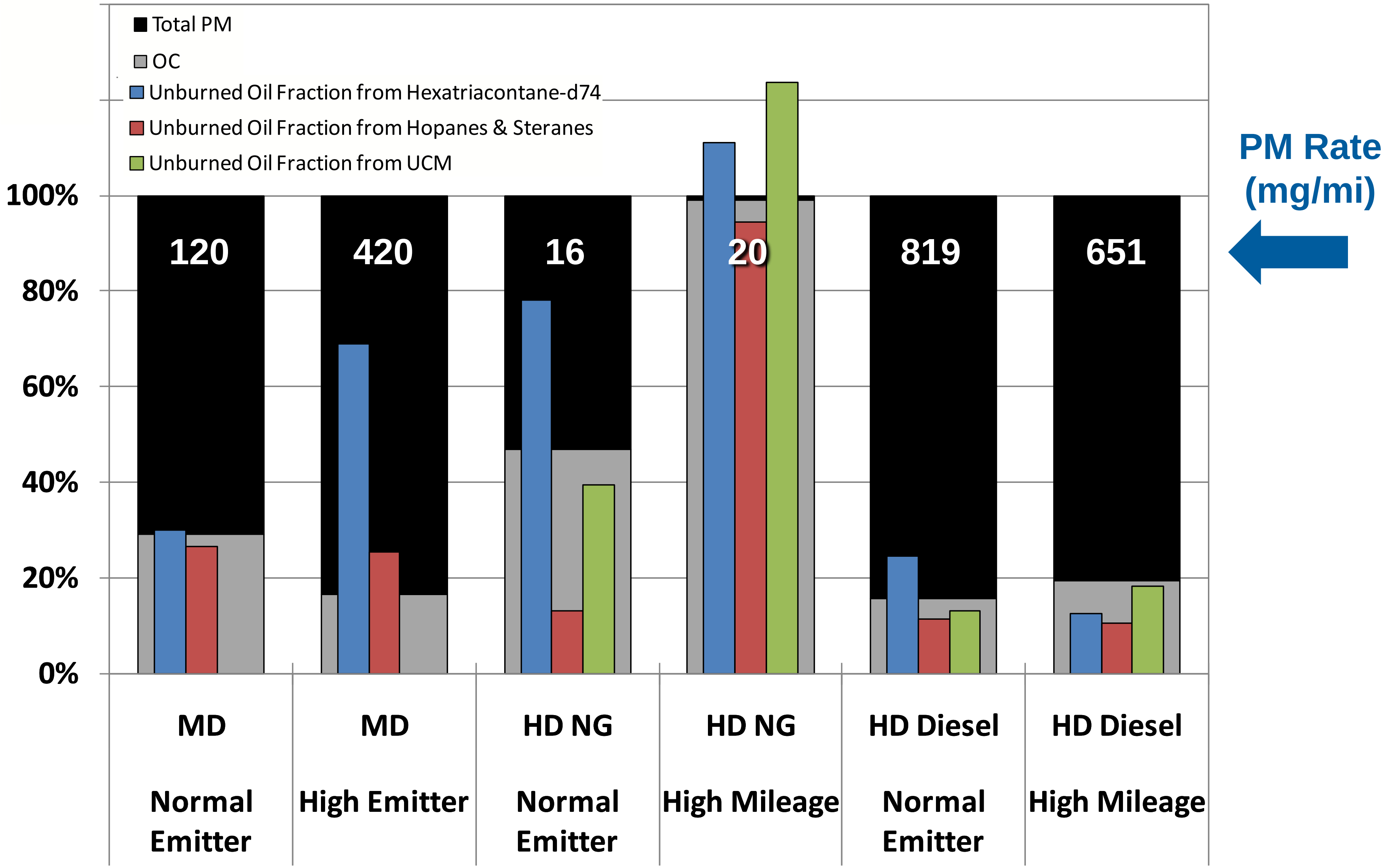
Where T is the oil tracer and A is a loss factor (less than 1) due to:

