Collaborative Lubricating Oil Study on Emissions

November 28, 2006 – March 31, 2011

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COLLABORATIVE LUBRICATING OIL STUDY ON EMISSIONS (CLOSE)

FINAL REPORT

NREL Subcontract Number AEV-7-66409-01
CRC Project Number AVFL-14

SwRI Project Nos. 03.13012 and 03.13029

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ENGINE, EMISSIONS AND VEHICLE RESEARCH DIVISION

FOREWORD

The Department of Emissions Research and Development of Southwest Research Institute (SwRI), in conjunction with the Desert Research Institute (DRI), performed this project in response to National Renewable Energy Laboratory (NREL) Request for Proposal (RFP) Number REV-6-66409, "Investigation of the Role of Lubricating Oil on Particulate Matter Emissions from Vehicles" under Subcontract Number AEV-7-66409-1, SwRI Project No. 03.13012. In addition, the Coordinating Research Council (CRC) augmented this study's funding under CRC Project No. AVFL-14 "Effect of Fuel and Lubricant Composition on the Emission of Vehicles, SwRI Project No. 03.13029. The program consisted of extensive chemical and physical characterizations of particulate matter (PM) emissions from a limited number of gasoline-, diesel- and natural gas-fueled vehicles operating on fresh and aged crankcase lubricants in an effort to evaluate the relative contributions of fuels and crankcase lubricants on PM and SVOC emissions from vehicles.

The project was performed from November, 2006 to March, 2011. Jim Carroll was the principal investigator on this project. Imad Khalek was responsible for the measurement and analysis of particle count and size distribution. For the medium- and heavy-duty vehicles, Lawrence Smith conducted PM apportionment. Eric Fujita of Desert Research Institute apportioned light-duty vehicle PM. Barbara Zielinska of Desert Research Institute coordinated all chemical analyses conducted for SwRI under contract. Robert Vara was responsible for all lab operations during testing of light- and medium-duty vehicles. Joe Anthony oversaw heavy-duty vehicle testing. Kevin Whitney was the overall project manager.

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ACRONYMS AND ABBREVIATIONS

AACOG	Alamo Area Council of Government
ACS	American Chemical Society
API	American Petroleum Institute
ASE	Accelerated Solvent Extractor
ASTM	American Society for Testing and Materials
B0	straight TxLED diesel fuel
B20	twenty percent bio-diesel blend with TxLED
BCF	baseline crankcase flush
Btu	British thermal unit
°C	degrees Centigrade
$C_{14}H_{10}$	phenanthrene
$C_{16}H_{10}$	pyrene
$C_{20}H_{42}$	eicosane
$C_{26}H_{54}$	hexacosane
$C_{36}D_{74}$	hexatriacontane-d74
CH_4	methane
CH_2Cl_2	dichloromethane
CLOSE	Collaborative Lubricating Oil Study on Emissions
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CPS	City Public Service Company (San Antonio)
CRC	Coordinating Research Council
CS	catalytic stripper
CVS	constant volume sampling
DCM	dichloromethane
DDC	Detroit Diesel Corporation
DDW	deionized-distilled water
DHA	detailed hydrocarbon analysis
DPF	diesel particulate filter
DR	dilution ratio
DRI	Desert Research Institute
DVPE	dry vapor pressure equivalent
E10	gasoline containing 10 percent volume denatured ethanol
EC	elemental carbon
EC/OC	elemental carbon/organic carbon
EDXRF	energy dispersive x-ray fluorescence
EEPS	engine exhaust particle size
EGR	exhaust gas recirculation
EI	electron impact
EPA	US Environmental Protection Agency
ERA	Environmental Research Associates
°F	degrees Fahrenheit
FBP	final boiling point
FIA	flame ionization analyzer
FID	flame ionization detector
FTP	Federal Test Procedure
g	gram

ACRONYMS AND ABBREVIATIONS (CONT'D)

GC/MS	gas chromatography/mass spectrometry
HC	hydrocarbons
HD	heavy-duty
HDCC	heavy-duty chassis cycle
HDDC	heavy-duty driving cycle
HD-D-NE	heavy-duty diesel normal emitter
HE	high (PM) emitter, or high mileage heavy-duty vehicle
HM	high mileage vehicle
IBP	initial boiling point
IC	ion chromatograph
ICP-MS	inductively coupled plasma-mass spectrometry
Kg	kilogram
KHP	potassium hydrogen phthalate
kPa	kilopascal
lb	pound mass
LD	light-duty
LNG	liquefied natural gas
LOC	lubricating oil consumption
LPG	liquified petroleum gas
MD	medium-duty
mg	milligram
MJ	megajoule
mL	milliliter
MON	motor octane number
MOUDI	micro orifice uniform deposit impactor
NABI	North American Bus Industries
NE	normal (PM) emitter
ng	nanogram
NIST	National Institute of Standards and Technology
NMHC	non-methane hydrocarbon
NMOG	non-methane organic gases
NO_X	oxides of nitrogen
NREL	National Renewable Energy Laboratory
OC	organic carbon
Orion	Orion Bus Industries
PAH	polynuclear aromatic hydrocarbon
PAPTG	American Chemistry Council Product Approval Protocol Task Group
PDP	positive displacement pump
PM	particulate matter
PN	particle number
PNA	polynuclear aromatics
POC	particle-phase organic compounds
ppm	parts per million
psi	pounds per square inch
QC	quality control
RFP	request for proposal
RON	research octane number
RVP	Reid vapor pressure
SCAQMD	South Coast Air Quality Management District

ACRONYMS AND ABBREVIATIONS (CONT'D)

SFC	supercritical fluid chromatography
SIS	selective ion storage
S/N	signal-to-noise
SOA	soluble organic aerosol
SOF	soluble organic fraction, percent
SPSS	solid particle sampling system
SRM	standard reference material
STN	Speciation Trends Network
SVOC	semi-volatile organic compounds
SwRI	Southwest Research Institute
TC	total carbon
TCEE	temperature controlled emissions enclosure
THC	total hydrocarbons
TIGF	Teflon-impregnated glass-fiber filters
TOR	thermal/optical reflectance
TOT	thermal/optical transmittance
TxLED	Texas low-emission diesel fuel (<15ppm sulfur)
UCM	unresolved complex mixture (alkanes)
UDC	unified driving cycles
UDDS	urban dynamometer driving schedule
µg	microgram
vol.	volume
XRF	x-ray fluorescence

EXECUTIVE SUMMARY

The Collaborative Lubricating Oil Study on Emissions (CLOSE) project was a pilot program to investigate methodologies to indicate how fuels and crankcase lubricants contribute to the formation of particulate matter (PM) and semi-volatile organic compounds (SVOC) in vehicle exhaust. It was conducted with a very limited number of vehicles, some of which did not have the latest engine and emission system technology, and no vehicles in this study were equipped with particle traps. The results of this study are not representative of the whole fleet of on-road vehicles. Long term lubricant effects on engine and aftertreatment were not investigated in this study.

Two vehicles from each of four categories were studied, for a total of eight test vehicles:

- Light-duty gasoline passenger cars,
- Medium-duty diesel pickup trucks,
- Heavy-duty natural gas fueled transit buses, and
- Heavy-duty diesel transit buses.

Within each of the four vehicle categories, one normal PM emitting vehicle and one high PM emitting vehicle were selected. Each high emitter vehicle was to be selected on a criterion of consistent smoke visible in the tailpipe exhaust. While the high emitter natural gas-fueled heavy-duty vehicle did not exhibit white smoke, it was a higher-mileage vehicle than the normal PM emitter. Similarly, the high emitter heavy-duty diesel vehicle did not exhibit consistent visible white smoke, but it exhibited high oil consumption and high blowby. Because the HD natural gas and HD diesel vehicles designated HE did not exhibit higher PM emissions, they are designated as high mileage (HM).

Vehicles were evaluated using the following fuels:

- Light-duty vehicles:
  - Non-ethanol containing gasoline (designated E0), and
  - 10 percent ethanol blend (designated E10)
- Medium-duty vehicles:
  - Conventional low-sulfur TxLED diesel (designated D), and
  - 20 percent bio-diesel blend (designated B20)
- Heavy-duty vehicles:
  - Conventional low-sulfur TxLED diesel (designated D), or
  - Natural gas

With the light- and medium-duty vehicles, the effects of ambient temperature at 20°F and 72°F on regulated and unregulated pollutant emission rates were also evaluated. With all the vehicles the effects of lubricating oil vintage (fresh and aged) on emission rates were evaluated.

All vehicle testing occurred on chassis dynamometers. Light- and medium-duty vehicles were operated over the California Unified Driving Cycle, while heavy-duty vehicles followed the Heavy Duty Urban Dynamometer Driving Schedule. The following exhaust emissions were determined:

- Regulated gaseous emissions (HC, CO, NO_X, CO_2)
- PM
  - Mass emission rate (gravimetric)
  - Elements (including lube oil markers)
    - XRF
    - ICP-MS for subset of 18 elements
  - Hopanes and steranes by GC/MS
  - “Elemental” and “organic” carbon by TOR/TOT
  - PAHs by GC/MS
  - C_{14} to C_{40} alkanes & cycloalkanes by GC/MS
  - A deuterated alkane as a lube oil tracer by GC/MS ($C_{36}D_{74}$)
  - Soluble organic fraction by extraction
  - Sulfate by ion chromatography
- Semi-volatile organic constituents by GC/MS
- Real-time particle count and size distribution by EEPS
  - Total particles
  - Solid particles only

Chemical markers were utilized to estimate the lubricant contribution to PM, which was based on the following assumptions:

- that the survival rate through the engine and catalyst was the same for a given marker as for the rest of the motor oil formulation components, and
- that confounding of fuel and lube oil derived markers was negligible (i.e. that fuel contributions to the marker count are negligible compared to lubricant derived contributions).

Potentially useful lubricant markers included oil additive metals, hopanes and steranes, and an unresolved complex mixture (UCM) of C_{20} to C_{35} alkanes and cycloalkanes. Additionally a deuterated alkane, n-hexatriacontane ($C_{36}D_{74}$), was added to the crankcase lubricant as a marker. Utilizing deuterated n-hexatriacontane tracer to estimate contributions of lubricants to exhaust particulate and SVOCs was not as successful as using the sum of hopanes and steranes or the unresolved complex mixture. However, none of these markers were consistently reliable for estimating engine oil consumption rates. Engine oil consumption could have been determined by physically measuring the loss of engine oil from the crankcase over a measured driving interval. This measurement was not done for the vehicles tested in this program with two exceptions – the light- and medium-duty high emitters. In two cases, the vehicle owner provided anecdotal oil consumption information. In hindsight, measurement of engine oil consumption rates would have been a valuable addition to the project.

Any large scale quantitative underprediction of lubricant consumption rates by utilized markers likely means the lubricant-derived species levels assessed in the tailpipe streams were lost via deposition or conversion within the engine/exhaust or measurement systems. Markers which might survive the engine and catalyst any more or less than other lubricant components could also bias the quantitative allocation of the PM.

Polynuclear aromatic hydrocarbon (PAH) compounds were used as markers for fuel combustion products; however, for vehicles with normally-functioning exhaust catalysts, the PAH levels were too low for the measurement technique, and thus uncertain data were obtained. Normal emitters also have much higher ratios of fuel consumed to lubricant consumed compared to high emitters. The reduced certainty of the derived PM allocations from normal emitters may also be due to confounding of fuel and lubricant derived markers. In general, as indicators, PAHs accounted for less than one percent of organic carbon (OC) emitted.

Results of measurements showed that unburned crankcase lubricant made up 60 to 90 percent of measured OC emissions from this small sample of on-road vehicles. These results were consistent across the four vehicle types and all fuels. This organic carbon represented 20 to 50 percent of all emitted PM, except for the normal emitting light-duty gasoline passenger car (OC was < 10 percent of PM) and the heavy-duty natural gas-fueled transit bus (OC was > 90 percent of PM).

The OC fraction of PM for the four compression ignition diesel vehicles was less than for the two spark ignition natural gas buses and the high emitter spark ignition gasoline light duty passenger car. However, overall OC mass emissions rates for the four diesel vehicles were up to an order of magnitude higher than from the normal emitter spark ignition light duty gasoline-fueled passenger car. The high PM emitter spark ignition vehicle had OC emissions rates comparable to the four diesel-powered vehicles.

Normally-functioning three-way catalysts are effective at reducing most of the organic carbon. With high PM emitters or vehicles with deteriorated aftertreatment, high molecular weight fuel components and unburned lubricant were emitted at higher rates (one to two orders of magnitude) than in vehicles in proper engine repair and functioning emissions systems. In most cases, over 75 percent of lubricating oil components were combusted or converted across exhaust catalysts.

For the normally-operating light-duty gasoline and medium-duty diesel vehicles and for both heavy-duty natural gas vehicles, fresh oil produced more particles than aged oil. The opposite trend occurred with the light- and medium-duty high PM emitters. This effect was not readily apparent with the heavy-duty diesel vehicles. One explanation could be that, since the lubricant represented a much smaller fraction of the total PM (around 20 percent) in the HD diesel vehicles, the effect was lost in the precision of the testing methodology.

In many cases, emitted PM was incompletely accounted for with chemical analyses. It is possible that some fraction of unburned and/or partially combusted fuel and oil, or some polar fraction of PM, was not measured with the analytical techniques used in this program.

Follow-up studies should assess the methods of PM allocations used in this study on vehicles representing the diverse spectrum between normal emitters and high emitters, and should estimate the precision of the allocations obtained by running multiple analyses. Vehicles should be tested with fuels without hopanes and steranes in order to help clarify the potential confounding (or lack thereof) when markers are parented by both fuel and lubricant. Studies should be conducted to understand the relative frequency of various types and intensities of 'high emitters' to facilitate modeling of the on-road vehicle fleet.

Future work could consider testing emissions from diesel vehicles equipped with normally-functioning particle filters to determine if this type of aftertreatment system produces similar results. Also, it would be informative to utilize the latest engine and emissions system hardware for all the vehicles to determine if the considerable efforts by regulators and OEMs have impacted PM levels. Noting that aged lubricants sometimes produce less PM than fresh oil, it would be interesting to investigate the effects of base oil volatility and type (i.e., mineral-based versus synthetic) on PM and SVOC formation.

SUMMARY OF MAJOR TECHNICAL FINDINGS

LIGHT-DUTY GASOLINE VEHICLE TESTS

Fresh and Aged Oil
- *Normal PM emitter:* PM nominally* increased in three of four configurations with aged oil.
- *High PM emitter:* PM nominally decreased with aged oil.

E0 and E10 Fuel
- *Normal PM emitter:* PM nominally increased with E10.
- *High PM emitter:* no trend was apparent.

Normal and High PM Emitters
- High PM emitter produced much higher rates of all emissions compared to low emitters.

Normal (72°F) and Low (20°F) Temperatures
- *Normal PM emitter:* PM nominally increased during cold starts.
- *High PM emitter:* PM nominally decreased during cold starts.
  - The lack of PM response to temperature from the HE vehicle is an important finding relevant to modeling fleet emissions. Because high emitters contribute disproportionately, the temperature effects across a full range of moderate to high emitter vehicles should be studied to ensure accurate modeling of the fleet.

Particle Number and Particle Size Distributions

Particle Number (PN) Emissions
- *Normal PM emitter:*
  - The combination of cold start and cold ambient temperature operation resulted in the highest PN emissions.
  - Fresh oil emitted higher number of solid and volatile particulates compared to emissions from aged oil.
  - E10 resulted in higher particulate emissions compared to E0 at 72°F.
  - At 20°F there was not a consistent trend between E0 and E10.
  - Greater than 70% of the particles emitted were solid.
- *High PM emitter:*
  - The highest PN concentrations were observed with the high emitter.
  - Emissions were dominated by volatile particles.

Particle Size Distribution
- The total and solid distributions exhibit similar bimodal lognormal structure that consists of a nuclei mode <20 nm, and an accumulation mode.
- For fresh oil, the accumulation mode peaked at about 50 to 60 nm and the nuclei mode peaked at 10 nm.

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* The terms ‘nominal’ and ‘nominally’ are used throughout this report to indicate a lack of statistical rigueur to the data discussed.

LIGHT-DUTY GASOLINE VEHICLE TESTS (CONT'D)

- For aged oil, the accumulation mode was lower than that for fresh oil in concentration and it was at least 20 nm smaller in diameter than that of the fresh oil.
- For high emitters, the accumulation mode is volatile in nature.
- For normal emitters, the accumulation mode is composed of solid particles.

PM Apportionment

- *Normal PM emitter:* While the presence of elemental tracers and UCM alkanes indicates some contribution of oil to the exhaust PM, the relative fuel and lubricant contributions are uncertain due to low emissions levels.
- *High PM emitter:* Nearly all of the exhaust PM is associated with the lubricating oil.

MEDIUM-DUTY DIESEL VEHICLE TESTS

Fresh and Aged Oil
- *Normal emitter (NE) vehicle:* PM emissions nominally decreased with aged oil.
- *High emitter (HE) vehicle:* PM emissions nominally increased with aged oil.

Neat Diesel (B0) and Twenty Percent Biodiesel (B20)
- *Normal emitter (NE) vehicle:* No effect of B20.
- *High emitter (HE) vehicle:* PM nominally increased for B20.

Normal (72°F) and Low (20°F) Temperatures
- *Normal emitter (NE) vehicle:* At low temp., PM nominally increased.
- *High emitter (HE) vehicle:* At low temp., PM nominally decreased.

Particle Number and Particle Size Distributions

Particle Number (PN) Emissions
- *Normal emitter (NE) vehicle:*
    - Fresh oil emitted more solid and volatile particles than aged oil.
    - B20 resulted in lower solid and volatile emissions (15% to 20%) than B0.
    - No major differences between normal/low temp. and cold-start/hot-start portions of the cycle.
    - Solid PN ranged from 50% to 83% of the total emissions (volatile PN range 50% to 37%).
- *High emitter (HE) vehicle:*
    - Aged oil emitted more solid particles than fresh oil.
    - No consistent trend observed between B0 and B20.
    - No major differences between normal/low temp. and cold-start/hot-start portions of the cycle.
    - Solid PN accounted for 26% to 65% of the total emissions (volatile PN range 74% to 35%).

Particle Size Distribution
- For both NE and HE vehicles, solid PM distributions exhibited monomodal lognormal distribution structure with accumulation mode peak between 50-70 nm.
- For both NE and HE vehicles, total PM distribution exhibited bimodal lognormal distribution structure with a volatile nuclei mode peak between 10-20 nm.
- More pronounced volatile mode was observed at low temperature and in a HE vehicle.

PM Apportionment
- *Normal emitter (NE) vehicle:*
    - No real vehicle oil consumption rate was measured; estimated oil consumption rate was 0.16 quarts/1000 miles.
    - Tracer and hopanes/sterane totals were used to estimate unburned oil emission rates that were similar to organic carbon measurements.
    - Total carbon emission rates were similar to measured values.
    - Carbon fraction from unburned oil was estimated to be 83% of measured organic carbon.

MEDIUM-DUTY DIESEL VEHICLE TESTS (CONT'D)

- *High emitter (HE) vehicle:*
  - Measured and estimated oil consumption rates matched and were found to be 0.49 quarts/1000 miles.
  - Total carbon emission rates did not correlate with measured values.
  - Variations in PM composition were obtained for different sampling protocols.

HEAVY-DUTY NATURAL GAS VEHICLE TESTS

Fresh and Aged Oil

- *Normal PM emitter and High Mileage (HM) vehicle:* PM nominally decreased on aged oil.

Fuel

- Only natural gas was used as a fuel.

Normal and High Mileage PM (HM) Emitter

- No trend in PM was evident between the normal and high mileage vehicles. PM emissions ranged from 14 to 22 mg/mi.

Normal (72°F) and Low (20°F) Temperatures

- No low temperature tests performed.

Particle Number and Particle Size Distributions

Particle Number (PN) Emissions

- *Normal PM emitter:*
  - More PN emissions were observed during the hot-start portion of the cycle compared to the cold start.
  - Fresh oil nominally increased PN emissions compared to used oil.
  - 25 to 55% of the number of particles emitted were solid in nature.
- *High mileage vehicle:*
  - >80% of the PM were volatile particles.
  - Fresh oil nominally increased PN emissions as compared to used oil.

Particle Size Distribution

- For the normal emitter with both fresh and used oil, the total and solid distributions seem to exhibit monomodal lognormal size distribution structures that consists of a nuclei mode. The nuclei peaks at 10 nm.
- Similar size distribution was observed with the high mileage vehicle.

PM Apportionment

- Estimated (calculated) oil consumption rates varied considerably when determined by different methods.
- Several parameters indicate the catalyst in the normal emitter may be more active than in the high mileage vehicle.
- Oil consumption rate may indicate that 99% of the consumed oil is burned or partially burned in the combustion chamber or in the vehicle catalyst system for the normal emitter, while 95 to 98% of the consumed oil was burned or partially burned for the high mileage vehicle.
- Both vehicles had similar PM emissions rates, but the makeup of the PM was very different. The high mileage vehicle PM consisted of nearly 80% organic material while the normal emitter consisted of 40% organic material.

HEAVY-DUTY DIESEL VEHICLE TESTS

Fresh and Aged Oil

- *Normal emitter (NE) & High mileage (HM) vehicle:* PM emissions were lower for aged oil.

Neat Diesel (B0) and Twenty Percent Biodiesel (B20)

- Only B0 tested.

Normal (72°F) and Low (20°F) Temperatures

- No low temperature tests performed.

Particle Number and Particle Size Distributions

Particle Number (PN) Emissions

- *Normal emitter (NE) vehicle:*
    - No major differences between normal/low temp. and cold-start/hot-start portions of the cycle.
    - Solid PN ranged from 70% to 90% of the total emissions (volatile PN range 30% to 10%).
- *High mileage (HM) vehicle:*
    - Solid PN accounted for over 70% of the total emissions (volatile PN range less than 30%).

Particle Size Distribution

- No notable differences observed between fresh/ aged oils, cold/hot start and NE/HM vehicles.
- Total and solid PM distributions exhibited monomodal lognormal distribution structure with accumulation mode peak between 50 – 70 nm.

PM Apportionment

- No real vehicle oil consumption rates were measured.
- Estimated (calculated) oil consumption rates varied considerably when determined by different methods.
- *Normal emitter (NE) vehicle:* Carbon fraction from unburned oil was estimated to be 89% of measured organic carbon.
- *High mileage (HM) vehicle:*
    - Carbon fraction from unburned oil was estimated to be 62% of measured organic carbon.
    - PAH emission rates were higher than NE.

1.0 INTRODUCTION

Despite significant recent legislative controls, particulate matter (PM) remains an important contributor to urban air quality, and internal combustion engine emissions are among the most significant contributors to ambient fine PM levels.[1,2] Technological developments in the area of in-cylinder PM control and the use of high-efficiency catalytic aftertreatment technologies will provide tremendous benefits when engines/vehicles employing these approaches become pervasive in the marketplace. But, given the relatively long life of vehicles, in both the light-duty and heavy-duty market, a significant fraction of older, higher-polluting vehicles will remain on the road for many years. In fact, a growing body of evidence is suggesting that these older, often poorly maintained vehicles contribute disproportionately to pollutant inventories.[3,4,5,6]

There are a number of contributing factors that determine the rate of production and the chemical nature of PM emissions including engine design and control measures, fuel and lubricant properties, and duty cycle. Improved power cylinder design, higher pressure fuel injection, and more recently, the introduction of high-efficiency particle filtration technologies have enabled significant reductions in the mass rate of PM emissions from new engines.[7] Fuel sulfur regulations were first implemented in the early 1990s and are being phased in here in the United States and around the world in an effort to reduce sulfate-derived PM emissions and to enable the aforementioned catalytic aftertreatment technologies.

Engine lubricating oil has also been implicated as a significant parent material in the formation of mobile source PM emissions, including nanoparticle emissions. This is true of both compression and spark-ignited engines independent of fuel source. Studies have shown that high-emitting engines (oil burners) are the most toxic in terms of potency per unit mass of emissions.[8, 9, 10]

However, to date much of the present understanding regarding the impact of lubricating oil on PM emissions has been anecdotal and not the subject of a focused and carefully conducted research study. Recognizing this knowledge gap and the potential benefits to air quality and human health, the U.S. Department of Energy Office of Vehicle Technologies through the National Renewable Energy Laboratory (NREL), and the Project Management Team which included the South Coast Air Quality Management District (SCAQMD), the California Air Resources Board (CARB), the Coordinating Research Council (CRC), with support and advice from the American Chemistry Council Product Approval Protocol Task Group (PAPTG), sought to characterize PM emissions from in-use low and high PM emissions vehicles.

A single high-emitting vehicle was chosen in each vehicle type to be a very high PM emitter with evidence of oil consumption or visible consistent white smoke, and each vehicle was expected to be near the end of its useful life. Additionally, allocation estimates on the normal emitter vehicle in each vehicle type are generally less precise than for high emitters. Thus results from this pilot study cannot be presumed to accurately represent the wide variety of on-road vehicles of various life stages and maintenance histories.

2.0 OBJECTIVE

The U.S. Environmental Protection Agency (EPA) revised the National Ambient Air Quality Standards (NAAQS) for PM10 and PM2.5 in October 2006, revoking the annual PM10 standard and lowering the 24-hour PM2.5 standard to 35 µg/m^3. The existing annual 24-hour standards for PM10 and PM2.5 (150 µg/m^3 and 15 µg/m^3, respectively) were retained. Control plans for the 2006 standards are to be submitted to EPA in the 2012-13 timeframe for areas that are in nonattainment. In preparing these plans, State and local agencies are using emissions models and chemical transport models to identify and evaluate potential emission reduction measures.

While predictions of PM concentrations have been reasonably accurate for sulfates and nitrates, model performance for particulate organic matter has been generally poor (Kleeman and Cass, 2001).[11] According to official government inventories, mobile sources currently account for a third of the directly emitted PM2.5 emissions in California's South Coast Air Basin (SoCAB) with gasoline-powered vehicles accounting for less than 10% (CARB, 2008).[12] However, model predictions have shown that gasoline-powered vehicles may account for 60% of the total predicted secondary organic aerosols (SOA) in the SoCAB during summer (Kleeman et al., 2007).[13] Furthermore, model results have under-predicted observed carbon concentrations by about 50% suggesting either the presence of an unknown or underestimated source of primary organic aerosol or that more SOA is being formed than is accounted for by current models (Ying and Kleeman, 2007).[14]

To supplement current knowledge of particulate emissions from mobile sources, and to investigate methods to identify the sources of compounds which make up particulate, the CLOSE project was undertaken with support from Federal, State, and local government agencies and industry The objective of this project was to conduct chemical and physical characterizations of particulate matter (PM) emissions from a limited number of vehicles fueled with gasoline, E10, diesel, biodiesel, and natural gas while operating on fresh and used crankcase lubricants in an effort to investigate methodologies to indicate how fuels and crankcase lubricants contribute to the formation of PM and semi-volatile organic compound (SVOC) emissions in vehicle exhaust.

3.0 SCOPE OF WORK

This project was initiated to characterize particulate matter (PM) emissions from four vehicle types operating on multiple fuels and lubricants at two test temperatures. The four vehicle types studied were: light-duty gasoline passenger cars, medium-duty diesel trucks, heavy-duty natural gas fueled transit buses, and heavy-duty diesel transit buses. Two vehicles of each vehicle type were selected and studied: one normal PM emitting vehicle and one high PM emitting (or high mileage) vehicle. PM characterizations were carried out to investigate whether the relative contribution of lubricant to particulate could be estimated, and whether the lubricant contribution to PM changed with different fuels and lubricant compositions.

This report covers emission testing of in-use light-duty and medium-duty vehicles with both normal and high rates of particulate emissions. Low- and high-mileage in-use heavy-duty vehicles were also tested with the expectation that the high-mileage vehicles would produce higher PM emissions. Light-duty vehicles were tested with regular (non-oxygenated) gasoline and ten percent ethanol fuel blends. Medium-duty vehicles were tested with both straight diesel and a twenty percent bio-diesel blend. Heavy-duty vehicles were tested with natural gas and straight diesel fuels. Light-duty and medium-duty vehicles were tested at room temperature (72°F) and 20°F. Heavy-duty vehicles were tested only at room temperature. All vehicles were tested with both fresh and aged lubricants.

Light-duty and medium-duty vehicles were tested over replicate cold-start Unified Driving Cycles (UDC). Thus, only one UDC per day was run. The UDCs were conducted as a cold-start, four-phase test, in a manner similar to the light-duty Federal Test Procedure. Heavy-duty vehicles were evaluated over the EPA Urban Dynamometer Driving Schedule (UDDS) for Heavy-Duty Vehicles. The heavy-duty UDDS is also known as the Heavy-Duty Chassis Cycle (HDCC). Heavy-duty vehicles were operated over a series of cold- and hot-start tests conducted on the same day. Only short-term effects were investigated in this study. Lubricants could have long-term effects on exhaust emissions which differ from the short-term effects.