- Deposition on surfaces of combustion chamber, exhaust system, transfer lines, and CVS
- Combustion oxidation of organic compounds and loss in the sampling train
- Factor can be dependent on particle size. Metallic ash particles versus soot-bound tracers
- Factor may be a constant or a complicated function

Average OC and Total PM Emissions



Average OC & Unburned Oil Fractions of Total PM



Oil Consumption vs. PM Emissions

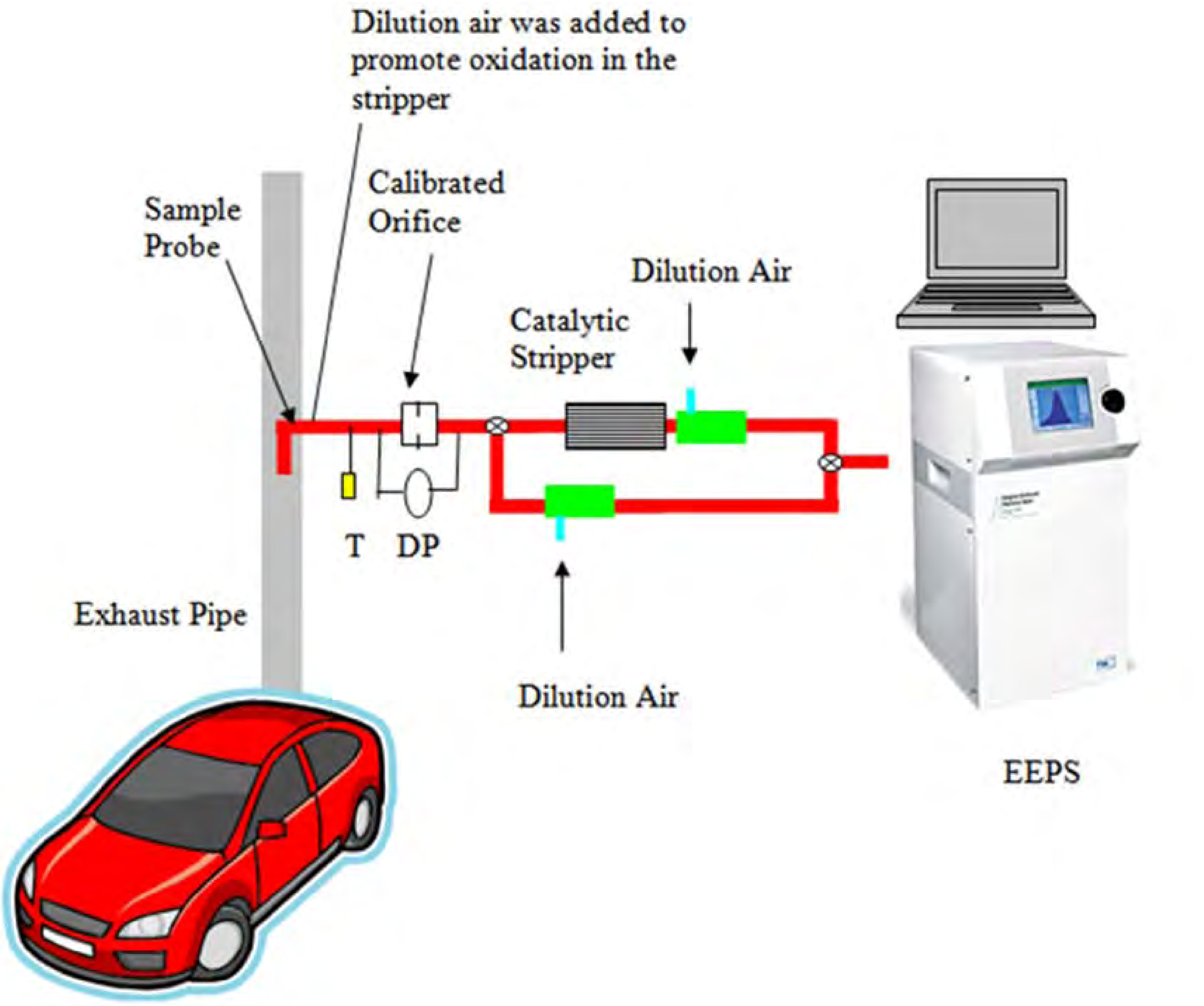
Vehicle	Oil Consumption Rate (mg/mi)		PM Emission Rate (mg/mi)		OC as % of Oil Consumption
	Calculated	Observed	Total PM	Organic Carbon	
MD Normal Emitter	133	---	120	35	26%
MD High Emitter	408	500*	420	70	17%
HD NG Normal Emitter	572	---	16	8	1%
HD NG High Mileage	359	---	20	20	6%
HD Diesel Normal Emitter	1260	858**	819	128	10%
HD Diesel High Mileage	603	---	651	127	21%