A summary of the complete project test matrix, tunnel blank or background sampling schedule, and tunnel cleaning and conditioning events is presented in Table 1. Because the HD natural gas and HD diesel vehicles designated HE did not exhibit higher PM emissions, they are sometimes designated as high mileage (HM).

Each emission test performed during the course of the project was given an individual test name and number according to the coding shown in Table 2. Acronyms were used to denote type of vehicle (LD, MD and HD), PM emission rate (normal or high), lubricant type (fresh or aged), fuel type, ambient test temperature, replicate test number, and sub-test letter (for multiple tests to capture PM mass). Project details are presented in the following sections.

SwRI's criteria for selecting high-emitting vehicles were not based on make, model, type of owner, mileage, or any other *a priori* assumptions regarding the likelihood of any specific type of vehicle being a good candidate. With decades of emission regulations in place, and manufacturers producing extremely durable engine and exhaust control systems, SwRI recognizes that 'smoking' vehicles are not the norm in the existing fleet of operational vehicles; therefore, any vehicle selected is atypical.

TABLE 1. PROJECT TEST MATRIX

TEST TEMPERATURE		**72°F**				**20°F**			
TEST LUBRICANT		**FRESH**	**FRESH**	**AGED**	**AGED**	**FRESH**	**FRESH**	**AGED**	**AGED**
SAMPLE		**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Clean and condition Light-Duty tunnel. Collect tunnel blank.									
LD E0 gasoline (Normal PM Emitter)	**No. of tests**[1]	8	8	8	8	2	2	2	2
	No. of miles[2]	158	158	158	158	39	39	39	39
	Background	X	X	X	X	X	X	X	X
Condition Light-Duty tunnel. Collect tunnel blank.									
LD E10 gasoline (Normal PM Emitter)	**No. of tests**	8	8	8	8	2	2	2	2
	No. of miles	158	158	158	158	39	39	39	39
	Background	X	X	X	X	X	X	X	X
Condition Light-Duty tunnel. Collect tunnel blank.									
LD E0 gasoline (High PM Emitter)	**No. of tests**	1	1	1	1	1	1	1	1
	No. of miles	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7
	Background	X	X	X	X	X	X	X	X
Condition Light-Duty tunnel. Collect tunnel blank.									
LD E10 gasoline (High PM Emitter)	**No. of tests**	1	1	1	1	1	1	1	1
	No. of miles	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7
	Background	X	X	X	X	X	X	X	X
Clean and condition Medium-Duty tunnel. Collect tunnel blank.									
MD diesel (Normal PM Emitter)	**No. of tests**	1	1	1	1	1	1	1	1
	No. of miles[2]	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7
	Background	X	X	X	X	X	X	X	X
Condition Medium-Duty tunnel. Collect tunnel blank.									
MD B20 (Normal PM Emitter)	**No. of tests**	1	1	1	1	1	1	1	1
	No. of miles	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7
	Background	X	X	X	X	X	X	X	X
Condition Medium-Duty tunnel. Collect tunnel blank.									
MD diesel (High PM Emitter)	**No. of tests**	1	1	1	1	1	1	1	1
	No. of miles	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7
	Background	X	X	X	X	X	X	X	X
Condition Medium-Duty tunnel. Collect tunnel blank.									
MD B20 oxygenated diesel (High PM Emitter)	**No. of tests**	1	1	1	1	1	1	1	1
	No. of miles	19.7	19.7	19.7	19.7	19.7	19.7	19.7	19.7
	Background	X	X	X	X	X	X	X	X
Condition Heavy-Duty tunnel. Collect tunnel blank.									
HD natural gas (Normal PM Emitter)	**No. of tests**	6	6	6	6				
	No. of miles[3]	34	34	34	34				
	Background	X	X	X	X				
Condition Heavy-Duty tunnel. Collect tunnel blank.									
HD natural gas (High PM Emitter)	**No. of tests**	6	6	6	6				
	No. of miles	34	34	34	34				
	Background	X	X	X	X				
Condition Heavy-Duty tunnel. Collect tunnel blank.									
HD diesel (Normal PM Emitter)	**No. of tests**	2	2	2	2				
	No. of miles	11	11	11	11				
	Background	X	X	X	X				
Condition Heavy-Duty tunnel. Collect tunnel blank.									
HD diesel (High PM Emitter)	**No. of tests**	2	2	2	2				
	No. of miles	11	11	11	11				
	Background	X	X	X	X				

[1] Number of test runs with one set of filters in order to sample enough PM for later analyses. When only two tests were run, then a third test was run without a complete filter set just to measure particle number and size. (Section 6.3, Table 15)

[2] LD, MD Driving Cycle: California Unified Cycle (19.7 miles per test, Section 7.4.1)

[3] HD Driving Cycle: EPA HD Urban Dynamometer Driving Schedule (5.6 miles per test, Section 9.4.1)

TABLE 2. CLOSE PROJECT TEST CODES

Type of Vehicle	**PM Code[1]**	**Lubricant Code[2]**	**Fuel Code**	**Run ambient temperature[3]**	**Test Number[4]**	**Sample run[5]**
LD = light-duty vehicle	NE = normal PM emitter	F = fresh oil	E0 = non-oxygenated gasoline	72 = nominal 72F	1, 2, 3….	A, B, C….
MD = medium-duty vehicle	HE = high PM emitter	A = aged oil	E10 = gasoline with 10% ethanol	20 = nominal 20F		
HD = heavy-duty vehicle	HM = high mileage		D = diesel			
			B20 = diesel with 20% bio-diesel			
			NG = natural gas			
[1] PM Code	A normal PM emitter is a vehicle in good working order that consumes its oil at a normal rate. A high PM emitter is a vehicle that consumes its oil at a higher than normal rate, thus producing PM at a higher rate.					
[2] Lubricant Code	Both fresh and aged oil are added to the engine after a flushing procedure, and then the vehicle is operated over 150 highway miles. Fresh oil has not been used in an engine, aged oil has been aged in fleet service then collected.					
[3] Run ambient temperature	Ambient temperature is the soak space temperature for the vehicle.					
[4] Test Number	Two replicate tests are run in each configuration, but multiple samples (over multiple test cycles) are collected onto single filters in order to deposit enough PM for analyses.					
[5] Sample run	Each letter represents a test cycle run. For LD and MD vehicles each test cycle is one cold plus one hot Unified Driving Cycle (UDC). For HD vehicles each test cycle is one Heavy-Duty Driving Cycle (HDDC). One cold HDDC for each day's start and then multiple hot-start test cycles are performed.					
Example: MD-NE-A-B20-20-2C is the Medium duty, normal PM-emitting vehicle filled with aged oil, operated on 20% biodiesel, with the soak temperature at a nominal 20F, during its second replicate test over the third cold/hot UDC.						

4.0 CLOSE PM SOURCE DETERMINATION APPROACH

Southwest Research Institute (SwRI) and Desert Research Institute (DRI) teamed to investigate the sources of PM using the PM, fuels, and lubricants analyses from DRI. Dr. Eric Fujita of DRI took the lead with the light-duty vehicle tests and produced a spreadsheet to review DRI's results. SwRI then used Dr. Fujita's spreadsheet as a template to input the medium- and heavy-duty analyses results and Dr. Lawrence Smith of SwRI reviewed those sets of data. The approach is discussed below:

SwRI and DRI compared fuel and oil speciation results to look for unique compounds that could serve as possible tracers for either fuel or oil. We started with a lubricant tracer (deuterated hexatriacontane, $C_{36}D_{74}$) which was blended into each engine's fresh and aged oil fills. The mass and mass fractions of the tracer in oil samples taken from the engines were measured. In addition, the mass of tracer was measured from the exhaust PM captured during testing. The mass of PM associated with oil was calculated by ratioing the mass of tracer found in the exhaust PM to the mass fraction of tracer found in the oil. However, there is the possibility that some of the tracer could crack or oxidize when it was exposed to heat during in-cylinder and post-exhaust combustion, thus biasing these results.

SwRI and DRI also analyzed both the lubricants and fuels for elements, and identified those elements that were unique to oil. These elements likely come from additive packages that include Zn, P, Mg, and Ca. The collected exhaust PM samples were also analyzed for elements. The PM lubricant ratios of elements were compared to the ratios from the tracer analyses. The results of these two types of analyses (tracer and elements) indicated the contributions of burned versus unburned lubricant contribution. The rates of oil consumption were estimated from the exhaust emissions of tracers and corresponding abundances in lubricating oil.

We also reviewed the results of hopanes, steranes and alkanes speciation for both fuels and lubricants and searched for hopanes/steranes that were unique to either fuel or oil.

- There were hopanes/steranes found in some test fuels used in the emission tests; DRI analyzed fuels they collected in the Reno, NV area to check for similar results.
- For oils, we examined compounds with boiling points that are halfway between fuel and oil crossover and the end point of speciation.
- For fuels, we searched for fuel-unique compounds with high boiling points, near (or in) the fuel and oil crossover range of their speciations.

We also analyzed fuels, lubricants, and PM for PAHs, but like alkanes, these are not necessarily good tracers for lubricants. We searched for compounds that were present in each lubricant that were not in the fuel.

Each unique compound or element could be used to calculate a range of potential fractions of fuel or lubricant contribution to PM. We followed this approach for each fuel and lubricant combination.

Regarding the continuous particle sizing and counting being performed during each test, we hypothesized that the solid particle number in the sub-20 nanometer size range was lube-oil related, mainly due to metallic ash.

5.0 LUBRICANTS AND FUELS

5.1 Lubricants

Two different crankcase lubricant conditions, fresh and aged, were evaluated during this test program. When changing crankcase lubricants, a drain and fill operation was first performed to install detergent flush oil–baseline crankcase flush (BCF) oil–which is used in the ASTM Sequence VIB procedure. Following this, a flush procedure was conducted to install each test lubricant in the crankcase. The lubricant flush and fill sequence was as follows:

1. Idle the engine for a minimum of 15 minutes and until the engine oil sump temperature reaches 150°F.
2. Drain the engine oil and fill with BCF flush oil.
3. Idle the engine for a minimum of 15 minutes.
4. Drain the engine flush oil and fill with the test oil (first fill).
5. Idle the engine for a minimum of 15 minutes.
6. Drain the test oil and fill with the test oil (second fill).
7. Idle the engine for a minimum of 15 minutes.
8. Drain the test oil and fill with the test oil (third fill).

Following the final fill, each lubricant was degreened over approximately 150 vehicle miles of operation. Items that influence oil shear stability include manufacturer, viscosity grade, engine conditions, and fuel dilution, among others. Although SwRI cannot predict how stable a crankcase lubricant might be in this test program, it is thought that this amount of operation was sufficient. Crankcase lubricant samples were collected at the end of each series of tests for analyses.

5.1.1 Description and Analyses

Lubricants were supplied by members of the American Chemistry Council on the Petroleum Panel Product Approval Protocol Task Group (PAPTG). Table 3 describes the lubricants used for all emission tests in this project. Table 4 shows the results from the supplier of analyses of the light-duty lubricants. Table 5 provides results from the supplier of analyses of the medium-duty lubricants. Table 6 shows the results from the supplier of analyses of the heavy-duty natural gas engine lubricants. Table 7 shows a summary of the lubricants used for heavy-duty vehicle testing. All lubricants were further analyzed by Desert Research Institute once they were used for emissions tests, and those results are included with the results of the associated emission tests.

TABLE 3. PROJECT LUBRICANTS SUPPLIED BY AMERICAN CHEMISTRY COUNCIL MEMBERS

Lubricant Type	Light-Duty Gasoline & Ethanol Blends	Medium-Duty Diesel	Heavy-Duty Natural Gas	Heavy-Duty Diesel
Performance Level	APISM/ILSAC GF-4	API CJ-4	Cummins CES20074 / DDC 7SE272	API CJ-4/SM
Viscosity Grade	GF-4 5W20	15W40	15W40	15W40
How Aged Oil was Generated	2.7L to 4.6L Detroit OEM vehicles. Drain Interval 7.5K miles and 10K miles.	Heavy-Duty Mack 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. Engines were DDC Series 50s and John Deere Natural Gas.	HD diesel line service running 50% of the time at 80,000 pound GVW. Drain interval was 25,000 miles. Engines were 2006 CAT C-15s and Cummins ISX.
SwRI Fresh Oil Code	LO-221459	LO-223289	LO-223360	LO-245408
SwRI Aged Oil Code	LO-223292	LO-223290	LO-223291	LO-244136
Supplier	Infineum	Afton	Oronite	Lubrizol
Supplier Code	Infineum Gold	RBR-010570-A-1	RPN GEO 15-40	Fresh OS218004AL Aged OS226608

TABLE 4. LIGHT-DUTY OIL ANALYSES FROM SUPPLIER

SwRI Oil Code		LO-221459	LO-223292
Property Measured	**Test Method [a]**	**Fresh Oil**	**Aged Oil**
Additive Metals			
Ca, % mass	ASTM D4951	0.1974	0.213
Mg, % mass	ASTM D4951	0.0015	0.0016
Mo, % mass	ASTM D4951	0.0075	0.008
P, % mass	ASTM D4951	0.0749	0.0676
Si, % mass	ASTM 2622	0.0003	0.0011
Na, % mass	ASTM D4951	0.0002	0.0005
Zn, % mass	ASTM D4951	0.0852	0.0818
Wear Metals			
Cu, ppm	ASTM D4951	0	16
Pb, ppm	ASTM D4951	0	0
Sn, ppm	ASTM D4951	3	0
Al, ppm	ASTM D4951	2	7
Fe, ppm	ASTM D4951	2	9
TBN, mg/KOH/g	ASTM D4739	9.4	9.9
TAN, mg/KOH/g	ASTM D664	1.9	2.21
IR for Oxidation, absorbance/cm		0	13
IR for Nitration, absorbance/cm		0	21
Fuel Dilution		0	0
kV@100°C, cSt		8.5	8.38
kV@40°C, cSt		48	49
CCS @-30°C, cP	D5293	6400	7010
MRV @-35°C, cP	D4684	21300/NYS	26700/NYS
Water, %		0	0
Pentane Insolubles	D893B	N/A	0.06
Sulfur, mg/gram (ppm) [b]	ICP-MS	2157	2160

[a] Analysis performed by Intertek

[b] Analysis performed by Elemental Analysis, Inc.

TABLE 5. MEDIUM-DUTY OIL ANALYSES FROM SUPPLIER

SwRI Oil Code	**LO-221459**	**LO-223292**
Property Measured	**Fresh Oil**	**Aged Oil**
Additive Metals, ppm		
Boron	432	223
Calcium	1860	1960
Phosphorus	1069	1110
Zinc	1230	1300
Wear Metals, ppm		
Copper	x	6
Lead	x	6
Tin	x	nil
Aluminum	x	5
Iron	x	29
TBN, D 4739, mg/KOH/g	7.8	3.7
TAN D 664, mg/KOH/g	4.9	3.5
IR for Oxidation, absorbance/cm	x	11.03
IR for Nitration, absorbance/cm	x	4.0
TGA Soot, %	x	1.2
Fuel Dilution,%	x	0.27
kV @ 100°C, cSt	14.97	14.58
kV @ 40°C, cSt	117.2	119.8
CCS @ -20°C, cP	6018	x
MRV @ -25°C, cP	x	29561
Yield Stress	x	0
Water, ppm	x	242
x Not reported by supplier		

TABLE 6. HEAVY-DUTY NATURAL GAS OIL ANALYSES FROM SUPPLIER

SwRI Oil Code	LO-223360	LO-223291
	RPM GEO 15-40	CNG
	FRESH	USED
ASTM D-445 Viscosity @ 40°C, cSt	113.47	85.32
ASTM D-445 Viscosity @ 100°C, cSt	15.42	11.61
ASTM D-4684 Borderline Pumping Temperature Test		
Apparent Viscosity @ -25°C, cP	23,100	14,800
Yield Stress, Pa	<35	<35
ASTM D-4739 Base Number, mg KOH/g	5.68	2.29
ASTM D-5185 Elemental Analysis by ICP		
Aluminum, ppm	1	5
Antimony, ppm	<1	<1
Barium, ppm	<1	<1
Boron, ppm	24	16
Cadmium, ppm	<1	<1
Calcium, ppm	1499	1395
Chromium, ppm	<1	<1
Copper, ppm	<1	10
Iron, ppm	1	21
Lead, ppm	1	6
Magnesium, ppm	5	13
Manganese, ppm	<1	<1
Molybdenum, ppm	34	287
Nickel, ppm	<1	<1
Phosphorus, ppm	765	341
Potassium, ppm	6	<5
Silicon, ppm	<1	5
Silver, ppm	<1	<1
Sodium, ppm	<5	16
Strontium, ppm	1	1
Tin, ppm	<1	<1
Titanium, ppm	<1	<1
Vanadium, ppm	<1	<1
Zinc, ppm	6	<5
ASTM D-5293 Apparent Viscosity @ -20°C, cP	6,630	5,860
ASTM D-6304 Determination of Water, Procedure C, mg/kg	-	827
ASTM D-664 Acid Number, mg KOH/g	1.29	1.12
ASTM E-168 Infrared Spectra	-	Enclosed
TGA Soot Test		
Residue, mass %	-	0.4
Volatiles, mass %	-	99.4
Soot, mass %	-	0.2

TABLE 7. HEAVY-DUTY DIESEL OIL ANALYSES FROM SUPPLIER

SwRI Oil Code		LO-245408	LO-244136
Measured	**Method**	**Fresh Oil**	**Aged Oil**
Calcium, %	ASTM D-5185, Elemental Analysis (ICP)	0.2191	0.2304
Boron, %	"	<0.001	0.0004
Barium, %	"	<0.001	<0.001
Copper, %	"	<0.001	0.0004
Chromium, %	"	0	0.0003
Iron, %	"	0	0.0044
Lead, %	"	0	0.0006
Phosphorus, %	"	0.1043	0.0997
Sulfur, %	"	0.3322	0.3414
Silicon, %	"	<0.001	0.0005
Zinc, %	"	0.1181	0.1182
TBN mg KOH/g	ASTM D2896	8.1	6.7
TBN mg KOH/g	ASTM 4739	8.36	7.6
Viscosity @ 100ºC cSt	ASTM D445_100	16.11	13.82
TGA Soot Test, %		x	1.47

x Not reported by supplier

5.1.2 Hexatriacontane Tracer

Deuterated n-hexatriacontane (n-$C_{36}D_{74}$) was to be mixed into the test lubricants at a rate of approximately 7.35 gram/gallon, to be used as a tracer in determining lube oil contribution to exhaust particulate and SVOCs. A recommended n-hexatriacontane blending procedure was obtained from the University of Washington and is shown in Appendix A.

The tracer was utilized to compare its concentration in the collected exhaust PM to the concentration in the oil. The proposed concentration blend for the oil was 7.35 g hexatriacontane per gallon of oil, but during the light-duty tests the blended concentration was 7.35 g tracer per quart of oil. The incorrect blend concentration was used for all the light-duty tests. Beginning with the medium-duty tests, and including the heavy-duty tests, the concentration was correctly blended to 7.35 g tracer per gallon of oil.

5.2 Fuels

5.2.1 Light-Duty Vehicles Fuels

Due to the participation of SCAQMD and CARB in the CLOSE project, there was a desire to evaluate the light-duty vehicles on a gasoline resembling California Phase 3 reformulated gasoline. SwRI was able to locate a fuel with properties similar to California Phase 3 fuel; except that the fuel was not oxygenated. For testing on E10, a California Phase 3 certification fuel was procured and splash-blended with ethanol to bring the ethanol content up to 10 volume percent. For testing at 20°F, SwRI used Cold CO test fuel; neat for E0 gasoline and splash-blended with ethanol for E10.

Table 8 shows a summary of the fuels used for light-duty vehicle testing. Table 9 shows the analyzed results of the light-duty fuels. Further analyses of the fuels were performed by Desert Research Institute and those results are included in the emission test results section. Two Cold CO fuels were used for testing because the first batch of fuel was discarded inadvertently. A discussion of the two Cold CO fuels is given in the next section.

TABLE 8. SUMMARY OF FUELS FOR LIGHT-DUTY VEHICLES

FUEL	REGULAR E0	COLD CO E0	E10	COLD E10	NEW COLD CO E0	NEW COLD CO E10
SwRI Fuel Code	EM-6314-F	EM-5574-F	EM-6391-F	EM-6378-F	EM-6802-F	EM-6856-F
H/C ratio	1.884	1.879	1.879	1.849	1.828	1.902
Carbon fraction	0.863	0.864	0.833	0.834	0.867	0.831
Hydrogen fraction	0.136	0.136	0.131	0.129	0.133	0.133
Oxygen fraction			0.035	0.036		0.037
Density, lb/gal	6.102	6.109	6.130	6.146	6.178	6.224

TABLE 9. ANALYTICAL RESULTS FOR LIGHT-DUTY FUELS

	DESCRIPTION	**REGULAR E0**	**COLD CO E0**	**NEW COLD CO E0**	**E10**	**COLD E10**	**NEW COLD CO E10**
	FUEL CODE	**EM-6314-F**	**EM-5574-F**	**EM-6802-F**	**EM-6391-F**	**EM-6378-F**	**EM-6856-F**
PROPERTY	**TEST METHOD**						
RVP by Grabner (psi)	ASTM D5191	6.99	11.6	11.56	6.82	12.47	12.2
Hydrocarbons by FIA (vol%)							
Aromatics	ASTM D1319	24	28.4	28.7	32	26.2	28.5
Olefins		3.3	10.3	9.2	9.6	8.6	9.6
Saturates		72.7	61.3	62.1	58.4	65.2	61.9
Corrected for Oxygenates (vol%)							
Aromatics	ASTM D1319			28.68	28.86	23.88	25.64
Olefins				9.19	8.66	7.84	8.64
Saturates				62.06	52.66	59.43	55.68
Sulfur Content (wt%)	ASTM D2622	0.0013	0.0027	0.0027	0.0064	0.0033	0.0024
Sulfur Content, (ppm)		13	27	27	64	33	24
API Gravity	ASTM D4052	62	61.7	59.6	61.1	60.7	58.2
Specific Gravity (kg/L)	ASTM D4052	0.7312	0.732	0.7403	0.7348	0.7364	0.7458
Oxygen and Oxygenates (wt%)					755.5		
MeOH	ASTM D4815	ND	NM	<0.2	<0.2	ND	<0.2
EtOH		ND	NM	<0.2	10.32 (9.82 vol%)	9.54	10.35 (9.72 vol%)
iPA		ND	NM	<0.2	<0.2	ND	<0.2
tBA		ND	NM	<0.2	<0.2	ND	<0.2
nPA		ND	NM	<0.2	<0.2	ND	<0.2
MTBE		ND	NM	<0.2	<0.2	ND	<0.2
sBA		ND	NM	<0.2	<0.2	ND	<0.2
DIPE		ND	NM	<0.2	<0.2	ND	<0.2
iBA		ND	NM	<0.2	<0.2	ND	<0.2
ETBE		ND	NM	<0.2	<0.2	ND	<0.2
tPA		ND	NM	<0.2	<0.2	ND	<0.2
nBA		ND	NM	<0.2	<0.2	ND	<0.2
TAME		ND	NM	<0.2	<0.2	ND	<0.2
Benzene		ND	NM	0.68	1.21	ND	0.6
Total Oxygen		ND	NM	<0.2	3.58	3.31	3.70
Elemental Analysis (wt%)							
Carbon Content	ASTM D5291	85.78	86.38	86.46	83.34	83.21	83.06
Hydrogen Content		13.56	13.62	13.26	13.14	12.91	13.26
Distillation, deg. F						3.88	
IBP	ASTM D86	93	88	82	110	81	88
5%		123	104	95	134	98	103
10%		139	113	108	140	107	112
15%		150	NM	117	144	113	119
20%		160	127	127	148	119	126
30%		180	144	149	154	130	139
40%		201	167	175	174	142	150
50%		220	198	203	216	154	160
60%		237	226	226	234	213	218
70%		256	252	247	258	243	242
80%		284	298	281	289	285	275
90%		317	334	331	329	334	330
95%		340	343	343	360	344	343
FBP		381	367	368	406	363	375
Recovered, mL		97.3	97.6	97.1	98	97.2	97.5
Residue, mL		0.8	1.0	0.5	0.7	1.0	0.7
Loss, mL		1.9	1.4	2.4	1.3	1.8	1.8

ND = Not detected, NM=Not measured

5.2.1.1 Cold CO Fuels

SwRI inadvertently discarded the Cold CO fuel that had been set aside to complete testing of the high PM emitting vehicle at 20°F. SwRI contacted the fuel vendor and requested more fuel from the same batch but was informed that only a small batch had been blended, and all of it was previously purchased by SwRI. SwRI ordered and received a replacement batch of Cold CO fuel. Samples of both the original and the replacement Cold CO fuels were analyzed by ASTM D6729 to speciate the hydrocarbons for comparison.

Hydrocarbon speciation results of the two Cold CO fuels are included in Appendix B. Table 10 shows a summary comparison of the hydrocarbons where the difference between the two fuels was greater than 0.5% (vol.). A graph of the differences of these components is shown in Figure 1. Figure 2 shows a comparison of the full speciation of the two Cold CO fuels as percentages of each species in the total volume. Ten components were different by more than 0.5 percent by volume. The greatest differences were found with i-pentane and toluene at +2.97 percent and -4.13 percent, respectively. The CLOSE project team reviewed the results of the new Cold CO fuel analysis and approved continuation of the project with this fuel.

TABLE 10. COLD CO FUEL COMPONENTS WITH GREATER THAN 0.5% DIFFERENCE

Hydrocarbon Type	Species	Original Cold CO Fuel, %	New Cold CO Fuel, %	Original – New, %	Ratio Of Original / New
		EM-5574-F	EM-6802-F		
Paraffin	n-Butane	0.528	2.422	-1.89	0.22
Paraffin	n-Pentane	5.841	5.173	0.67	1.1
I-Paraffins	i-Butane	2.959	4.022	-1.06	0.74
I-Paraffins	i-Pentane	20.161	17.194	2.97	1.2
I-Paraffins	2,2,4-Trimethylpentane	3.741	4.542	-0.80	0.8
Mono-Aromatics	Toluene	11.942	16.076	-4.13	0.74
Mono-Aromatics	1,2,4-Trimethylbenzene	4.311	3.419	0.89	1.26
Mono-Aromatics	1,2-Dimethyl-4-ethylbenzene	1.085	0.436	0.65	2.49
n-Olefins	Hexene-1	2.812	4.587	-1.78	0.61
Iso-Olefins	3-Methyl-t-hexene-2	5.403	4.294	1.11	1.26