* - measured by SwRI over ~2,000 miles

** - reported by transit agency

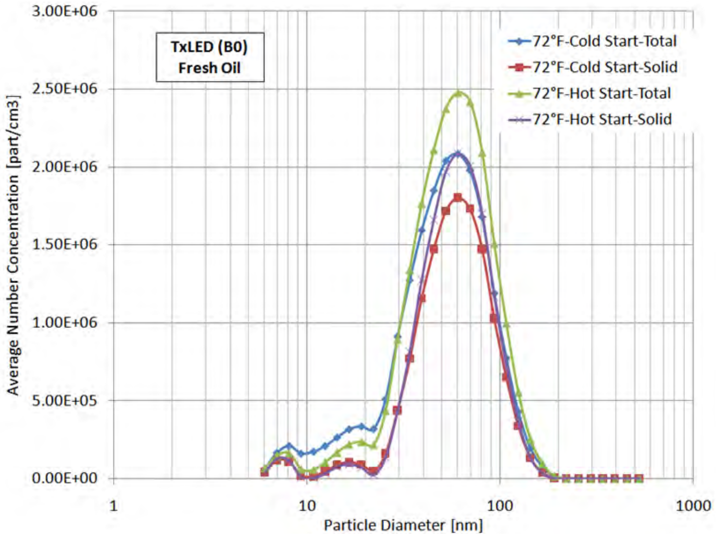
If we assume all OC comes from lube, then >70% of consumed oil is oxidized and not emitted as direct PM.
(Calculated oil consumption assumes no oil deposition in exhaust.)

Set-up for Particle Number and Size Measurements

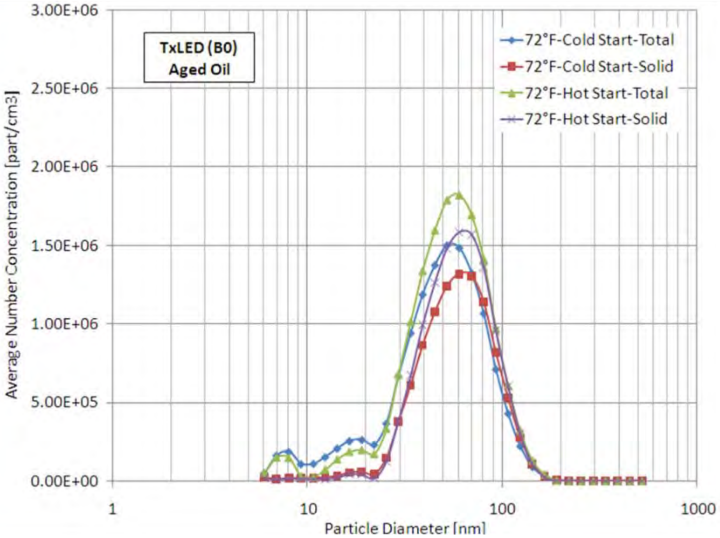


Ultrafine Particle Number Count/Size Distributions
MD Diesel Normal and High Emitters using TxLED Fuel

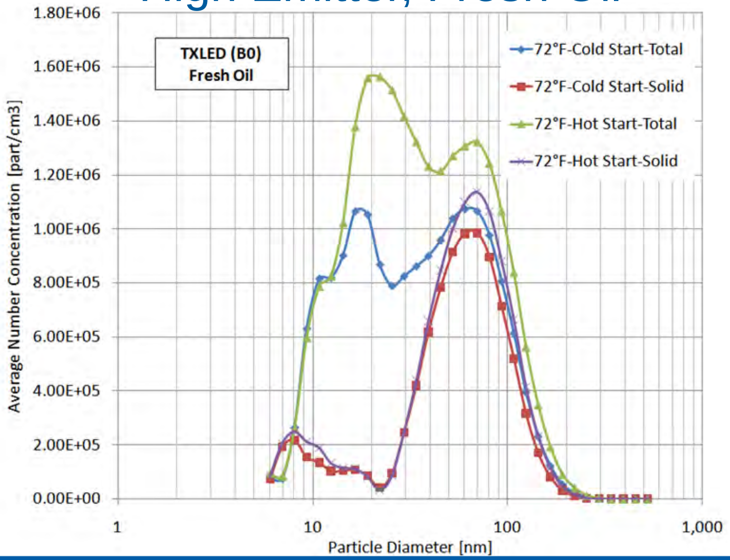
Normal Emitter, Fresh Oil



Normal Emitter, Aged Oil



High Emitter, Fresh Oil



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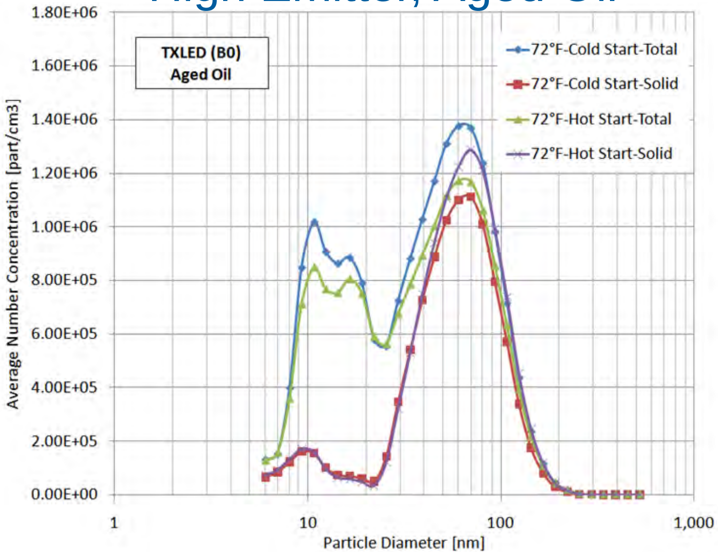

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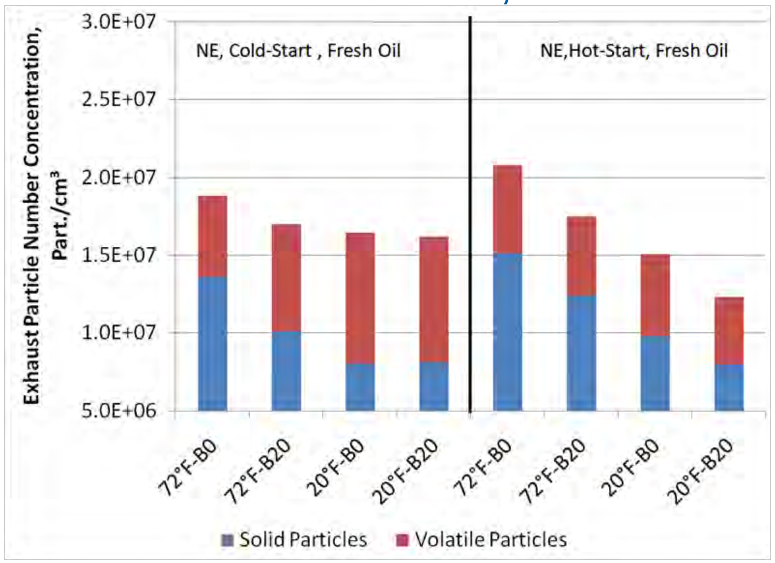