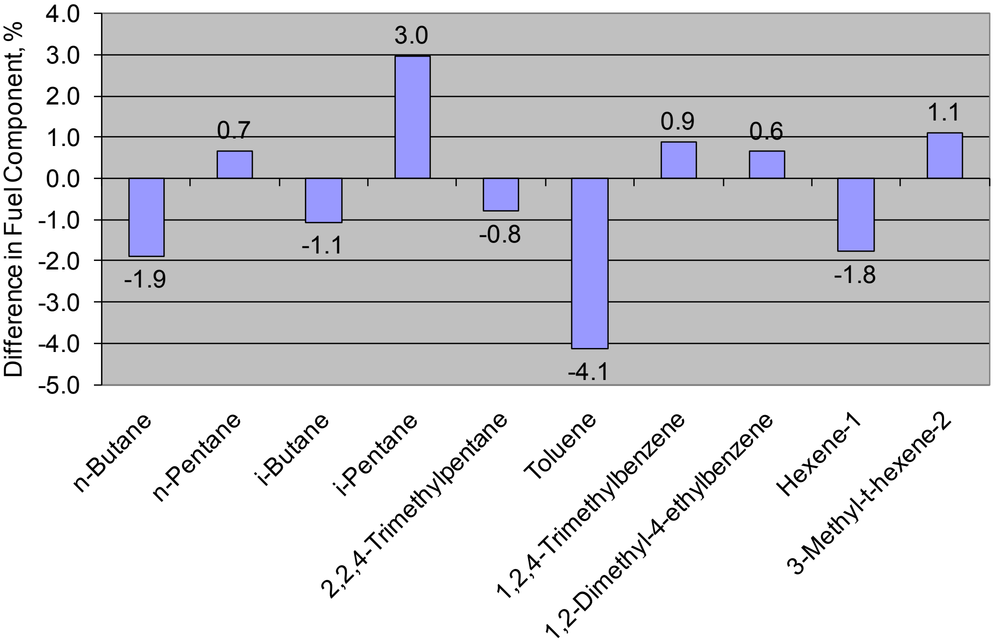

FIGURE 1. COMPARISON OF TWO COLD CO FUELS SHOWING COMPONENTS WITH GREATER THAN 0.5 PERCENT DIFFERENCE

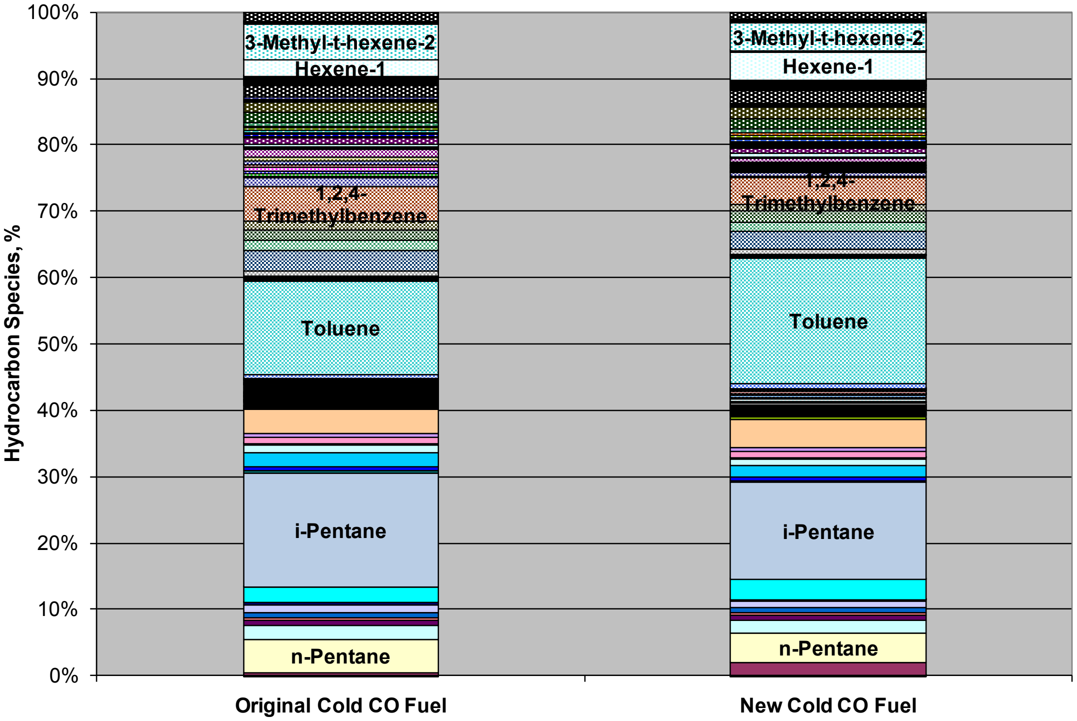

FIGURE 2. COMPARISON OF TWO COLD CO FUELS SHOWING ALL SPECIES AS PERCENTAGES OF EACH FUEL

5.2.2 Medium-Duty Vehicle Fuels

The fuels used for emissions testing of the medium-duty vehicles are shown in Table 11. Initially we planned to use CARB specification commercial diesel fuel. However, in discussion with the CARB, it became apparent that diesel fuel sold in California does not always meet the exact specifications. CARB grants waivers to the refiners in California which allow them to sell fuels that do not actually meet CARB specifications. Typical commercial California diesel fuels were compared to Texas commercial low-sulfur diesel fuels. The idea of purchasing commercial fuel in California and shipping it to Texas was discussed but the cost of procuring and shipping fuel from California was high. Through discussion with the CLOSE project team it was decided that we would use Texas commercial diesel with low sulfur content for all straight diesel tests. The diesel fuel is called Texas low emission diesel or TxLED, which must have less than 15 ppm sulfur. A quantity of pure bio-diesel was purchased from Mid-America Bio Fuels and blended with the TxLED diesel to make a twenty percent blend, or B20. The bio-diesel was treated with a donated sample of BioExtend$^{(TM)}$ oxidation stabilizer from Eastman Chemical Company.

TABLE 11. ANALYTICAL RESULTS FOR MEDIUM-DUTY FUELS

		DESCRIPTION	DIESEL - TxLED	100% BIO-DIESEL	B20 DIESEL
		FUEL CODE	EM-6952-F	EM-6981-F EM-7029-F [a]	EM-7002-F
PROPERTY	**UNITS**	**TEST METHOD**	**TEST RESULTS**	**TEST RESULTS**	**TEST RESULTS**
Hydrocarbon Type by FIA					
Aromatics	Volume %	ASTM D1319	19.7	Not Applicable [b]	Not Applicable
Olefins	Volume %		5.2	Not Applicable	Not Applicable
Saturates	Volume %		75.1	Not Applicable	Not Applicable
Sulfur Content	wt%	ASTM D2622	<0.001	<0.001	<0.001
Sulfur Content	ppm	ASTM D2622	<10	<10	<10
API Gravity	--	ASTM D287	37.5	28.3	35.4
API Gravity	--	ASTM D4052	37.4	28.2	35.5
Specific Gravity	--	ASTM D4052	0.8378	0.8863	0.8472
Density at 15°C	grams/L	ASTM D4052	837.3	885.7	846.7
Kinematic Viscsosity at 40°C	cSt	ASTM D445	2.677	4.06	2.874
Total Aromatics by SFC					
Total Aromatics	wt%	ASTM D5186	21.7	Could not maintain baseline - Sample not applicable for D5186.	21.4 [c]
Mono-aromatics	wt%		19.6		19.4
Polynuclear-aromatics (PNA)	wt%		2.1		2
Elemental Analysis					
Carbon Content	wt%	ASTM D5291	86.43	77.16	85.08
Hydrogen Content	wt%		13.29	12.00	13.47
Carbon fraction	--		0.867	0.772	0.851
Hydrogen fraction	--		0.133	0.120	0.135
Oxygen fraction	--		0	0.108	0.0145 [d]
Cetane Number	--	ASTM D613	47.8	53.6	48.9
Flash Point	Deg. F	ASTM D93	147	205	153
Flash Point	Deg. C		63.9	96.1	67.2
Cetane Index	calculated	ASTM D976	50.5	46.7	50.8
Oxidation Stability by Rancimat	hours	EN 14112	>17	2.3	10.7
Distillation					
IBP	Deg. F	ASTM D86	351	231	350
5%			NM	624	400
10%			421	630	427
15%			NM	630	446
20%			NM	632	460
30%			NM	634	487
40%			NM	635	510
50%			504	636	532
60%			NM	637	556
70%			NM	640	581
80%			NM	643	605
90%			600	645	627
95%			NM	644	638
FBP			644	647	650
Recovered, mL	ml		97.7	98.6	98
Residue, mL	ml		1.2	0.6	1
Loss, mL	ml		1.1	0.8	1

[a] Fuel code was changed to EM-7029-F with the addition of an oxidation stabilizer.

[b] Fatty Acid Methyl Esthers in bio-diesel cannot be measured.

[c] Esthers in the bio-diesel are not accounted for. These results are from the diesel portion of the fuel.

[d] 20% of the oxygen fraction in the B100 is 0.021. The result shown is within the accuracy of the method. Oxygen content was assumed to be the residual after subtracting the carbon and hydrogen fractions which are measured.

5.2.3 Heavy-Duty Diesel Fuel

The analysis of the diesel fuel used for all tests of the heavy-duty vehicles is shown in Table 12. For the testing of heavy-duty diesel vehicles, the fuel tanks on the vehicles were disconnected from their fuel systems, and a fuel line from the appropriate TxLED or B20 underground tank was connected to the engine. The commercially available TxLED low sulfur diesel fuel was a different batch than the fuel used for medium-duty vehicle tests.

TABLE 12. ANALYTICAL RESULTS FOR HEAVY-DUTY DIESEL FUELS

		DESCRIPTION	**DIESEL - TxLED**
		FUEL CODE	**EM-7006-F**
PROPERTY	**UNITS**	**TEST METHOD**	**TEST RESULTS**
Hydrocarbon by FIA			
Aromatics	Volume %	ASTM D1319	22.8
Olefins	Volume %		1.1
Saturates	Volume %		76.1
Sulfur Content	wt%	ASTM D2622	<0.001
API Gravity	--	ASTM D287	37.6
API Gravity	--	ASTM D4052	37.8
Specific Gravity	--		0.836
Density at 15°C	grams/L		835.5
Kinematic Viscsosity at 40°C	cSt	ASTM D445	2.656
Total Aromatics by SFC			
Total Aromatics	wt%	ASTM D5186	21.3
Mono-aromatics	wt%		19.0
Polynuclear-aromatics (PNA)	wt%		2.3
Elemental Analysis (WT%)			
Carbon Content	wt%	ASTM D5291	85.65
Hydrogen Content	wt%		13.67
Carbon fraction	--		0.862
Hydrogen fraction	--		0.138
Cetane Number	--	ASTM D613	52.6
Flash Point	Deg. F	ASTM D93	142
Flash Point	Deg. C	ASTM D93	61
Cetane Index	calculated	ASTM D976	52.4
Oxidation Stability by Rancimat	hours	EN-14112	21.2
Distillation, deg. F			
IBP	Deg. F	ASTM D86	353
10%			406
50%			515
90%			596
FBP			628
Recovered	ml		97.9
Residue	ml		1.3
Loss	ml		0.8

5.2.4 Heavy-Duty Natural Gas Fuel

The analysis results of the natural gas fuels used for heavy-duty emissions tests are shown in Table 13. Two blends were made for each vehicle tested. Table 13 also shows specifications and tolerances for the fuel that were designed to meet the CARB and EPA blend specifications for certification-grade natural gas fuel. The natural gas fuels were blended by SwRI into large mobile high pressure (2500 psi) spheres which were plumbed to the heavy-duty vehicles in place of their fuel tanks.

TABLE 13. NATURAL GAS FUEL BLENDS FOR HEAVY-DUTY VEHICLES

Fuel Component	SwRI Specification, % vol	Tolerance, % vol.	Normal PM Emitter Natural Gas Bus		High Mileage Natural Gas Bus	
			Blend 1	Blend 2	Blend 1	Blend 2
Nitrogen	3.50	0.50	3.42	3.58	3.40	3.74
Methane	90.00	1.00	90.18	89.83	90.72	89.99
Carbon dioxide	--	0.50	0.00	0.00	0.00	0.00
Ethylene	--	--	0.00	0.00	0.02	0.02
Ethane	4.00	0.50	4.49	4.61	3.94	4.25
Propane	2.00	0.30	1.90	1.95	1.92	1.99
Butane	--	--	0.00	0.00	0.00	0.00
Elemental Fractions						
Carbon	--	--	0.715	0.713	0.715	0.711
Hydrogen	--	--	0.231	0.230	0.231	0.229
Nitrogen	--	--	0.054	0.057	0.054	0.059

6.0 ANALYTICAL PROCEDURES

6.1 Regulated Emissions

6.1.1 Sampling and Analyses

For the light-duty gasoline vehicles and heavy-duty natural gas vehicles, proportional dilute exhaust samples for the determination of hydrocarbons (HC), oxides of nitrogen (NO_X), carbon monoxide (CO) and carbon dioxide (CO_2), as well as ambient samples of THC, CO, CO_2, and NO_X, were collected in Tedlar bags for analysis and were used in the determination of gaseous mass emissions rates.[11]

For the medium-duty and heavy-duty diesel vehicles, HC and NO_X were sampled continuously from the dilution tunnel using a heated sample probe and filter assembly, and a heated sample line, that were all maintained at 375°F±10°F. Proportional dilute exhaust samples for CO and CO_2, as well as ambient samples of HC, CO, CO_2, and NO_X were collected in Tedlar bags.[11]

6.2 Non-Regulated Emissions

This section describes the analysis methods for characterization of PM and unregulated emissions. All PM analyses were conducted by DRI. The project required the analysis of semi-volatile organic compounds (SVOC), in general, and specifically hopanes, steranes, alkanes, polycyclic aromatic hydrocarbons, and speciated hydrocarbons in the exhaust samples. The compositions of the lubrication oils were compared to the corresponding exhaust samples to determine the degree of association in the chemical compositions, thus we analyzed both exhaust samples and lube oils for SVOC, as detailed below. In addition, PM samples were analyzed for sulfates and their soluble organic fraction (SOF).

6.2.1 Particulate Matter and Semi-Volatile Organic Compounds

Positive displacement pump-type constant volume sampling (CVS) systems, including stainless steel dilution tunnels, were used for all PM sample collection. Separate CVS systems were used for the light-, medium-, and heavy-duty vehicles. All dilution air was filtered prior to entering the CVS systems. HEPA filters were used to remove particles from the dilution air and charcoal filters were used to adsorb background hydrocarbons. Multiple sample probes as shown in Figures 3 and 4 were used in each tunnel to facilitate the simultaneous collection of PM samples for subsequent analysis as follows:

- 47-mm Teflon membrane filters: PM mass emission rate, elements by EDXRF and ICP-MS,
- 47-mm glass-fiber filters: SOF
- 47-mm quartz fiber filter: OC and EC by TOR and TOT, sulfate by IC
- 10-cm TIGF backed up by XAD-4: PAH, hopanes and steranes, higher molecular weight alkanes, cycloalkanes
- EEPS: particle size and number count

The tunnel temperatures at the PM collection zones did not exceed 125°F during testing. All PM and SVOC samples, except for those collected to determine PM mass emission rates, were shipped to DRI for subsequent analysis.

The project targeted a minimum filter weight gain in the range of 300 to 500 mg to have sufficient material for subsequent chemical analyses. All test durations were based on this target.