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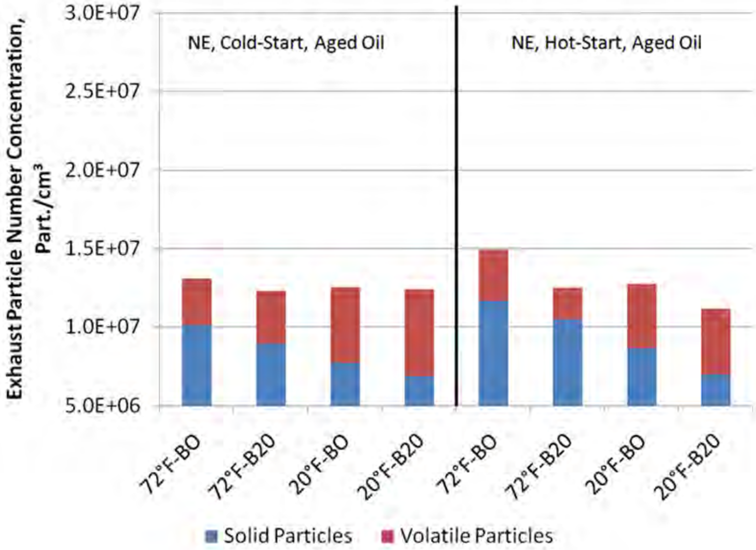

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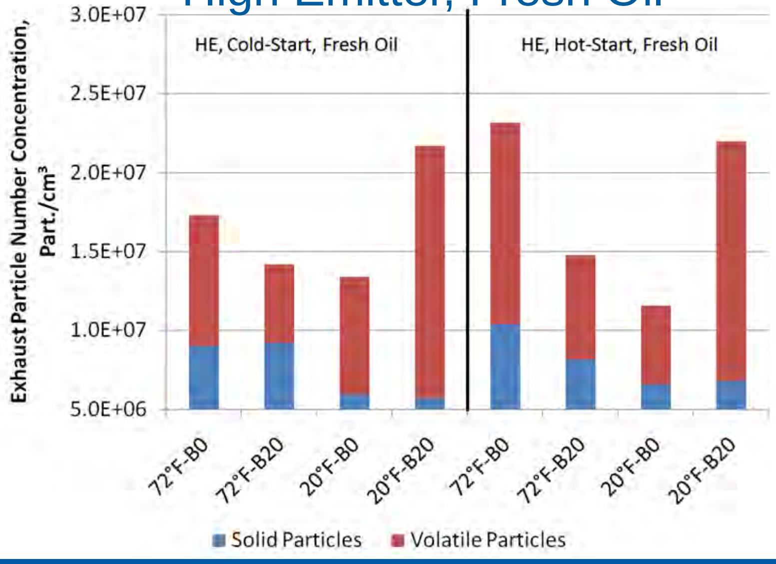
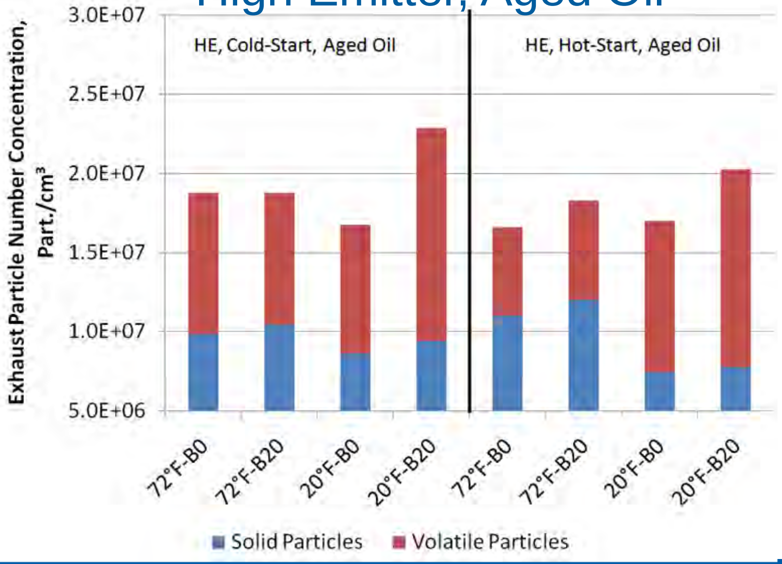
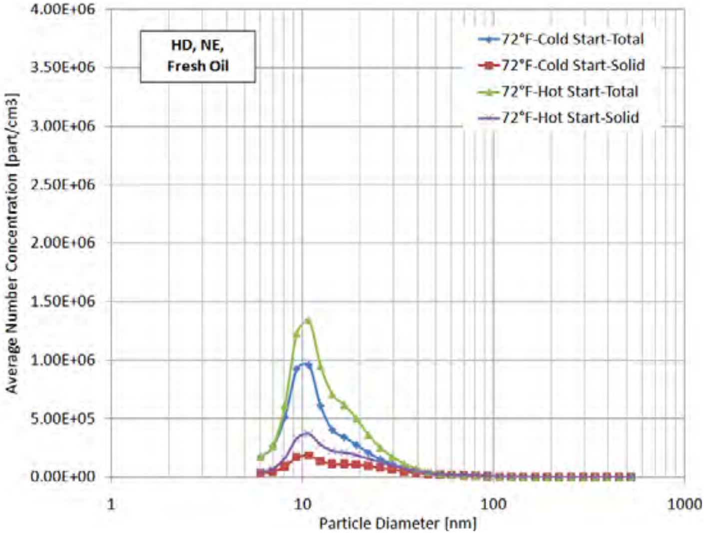


High Emitter, Aged Oil

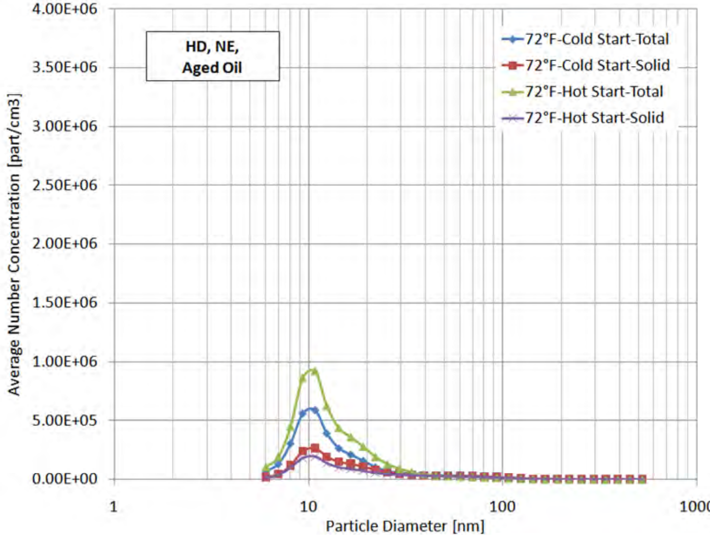


Ultrafine Particle Number Count/Size Distributions
HD CNG Normal Emitter and High Mileage Buses