FIGURE 3. MULTIPLE PM SAMPLING PROBE INSERT

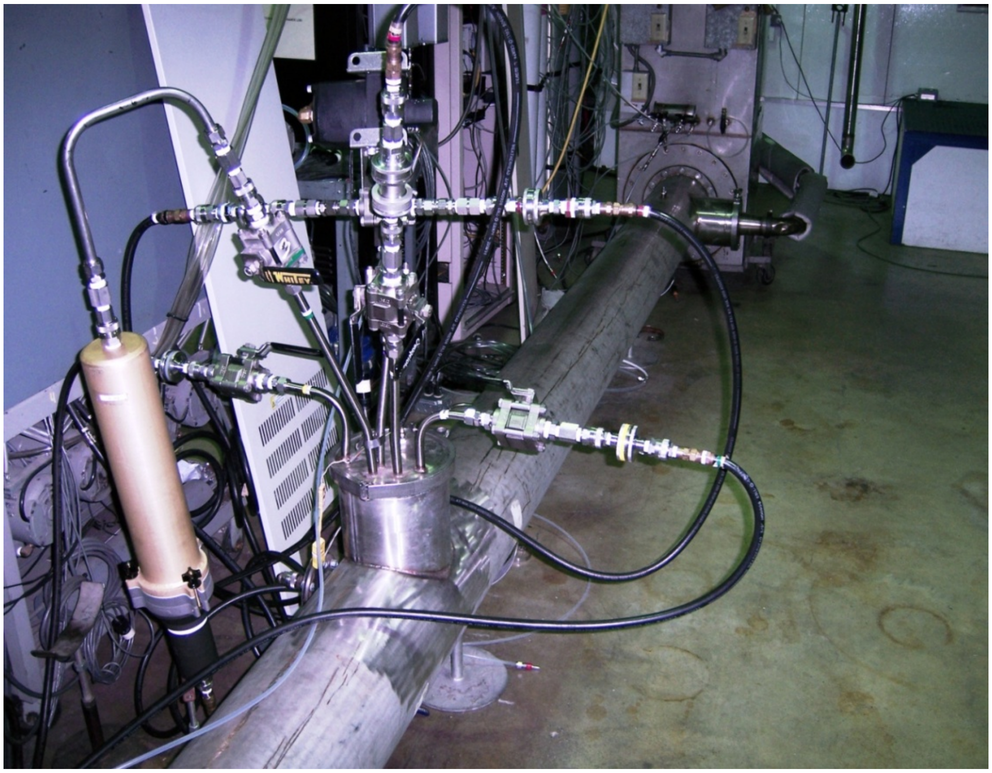

FIGURE 4. MULTIPLE PM SAMPLING PROBE INSERTED IN LIGHT-DUTY DILUTION TUNNEL

6.2.1.1 Particulate Matter

The CVS system for the light-duty vehicle testing utilized a 10-inch diameter by 16-foot long stainless steel dilution tunnel. The CVS system used for medium-duty tests utilized an 18 inch diameter by 16 foot long stainless steel dilution tunnel. A multi-sample probe was used to simultaneously sample 47-mm filters and a 10-cm filter followed by a 2-inch diameter XAD-4 cartridge. The stainless steel dilution tunnel used in the HD vehicle sampling system is 22 inches in diameter by 24 feet long, and is configured with two positive displacement pumps (PDPs) designed to displace up to a nominal 4,000 cubic feet per minute of dilute exhaust. It was equipped with the same multi-probe sampling system used with the light-duty CVS.

All filters at SwRI were weighed prior to and following sample collection to measure filter mass increases, using microbalances with a precision (standard deviation) and readability of either 1 microgram (0.001 mg) for quartz and TIGF filters or 0.1 microgram (0.0001 mg) for Teflon membrane filters. All filters were conditioned in weighing chambers prior to weighing in accordance with the 40 CFR Part 86, which specifies the weighing chambers be maintained from 66 to 77°F and from 37 to 53 percent relative humidity.[11] Typically, the conditions in the weighing chambers are maintained at 71±5°F and 45±8% relative humidity. Weighing chamber temperature, pressure, conditioned air flow rate and relative humidity were monitored on a regular basis to ensure that values were within required limits. Prior to weighing, each filter was placed on a static neutralizer or over an ionizer-blower for at least 30 seconds to avoid any problems with static charge.

Two weighed unused 47-mm reference filters and a reference mass remain in the weighing chamber at all times. The reference filters are weighed within four hours of any sample filter weight, while the reference mass is weighed weekly. If the weight of both reference filter(s) change by more than 20 micrograms between sample filter weighing, or if the weight of reference mass changes by more than 10 micrograms, an investigation of the cause is conducted and filters are reweighed following implementation of a solution.

Proportional PM samples drawn from the dilution tunnels were simultaneously collected on all filter media and XAD cartridges. For integrated PM samples that were collected over multiple days, filters were stored in their holders in the weighing chambers when not in use. Following collection, all PM and SVOC samples were stored at -10°C prior to shipment to DRI. Samples were shipped overnight to DRI in coolers packed with Blue Ice.

6.2.1.2 Semi-Volatile Organic Compounds Media Handling by DRI

Particulate matter and semi-volatile organic compounds (SVOC) analyzed for this work include: PAH, hopanes/steranes, higher molecular weight alkanes, and cycloalkanes. They were collected using Teflon-impregnated glass-fiber filters (TIGF) followed by XAD-4 resin cartridges.[15] Prior to sampling, XAD-4 resins were extracted with methanol followed by dichloromethane (CH_2Cl_2), using an Accelerated Solvent Extractor (Dionex 3000). The cleaned resin was dried in a vacuum oven heated to 40 ºC and stored in sealed glass containers in a clean freezer. The TIGF filters were cleaned by sonification in CH_2Cl_2 for 30 minutes, followed by another 30-minute sonification in methanol. Then they were dried, placed in aluminum foil, and labeled. Each batch of precleaned XAD-4 resin and ~10% of precleaned TIGF filters were checked for purity by solvent extraction and GC/MS analysis of the extracts. The XAD-4 resins were assembled into glass cartridges (20g of XAD) and stored in a clean freezer prior to shipment to the field. All samples were stored in the freezer, after receiving them from the field and prior to extraction. All samples were extracted within two weeks of being received in the laboratory.

For each sample, XAD-4 cartridges and TIGF filters were extracted and analyzed separately. Prior to extraction, the following deuterated internal standards were added to each filter and XAD sorbent: naphthalene-d_8, biphenyl-d_{10}, acenaphthene-d_{10}, phenanthrene-d_{10}, anthracene-d_{10}, pyrene-d_{12}, benz(a)anthracene-d_{12}, chrysene-d_{12}, benzo[e]pyrene-d_{12}, benzo[a]pyrene-d_{12}, benzo[g,h,i]perylene-d_{12}, coronene-d_{12}, cholestane-d_6, hexadecane-d_{34}, and eicosane-d_{42}.

Filters and XAD-4 resins were extracted separately with dichloromethane (DCM) using the Dionex ASE followed by hexane extraction under the same conditions. The dichloromethane extraction method has been reported to yield high recovery of PAH.[16,17] The combination of dichloromethane with hexane also gives good recovery for aliphatic hydrocarbons, cycloalkanes, hopanes, and steranes.

All extracts were then concentrated by rotary evaporation at 35 °C under gentle vacuum to ~1 mL and filtered through a 0.2 µm PTFE disposal filter device (Whatman Pura disc™ 25TF), rinsing the flask three times with 1 ml dichloromethane and hexane (50/50 by volume) each time. The solvent was exchanged to acetonitrile under ultra-high purity nitrogen.

The extracts were analyzed first by GC/MS for higher molecular weight (C>14) semi-volatile aliphatic hydrocarbons and cycloalkanes, which are the most abundant species in the motor vehicle exhaust. Subsequently, the extracts were precleaned by the solid-phase extraction technique. Superclean LC-SI SPE cartridges (Supelco) were sequentially eluted with hexane, and hexane/benzene (1:1). The hexane fraction contains hopanes and steranes, and the hexane/benzene fraction contains PAH and oxy-PAH. These two fractions were combined and concentrated to ~100 µL and analyzed by a GC/MS technique for hopane, steranes, PAH and oxy-PAH.

6.2.2 PM Elemental Analysis by DRI

6.2.2.1 Gravimetric Analysis by DRI

Unexposed and exposed Teflon-membrane filters and glass-fiber filters were equilibrated at a temperature of 21.5±1.5°C and a relative humidity of 35±5% for a minimum of 24 hours prior to weighing. Weighing was performed on a Mettler Toledo MT5 electro microbalance with ±0.001 mg sensitivity. The charge on each filter was neutralized by exposure to a polonium source for 30 seconds prior to the filter being placed on the balance pan. The balance was calibrated with a 200 mg Class 1 weight and the tare was set prior to weighing each batch of filters. After every 10 filters were weighed, the calibration and tare were re-checked. If the results of these performance tests deviated from specifications by more than ±5 µg, the balance was re-calibrated. If the difference exceeded ±15 µg, the balance was recalibrated and the previous 10 samples were re-weighed. 100% of the initial weights and 30% of the final weights were checked by an independent technician, and samples were re-weighed if these check-weights did not agree with the original weights within ±0.010 mg. Pre- and post-weights, check weights, and re-weights (if required) were recorded on data sheets and directly entered into a database via an RS232 connection.

6.2.2.2 Energy Dispersive X-Ray Fluorescence (EDXRF) by DRI

Energy Dispersive X-ray Fluorescence (EDXRF) analysis was performed on Teflon-membrane filters. XRF analyses were performed primarily on a PANalytical Epsilon 5 EDXRF analyzer. Ten XRF analyses were averaged by the PANalytical instrument on each sample to optimize the detection limits for the specified elements. Calibration against the same standards and regular cross-checks between excitation conditions assured comparability of the results.

Two types of EDXRF standards were used for calibration, performance testing, and auditing: (1) vacuum-deposited thin-film elements and compounds from Micromatter Co. (Deer Harbor, WA), and (2) polymer films. The vacuum deposit standards cover all elements except for Ir, Ta, Zr, and Hf (which may be determined by interpolation) and were used as calibration standards. The polymer film and National Institute of Standards and Technology (NIST) standards were used as QC standards. During EDXRF analysis, filters were removed from their Petri slides, and loaded into holders for entry into the X-ray analysis chamber. The vacuum in the X-ray chamber and the heat induced by the absorption of X-rays may volatilize some materials, such as ammonium nitrate. A QC standard and a replicate from a previous analysis were analyzed with each set of 10 filters. When a QC value differed from specifications by ±10% or more, or when a replicate value differed from the original value (where values exceeded 10 times the detection limits) by ±10% or more, the previous 10 filters were reanalyzed. If further tests of standards showed that the system calibration had changed by more than ±5%, the instrument was recalibrated. In addition, DRI maintained a set of laboratory blanks that were analyzed periodically (~1 blank for every 20 filters analyzed) to test for baseline shifts in blank values. Also, as part of Level II data validation, field blank values for each shipment were plotted by element in time series to check for potential shifts in baselines and potential contamination. After EDXRF analysis, the Teflon-membrane filters were returned to their Petri slides and stored under refrigeration until the XRF data validation was completed and indicated that the runs were acceptable. The EDXRF instrument was also set up for the analysis of liquid samples, including lubricating oils and fuels.

6.2.2.3 Inductively Coupled Plasma Mass Spectrometry (ICP-MS) by DRI

The elemental analysis was done with the Thermo Elemental X-7 (Waltham, MA) inductively coupled plasma-mass spectrometer (ICP-MS). Filter samples are digested in an acidic solution and the resultant 50 ml of the liquid sample is introduced into the system where individual elements are measured.

A pump is used to draw 5-10 ml of the liquid sample solution into a nebulizer. The nebulized solution is then passed through a plasma torch, which ionizes the dissolved metals. The ionized metals pass through a skimmer and sampler cone and then enter a quadrupole. The quadrupole filters out all ions except for those within a narrow range of mass-to-charge ratio. The ion within this mass-to-charge ratio is then detected by a dynode detector (electron photomultiplier). The quadrupole is controlled to allow a series of ions with different mass-to-charge ratios pass through it, permitting a series of different elements to be detected. The ion signal detected by the dynode detector is proportional to the amount of the element present in the solution. Sample extraction from the PM filter was performed as follows:

Extraction of Filters

- Cut the support ring of the filter in about 8 - 10 places and place it in a digestion vessel.
- Add 0.2 ml of ethanol.
- Add 2 ml of 1:1 HNO_3:H_2O mixture.
- Add 5 ml of 1:4 HCl:H_2O mixture.
- Add 0.1 ml of HF.
- Place a digestion reflux cap on the digestion vessel and place it in the hot block.
- Turn on the hot block and heat the digestion vessel for 90 minutes.
- After 90 minutes, turn off the hot block and remove the digestion vessel. Place the vessel in a tray and keep it in the hot block hood to allow the digestion vessel to cool.
- After cooling, bring the digested filter volume up to 50 ml.
- Cap the digestion vessel, overturn it several times and let sit overnight.

6.2.3 Polycyclic Aromatic Hydrocarbons and Alkanes by DRI

The filters and XAD extracts were analyzed by gas chromatography/mass spectrometry (GC/MS), using a Varian CP-3800 GC equipped with a CP8400 autosampler and interfaced to a Varian 4000 Ion Trap; due to the high sensitivity of Ion Trap MS, it was used for analysis of all semi-volatile and particulate phase organic compounds, with the exception of hopanes and steranes. An Electron impact (EI) ionization method was used. Injections (1 µL) were made in the splitless mode onto a 30m 5% phenylmethylsilicone fused-silica capillary column (DB-5ms, J&W Scientific or equivalent). Quantification of the individual compounds was obtained by selective ion storage (SIS) technique, monitoring the molecular (or the most characteristic) ion of each compound of interest and the corresponding deuterated internal standard. Calibration curves for the GC/MS quantification were made for the most abundant and characteristic ion peaks of the compounds of interest using the deuterated species most closely matched in volatility and retention characteristics as internal standards. National Institute of Standards and Technology (NIST) Standard Reference Material (SRM) 1647 (certified PAH) with the addition of deuterated internal standards and of those compounds not present in the SRM (i.e., oxy-PAH, hopanes, steranes, hydrocarbons, cycloalkanes) were used to make calibration solutions. A six- to eight-level calibration was performed for each compound of interest and the calibration check (using median calibration standards) was run every 10 samples to check for accuracy of analyses. If the relative accuracy of measurement (defined as a percentage difference from the standard value) was less than 20%, the instrument was recalibrated. PAHs and alkanes in the fuels and lubricants were also measured in this manner.

6.2.4 Hopanes and Steranes by DRI

The hopanes/steranes were analyzed using the Varian 1200 triple quadrupole gas chromatograph/mass spectrometer (GC/MS/MS) system with a CP-8400 autosampler. The tandem MS/MS system allows for structural elucidation of unknown compounds with precursor, product and neutral loss scan. The GC interface allows for sensitive analyses of complex mixtures in electron impact (EI) mode. The sensitivity of this instrument in full scan EI/MS mode is approximately 1 pg/µl with 20:1 signal-to-noise ratio (S/N). In EI/MS SIM mode, it reaches 50 fg/microliter (µl) with 10:1 S/N. This superior sensitivity offers the advantage of analyzing small samples collected during a short sampling time. Hopanes and steranes in the fuels and lubricants were also measured in this manner.

6.2.5 PM Elemental and Organic Carbon by DRI

The Thermal/Optical Reflectance (TOR) and Transmittance (TOT) methods measure "organic" (OC) and "elemental" (EC) carbon. The TOR method is based on the principle that different types of carbon-containing particles are converted to gases under different temperature and oxidation conditions. The different carbon fractions from TOR are useful for comparison with other methods, which are specific to a single definition for organic and elemental carbon. These specific carbon fractions also help distinguish among seven carbon fractions reported by TOR:

1) The carbon evolved in a helium atmosphere at temperatures between ambient and 120°C (OC1)
2) The carbon evolved in a helium atmosphere at temperatures between 120 and 250°C (OC2)
3) The carbon evolved in a helium atmosphere at temperatures between 250 and 450°C (OC3)
4) The carbon evolved in a helium atmosphere between 450 and 550°C (OC4)
5) The carbon evolved in an oxidizing atmosphere at 550°C (EC1)
6) The carbon evolved in an oxidizing atmosphere between 550 and 700°C (EC2)
7) The carbon evolved in an oxidizing atmosphere between 700 and 800°C (EC3)

The thermal/optical reflectance carbon analyzer consists of a thermal system and an optical system. The thermal system consists of a quartz tube placed inside a coiled heater. Current through the heater is controlled to attain and maintain pre-set temperatures for given time periods. A portion of a quartz filter is placed in the heating zone and heated to different temperatures under non-oxidizing and oxidizing atmospheres. The optical system consists of a He-Ne laser, a fiber optic transmitter and receiver and a photocell. The filter deposit faces a quartz light tube so that the intensity of the reflected laser beam can be monitored throughout the analysis.

As the temperature increases from ambient (~25°C) to 550°C, organic compounds are volatilized from the filter in a non-oxidizing (He) atmosphere while elemental carbon is not oxidized. When oxygen is added to the helium at temperatures greater than 550°C, the elemental carbon burns and enters the sample stream. The evolved gases pass through an oxidizing bed of heated manganese dioxide where they are oxidized to carbon dioxide, then across a heated nickel catalyst, which reduces the carbon dioxide to methane (CH_4). The methane is then quantified with a flame ionization detector (FID).

The reflected laser light is continuously monitored throughout the analysis cycle. The negative change in reflectance is proportional to the degree of pyrolytic conversion from organic to elemental carbon, which takes place during organic carbon analysis. After oxygen is introduced, the reflectance increases rapidly as the light-absorbing carbon is burned off the filter. The carbon measured after the reflectance attains the value it had at the beginning of the analysis cycle is classified as elemental carbon. This adjustment for pyrolysis in the analysis is significant, as high as 25% of organic or elemental carbon, and it cannot be ignored.

The system was calibrated by analyzing samples of known amounts of methane, carbon dioxide, and potassium hydrogen phthalate (KHP). The FID response was ratioed to a reference level of methane injected at the end of each sample analysis. Performance tests of the instrument calibration were conducted at the beginning and end of each day's operation. Intervening samples were re-analyzed when calibration changes of more than ±10% were found.

Known amounts of American Chemical Society (ACS) certified reagent grade crystal sucrose and KHP were analyzed by TOR as a verification of the organic carbon fractions. Fifteen different standards were used for each calibration. Widely accepted primary standards for elemental and/or organic carbon are still lacking. Results of the TOR analysis of each filter were entered into the DRI database.

The Speciation Trends Network (STN) Protocol uses a thermal/optical transmittance (TOT) method.[18,19] The difference is that the transmitted laser light is continuously monitored throughout the analysis cycle. Also, the temperature steps in the STN thermal evolution protocol are 310°C, 480°C, 615°C, and 900°C in a nonoxidizing helium atmosphere and 600°C, 675°C and 825°C, in an oxidizing atmosphere. The STN method uses fixed hold times of 45 to 120 seconds at each heating stage, while IMPROVE method uses variable hold times of 150-580 seconds so that carbon responses return to baseline values.

6.2.6 PM Sulfates

6.2.6.1 Filter Extraction by DRI

Water-soluble sulfates were obtained by extracting the quartz-fiber particle filter. The filters were extracted in 15 mL of deionized-distilled water (DDW) in a 15 mL polystyrene extraction tube with a screw top cap. The DDW has a measured conductivity of less than 1.8 milliohms/mL. Each vial was labeled with a barcode sticker containing the filter ID code. The extraction tubes were placed in tube racks, and the extraction solution was added. The tubes were capped and sonicated for 60 minutes, shaken for 60 minutes, than aged overnight to assure complete extraction of the deposit into the solvent. The ultrasonic bath water was monitored to minimize temperature increases from the ultrasonic energy in the water. After extraction the tubes were stored under refrigeration prior to analysis.

6.2.6.2 Ion Chromatographic Analysis for Inorganic Ions and Organic Acids by DRI

Water soluble sulfates were measured with the Dionex 500 (Sunnyvale, CA) ion chromatograph (IC). In IC, an ion exchange column separates the sample ions in time for individual quantification by a conductivity detector. Prior to detection, the column effluent enters a suppressor column where the chemical composition of the component is altered, resulting in a matrix of low conductivity. The ions are identified by their elution/retention times and are quantified by the conductivity peak area.

Approximately two mL of the filter extract were injected into the ion chromatograph. The Dionex 500 system of analysis uses a guard column (AG14) for pre-filtering followed by a separation column (AS14). The eluent then passes through a self-regenerating suppressor and then to the conductivity detector. The resulting peaks were integrated and the integrals were converted to concentrations using calibration curves derived from solution standards.

The working calibration standards were prepared from an NIST traceable solution purchased from Dionex. They were prepared in concentrations that are compatible in range with the expected concentrations of the samples, ordinarily from 0.05 to 5.0 micrograms per mL. A calibration curve was generated at the beginning of each run using these prepared standards, which were also run as check standards after every tenth sample. Secondary NIST traceable check standards from Environmental Research Associates (ERA) were used in each run as quality assurance standards. Working standards were prepared as needed, but at least once a month. Replicate samples of the extracts were run every ten samples.

After analysis, the resulting chromatograms were reviewed on screen for the following: proper operational settings, peak shapes, peak overlaps, and quality control comparisons. When the values of the standards or the replicate samples varied by more than a percentage based on their concentration, the previous 10 samples were rerun. Dilutions were prepared and run if the extracts were outside of the calibration range.

6.2.6.3 PM Soluble Organic Fraction by DRI

Unexposed and exposed Teflon-membrane filters (47 mm) and glass-fiber filters were equilibrated and weighed, as described in Section 6.2.2. These filters were subsequently extracted with dichloromethane followed by hexane in an Accelerated Solvent Extractor (Dionex 3000), dried, reconditioned and re-weighed to determine the Soluble Organic Fraction (SOF). DRI used the combination of dichloromethane with hexane, because it gives good recovery for aliphatic hydrocarbons, cycloalkanes, PAH, hopanes, and steranes, i.e., the classes of compounds that are prevalent in lubricating oil and relevant to this study. These solvents do not extract very polar organic compounds, such as diacids or polyalcohols. To account for these classes of compounds much more polar solvents are needed, such as acetone, methanol or water. However, these solvents extract inorganic compounds as well, thus overestimating SOF.

6.3 Particulate Number Count and Size Distribution by SwRI

Particle number (PN) and size were measured using the TSI Engine Exhaust Particle Sizer (EEPS). The EEPS was used to measure the number and size of particles from vehicle exhaust on a second-by-second basis. The EEPS covers a particle size range from 5.6 nm to 560 nm. To characterize total (solid plus volatile) and solid particle number-weighted size distributions, we used a solid particle sampling system (SPSS) between the engine exhaust sample probe and the EEPS. The SPSS is a dilution system that facilitates the measurement of total and solid PN. For solid PN measurement with the SPSS, the dilute sample was routed through a heated catalytic stripper (CS) that is maintained at 300°C. The CS is a small core of a diesel oxidation catalyst designed to have a 100 percent penetration of solid particles and complete removal of the volatiles. The volatile materials are typically oxidized at the surface of the catalyst.

All particle size and number measurements conducted on this program were taken from engine exhaust using the SPSS/EEPS system. Figure 5 shows a typical experimental setup. The overall dilution ratio (DR) was held constant during testing, but the DR level was different for different vehicles. The DR is defined as:

$$DR = \frac{(sample\ flow + dilution\ air\ flow)}{sample\ flow}$$

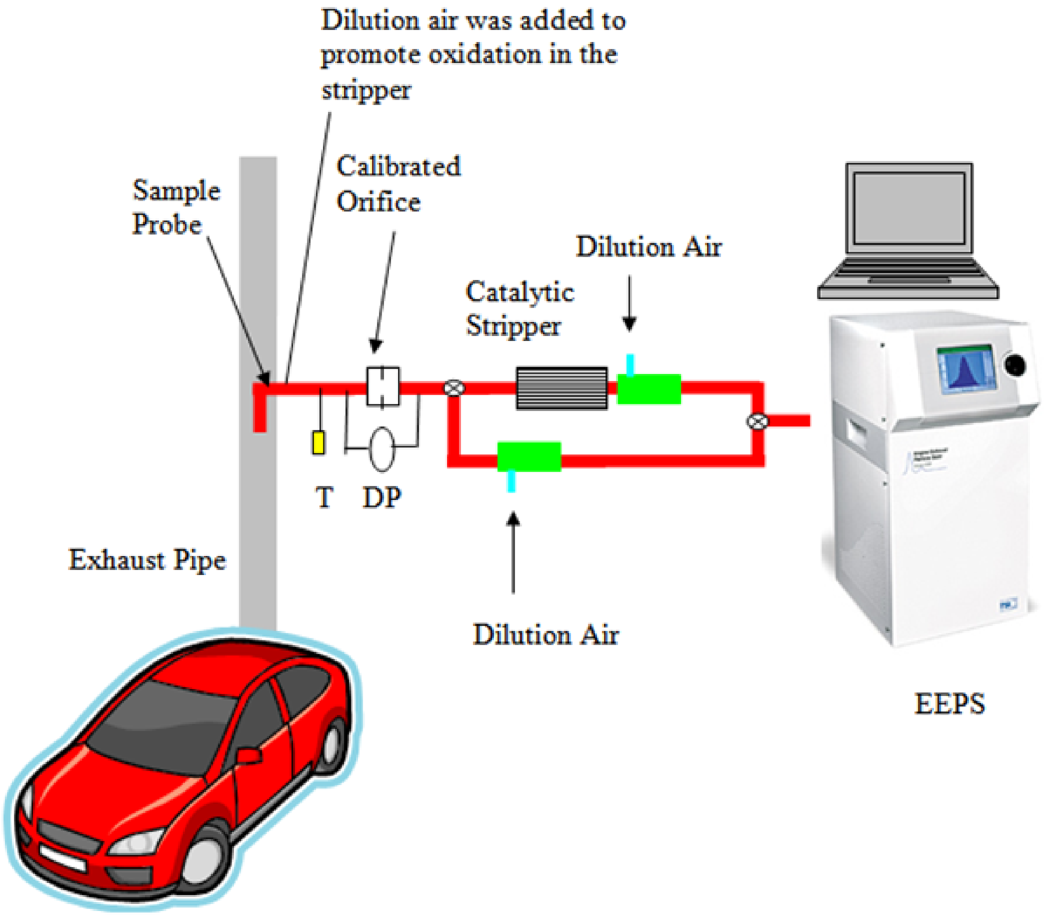

FIGURE 5. EXPERIMENTAL SETUP FOR PARTICLE SIZE AND NUMBER MEASUREMENTS

Table 14 shows the type of vehicles tested, along with the DR. The DR ranged from 7 for the light-duty gasoline normal emitter to 60 for diesel vehicles. For the EEPS to operate properly, a minimum DR of 7 was required to cool the exhaust temperature by dilution to an ambient level below 35°C. Cooling by dilution also minimizes thermophoretic particle loss. The DR was also chosen to balance between improving the detection limit with the EEPS at low concentrations while avoiding instrument saturation at high concentrations.

TABLE 14. DILUTION RATIO USED FOR DIFFERENT VEHICLES

	Normal Emitter	**High Emitter (or High Mileage)**
	DR	**DR**
Light-Duty Gasoline	7	16
Medium-Duty Diesel	60	60
Heavy-Duty Natural Gas	20	50
Heavy-Duty Diesel	60	60

For each vehicle, fuel, and lube oil combination tested, three measurements were taken with the EEPS over three separate cold-start and hot-start UDCs, performed over a period of three days. On Day 1 and Day 3, we measured total particle size and number, and on Day 2 we measured the solid particle size and number. Throughout this report, the average total particle size and number were determined based on two measurements performed on two separate days. The solid particle size and number were reported based on one measurement only. Table 15 shows a summary of the test matrix with each vehicle tested.

TABLE 15. TEST MATRIX USED FOR EACH VEHICLE, FUEL AND OIL COMBINATION

	Particle Size And Number Measurement
Day 1	Total (Solid and Volatile)
Day 2	Solid
Day 3	Total (Solid and Volatile)

6.3.1 Particle Mass and Size Distribution

Particle mass-weighted size distribution were measured using the Micro Orifice Uniform Deposit Impactor (MOUDI) and nano-MOUDI. This work was done with the light-duty normal emitter only using E0 at 72°F with fresh oil. The MOUDI covers a size range from 18 nm to 56 nm with four size intervals per decade. The nano-MOUDI extends the lower size limit of the MOUDI down to 10 nm. Selective stages were used covering the following sizes in nanometer: 3200, 1800, 1000, 560, 320, 180, 56, 32, 18, and 10. Nuclepore filters were used at each stage for PM collection. The mass collected on stages 1000, 320, 180, 56, 32, 18 and 10 nm were used for elemental analysis using ICP-MS. Analyses were performed for lube oil derived elements such as sulfur, phosphorus, calcium and zinc. The main goal of the MOUDI and nano-MOUDI work was to determine the size-specific elemental composition of PM.

Particle mass-weighted samples were measured only once from a single test configuration. This work was added to the project at the request of NREL.

7.0 LIGHT-DUTY VEHICLE TESTS

7.1 Vehicle Selection and Description

Light-duty vehicle selection was made in collaboration with the CLOSE Project Management Team. SwRI identified potential candidate vehicles for testing and made vehicle recommendations to the Project Management Team. We then waited for technical approval prior to procuring the test vehicles. Two LD vehicles were selected and tested, one normal PM emitter vehicle and one high PM emitter vehicle.

7.1.1 Light-Duty Vehicle Selection Criteria

- Normal-emitting gasoline vehicle: This was to be a 2002 model year or newer gasoline-fueled vehicle with between 30,000 and 75,000 miles on the odometer. The target odometer mileage was approximately 50,000. It was expected that this would be a high-volume, four-door family sedan equipped with a V-6 engine, and would be recruited from a local leasing agent.