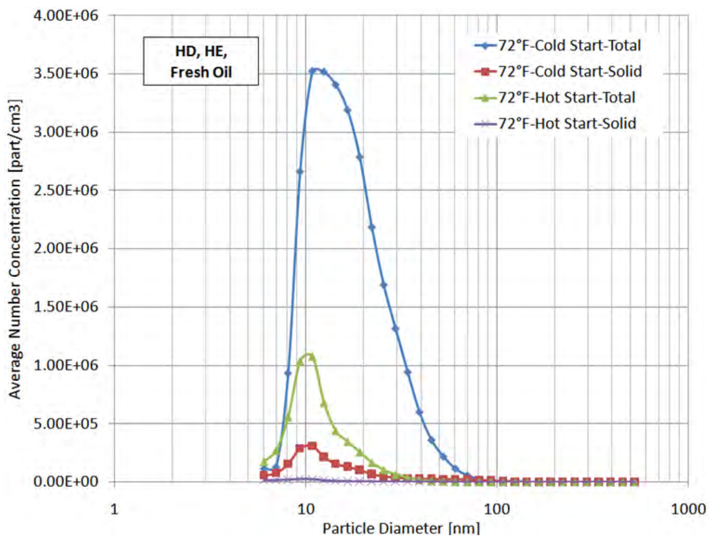
Normal Emitter, Fresh Oil



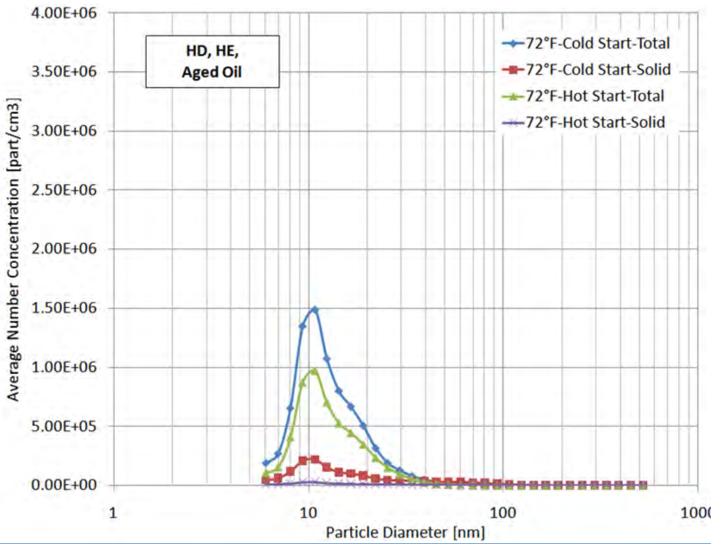
Normal Emitter, Aged Oil



High Mileage, Fresh Oil



High Mileage, Aged Oil



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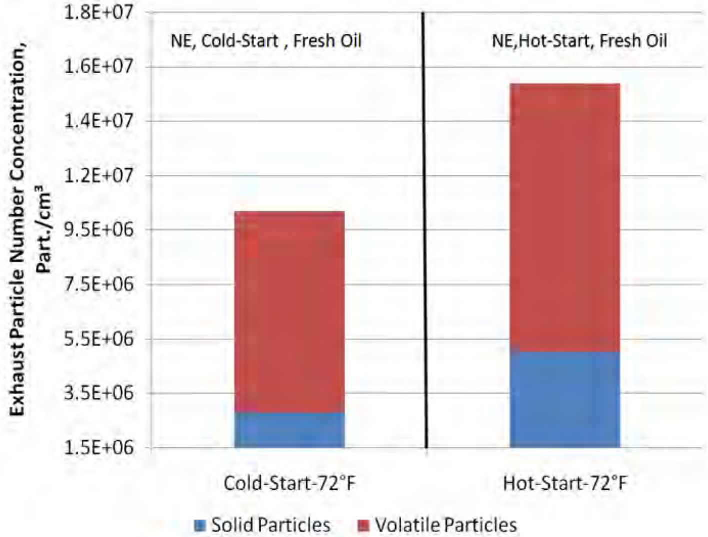
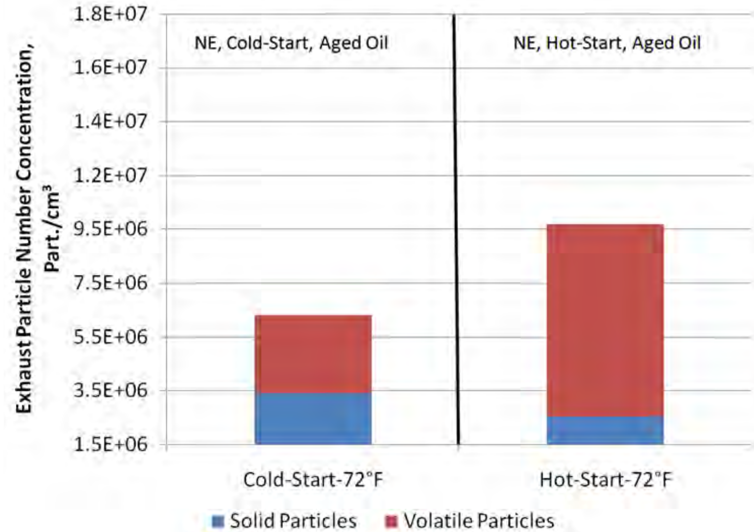


Normal Emitter, Aged Oil



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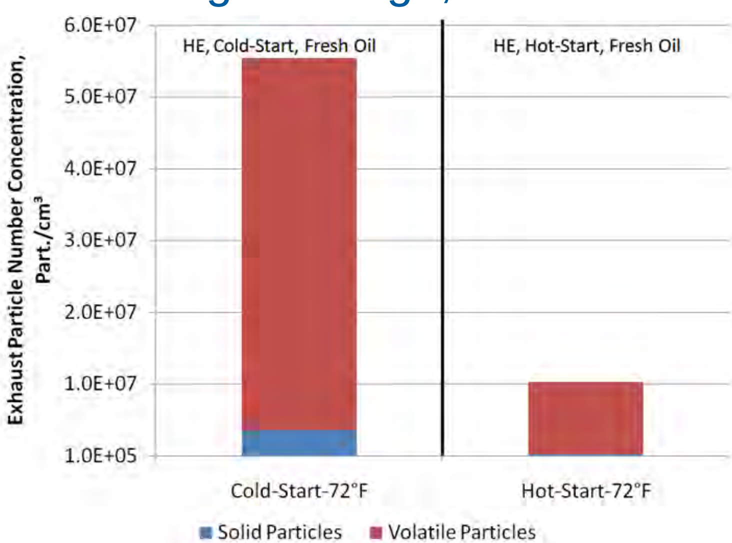

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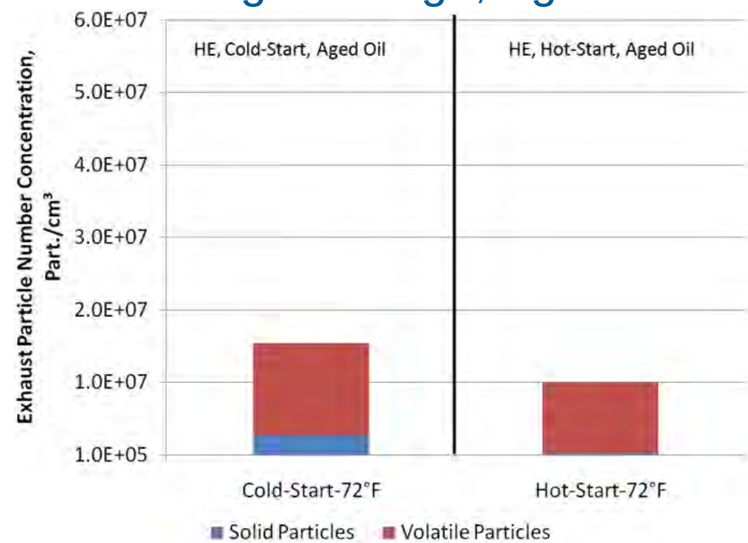

CLOSE Project Summary

- Exhaust emission rates of oil tracers are useful indicators of unburned oil contribution to PM emissions
  - Multiple methods often show good correlation with OC (elements, hopanes/steranes, UCM, PAHs (not sufficient time today to show all results)
  - Analytical variability needs to be assessed with larger sample and emissions amounts
  - hexatriacontane-d74 ($C_{36}D_{74}$) expensive and sometimes overestimates lube oil fraction of PM
  - Method does not account for deposition of oil in exhaust system
- Effects of fuel, test temperature, and oil vintage on PM mass emissions varied by vehicle (normal vs. high emitters / high mileage vehicles)
  - Ethanol content influenced PM emissions in LD normal emitter (not shown today)
  - Sample size too small to see general trends, except NG vs diesel
  - PM number and size distributions are influenced by age of oil
- More than 70% of consumed oil was oxidized and not present on filters as PM
- Chemical markers indicate unburned oil makes up >70% of OC
  - Method sometimes results in >100% contribution of unburned oil to OC
- Oil consumption calculation should be validated with actual measurements
- Results from the CLOSE vehicles may not represent those from the entire, on-road fleet or the newest technology vehicles
- Future Work – Dependent upon level of support from DOE and other sponsors