- High-emitting gasoline vehicle: This was to be a gasoline-fueled vehicle with visible smoke related to lubrication oil. The RFP requested a PM emission rate greater than 200 mg/mi over the Unified Driving Cycle (UDC). This vehicle was solicited from SwRI employees, families, and friends. Candidate vehicles were to be screened for visual indication of consistent "white" smoke emissions during a variety of driving conditions. Consideration was given to the representativeness of the vehicle, as well as its ability to be safely and repeatedly tested on a chassis dynamometer. Because the specific goal in this project was to obtain a high emitter vehicle which demonstrated visually consistent white smoke associated with oil burning, extreme care should be taken in extrapolating the allocation results of this single vehicle to any more generalized on-road population, even to other high emitter vehicles. This vehicle is atypical and may not be representative of any other make or model of on-highway high mileage vehicle. The CLOSE team did not make any effort to determine or judge the prevalence or relative population of such vehicles.

7.1.2 Light-Duty Normal PM Emitter Vehicle Selection and Description

The light-duty normal emitter was a 2006 four-door family sedan with a 3.5L V6 engine. It had 30,695 miles on the odometer at the start of testing. It had the fifth highest unit sales among passenger cars in calendar year 2006. This car was certified to U.S Federal Tier 2 Bin 8 standards of 0.125 g/mile for NMOG, 4.2 g/mile for CO, 0.20 g/mile for NO_X, and 0.02 g/mile for PM at 120,000 miles. It was selected from a list of vehicles available for rental at the beginning of the program with input from the Technical Monitor and Project Management Team.

7.1.3 Light-Duty High PM Emitter Vehicle Selection and Description

The light-duty high PM emitter was a 1993 four-door family sedan with a 4.6L V8 engine. It had approximately 116,000 miles on the odometer at the start of testing. This car was certified to the U.S Federal Tier 1 standard of 0.31 g/mile of NMHC, 4.2 g/mile of CO, 0.6 g/mile of NO_X, and 0.10 g/mile of PM at 100,000 miles. It was solicited from SwRI employees and families. A report on the light-duty high PM emitter vehicle was prepared for the CLOSE participants. The report in Appendix C describes how the candidate vehicles were solicited and gives a description of all the candidates. In addition, the condition of the selected vehicle was examined further, and emissions tests were performed to assess its repeatability, plus its oil consumption was measured over 300 miles.

7.1.4 Gaseous and PM Emissions Check-Out Tests

A set of three four-phase Unified Cycle check-out tests were conducted to evaluate the repeatability of this vehicle before beginning any testing. These tests were performed on three separate days with commercial gasoline and engine lubricant as received. Composite and phase-level PM emission results are given in Table 16. Composite gaseous emission results are given in Table 17. These results indicated that the candidate test vehicle had relatively repeatable emissions. Following additional vehicle inspections, including determination of oil consumption and engine compression checks, it was accepted into the program by the CLOSE Project Management Team.

TABLE 16. LIGHT-DUTY HIGH EMITTER FOUR-PHASE UNIFIED CYCLE PM EMISSION RATE REPEATABILITY CHECK, mg/mi

	Phase 1	Phase 2	Phase 3	Phase 4	Composite
Test 1	31.2	77.3	133.6	130.3	101.1
Test 2	41.4	79.5	133.9	142.9	108.3
Test 3	35.8	61.7	156.7	118.8	91.0

These tests are not part of the PM characterization tests.
Tests were performed at a nominal 72°F, with commercial fuel and lubricant as received.

TABLE 17. COMPOSITE UNIFIED CYCLE GASEOUS EMISSION RATE REPEATABILITY CHECK, g/mi

	THC	CO	NO_X
Test 1	31.2	77.3	133.6
Test 2	41.4	79.5	133.9
Test 3	35.8	61.7	156.7

These tests are not part of the PM characterization tests.
Tests were performed at a nominal 72°F, with commercial fuel and lubricant as received.

7.2 Lubricants

The light-duty vehicles were tested with both fresh and aged lubricants that were supplied by the American Chemistry Council Product Approval Protocol Task Group. A description of the lubricants and the suppliers' analyses is provided in Section 5.1.1 in Tables 3 and 4. The engine's drain and fill procedure and the lubricant's initial degreening procedure are also described in Section 5.1. Oil samples include the fresh and aged oils as received, and samples taken after the cold (20°F) tests with fresh and aged oils on E0 and then E10 for both the normal and high emitter. eg. The normal emitter was operated over multiple emission tests with fresh oil and a sample was taken from the crankcase drain oil after the cold tests on EO fuels, and then the normal emitter was operated over multiple emissions tests with fresh oil on E10 fuels and a sample was taken from the crankcase drain oil after the cold tests. Thus five oil samples were taken from the normal-emitter (two fuel types and two oils, plus one repeat test on E0 with fresh oil), and four oil samples were taken from the high emitter.

7.3 Fuels

The light-duty vehicles were tested with non-oxygenated gasoline similar to California Phase 3 reformulated gasoline, but without ethanol (CA P3 RFG), gasoline with ten percent ethanol, which met CA P3 RFG specifications, a certification-grade cold-CO (carbon monoxide), gasoline for cold (20°F) tests, and a splash-blend of the cold-CO fuel with denatured ethanol to make a ten percent ethanol blend. A second batch of cold-CO fuel was also used in the study and it was also blended with ethanol to make a cold-E10 fuel. Descriptions of all the fuels used for light-duty testing are included in Section 5.2.1.

Prior to the initiation of testing on each fuel, the vehicles' fuel tanks were flushed. An example fuel flushing sequence is shown below:

Fuel Flush Procedure for Light-Duty Vehicles

1. Drain fuel from vehicle.
2. Fill tank with approximately 2 gallons of test fuel.
3. Cycle ignition twice to build fuel pressure before starting vehicle. Idle vehicle for approximately 2 minutes.
4. Drain fuel from vehicle.
5. Fill tank with approximately 2 gallons of test fuel.
6. Cycle ignition twice to build fuel pressure before starting vehicle. Idle vehicle for approximately 2 minutes.
7. Drain fuel from vehicle.
8. Fill vehicle full with test fuel.
9. Cycle ignition twice to build fuel pressure before starting vehicle.

7.4 Emission Test Procedures

This is a pilot study of exhaust emissions effects from the use of different fuels and lubricants with some tests conducted at different temperatures. It is important to note that the scope of work in this study is limited to short-term effects on emissions when a fuel or lubricant was changed. The fuels and lubricants used in this study could have long-term effects on emissions which were not measured.

7.4.1 Driving Cycle

The California Air Resources Board LA92 Dynamometer Driving Schedule, often called the Unified Driving Cycle (UDC) or LA92, was developed as an emission inventory improvement tool.[20] A graphic representation of speed versus time for the UDC is presented in Figure 6. The distance covered is 9.8 miles for Phases 1 and 2 and average speed is 24.6 mph. The UDC is designed to be more representative of all the modes of vehicle operation (hard accelerations, etc.) than is the FTP-75. The UDC test has a three-bag structure similar to the FTP-75, but is a more aggressive driving cycle than the federal FTP-75. Compared to the FTP-75, the LA92 cycle has a higher top speed (67.0 mph versus 56.7 mph), a higher average speed (24.8 mph versus 19.6 mph), less idle time (16.4 percent versus 19.0 percent), fewer stops per mile (1.52 versus 2.41), and a higher maximum rate of acceleration (3.02 m/s^2 versus 1.48 m/s^2). The LA92 is 9.8 miles long; the FTP-75's length is 7.5 miles.

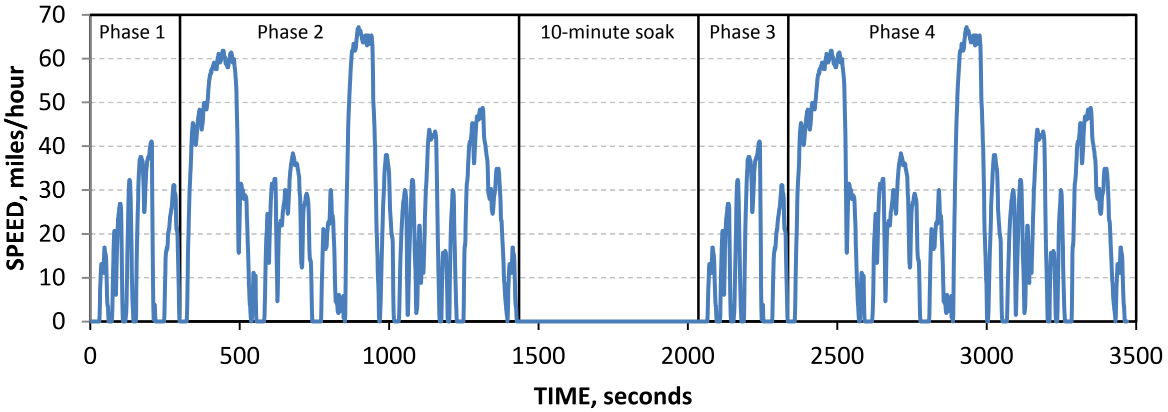

FIGURE 6. LA92 UNIFIED DRIVING CYCLE (UDC)

Light-duty vehicles were tested over replicate cold-start UDCs. Thus, only one UDC per day was run. The UDC was conducted as a cold-start, four-phase test, in a manner similar to the light-duty Federal Test Procedure (FTP). The UDC consisted of a 300-second cold-start phase (bag 1) followed by an 1,135-second hot stabilized phase (bag 2), a 10-minute soak, and a hot-start phase (bag 3) which is a repeat of the 300-second bag 1, and (bag 4) 1,135-second hot stabilized phase which is a repeat of bag 2. For all emission tests the vehicles were soaked for at least 12 hours at test temperature prior to emissions evaluations. The FTP weights emission rates from bags 1 and 2 at 43 percent, and emission rates from bags 3 and 4 at 57 percent, which are then added together to get a composite emission rate. In this study, because particulate matter was agglomerated onto single filters over multiple UDCs, and cold-start PM could not be separated from hot-start PM, fifty/fifty weighting factors were used to calculate composite UDC emission rates for all emissions.

Based on previous experience measuring vehicle PM exhaust emissions during programs conducted for NREL and CRC, it is possible for initial PM emission rates to be higher than those measured after a number of replicate tests.[10,21] It is thought that the PM deposition mechanism in the vehicles' exhaust systems may not have a chance to reach equilibrium during a standard vehicle conditioning procedure. This effect could have a major impact on the results of this study; therefore, to minimize this effect SwRI performed a conditioning sequence of repeated driving cycles with each vehicle prior to sample collection. This conditioning was conducted in conjunction with tunnel and sample system conditioning. Tests runs for the light-duty vehicles are described as follows:

- Normal-Emitting Vehicle
  - 72°F (nominal): SwRI conducted 8 cold-start UDCs (approximately 88 miles) to generate each set of PM samples. Thus, a total of 64 cold-start UDCs were conducted at this temperature (8 UDCs per sample × 2 oils × 2 replicate samples × 2 fuels). For repeatability assessment, an additional repeat test (8 UDCs) of the normal-emitting gasoline vehicle operating on gasoline was performed following the full test sequence.
  - 20°F (nominal): SwRI conducted 2 cold-start UDCs (approximately 22 miles) to generate each set of PM samples. Thus, a total of 16 UDCs were conducted at this temperature (2 UDCs per sample × 2 oils × 2 replicate samples × 2 fuels). One additional test was run for the EEPS measurement without collecting PM samples for each condition.
- High-Emitting Vehicle: A single cycle was found to be more than enough to collect sufficient sample mass for subsequent analysis at both 72°F and 20°F. Thus, a total of 16 UDCs were conducted with this vehicle (1 UDC per sample × 2 oils × 2 replicate samples × 2 temperatures × 2 fuels). One additional test was run for the EEPS measurement without collecting PM samples for each condition.

7.4.2 Chassis Dynamometer

For light-duty vehicles, Clayton Model ECE-50 passenger car dynamometers with direct-drive variable inertia flywheel systems were used for testing. The inertia systems on these dynamometers can simulate vehicle weights either from 1,000 pounds (lb) up to 4,875 lb in 125-lb increments or up to 7,250 lb in 250-lb increments. The chassis dynamometers are located in an SwRI-built enclosed cell, known as the Temperature Controlled Emissions Enclosure (TCEE). The TCEE was designed for testing vehicles from 10°F to 120°F over most driving cycles, and was cooled to 20°F for cold-start tests.

7.5 Emission Test Results

7.5.1 Regulated Gaseous and PM Mass Emissions

Summaries of the gaseous and PM emissions for the light-duty vehicle tests are reported in this section. Results from detailed characterizations of the PM are reported in subsequent sections. The light-duty vehicles were emissions tested with two fuels: a non-oxygenated fuel (E0) and an oxygenated fuel (E10), fresh and aged lubricants, and at 72°F and 20°F ambient temperatures. Two light-duty vehicles were tested, a normal PM emitter vehicle and a high particulate emissions vehicle. The normal PM emissions vehicle is referred to as the normal emitter (NE) throughout this document. Likewise, the high PM emissions vehicle is referred to as the high emitter (HE).

The Unified Driving Cycle (UDC), or LA-92, was used for all light-duty emissions tests, and each light-duty emission test consisted of a cold-start UDC, a ten-minute soak, and a hot-start UDC. For simplicity, a UDC in this project refers to this cold- and hot-start combined test. A single cold- and hot-start combined test was performed on any one day, and the vehicles were soaked overnight before performing subsequent UDCs. The day before any emission tests for record were run, two hot-start UDC cycles were used to prepare the vehicle unless a cold- and hot-start UDC has been run already, and then vehicles were soaked overnight.

Tables 18 and 19 show the average results from the light-duty normal PM emitter (NE) vehicle tests at 72°F and 20°F, respectively. Sixteen UDCs for each fuel and lubricant combination were performed at 72°F. Two sets of composite PM samples were collected for PM characterization. Each composite sample set was collected over eight UDCs, to capture enough material for analysis. Four UDCs were performed at 20°F for each fuel and lubricant combination. Separate composite PM samples were collected over the first and second series of two UDCs, to capture enough PM mass for later characterization analysis.

TABLE 18. LIGHT-DUTY NORMAL PM EMITTER VEHICLE AT 72°F
(No Statistical Analyses Were Performed On These Data)

	72°F -- AVERAGE (AVG) OF 16 UDCS WITH EACH FUEL / LUBRICANT COMBINATION											
	GASOLINE						E10					
	FRESH OIL			AGED OIL			FRESH OIL			AGED OIL		
	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation
THC, g/mile	0.050	0.007	13%	0.065	0.007	10%	0.086	0.009	10%	0.095	0.009	10%
CO, g/mile	0.639	0.119	19%	0.859	0.137	16%	0.844	0.112	13%	1.019	0.135	13%
NOx, g/mile	0.023	0.004	15%	0.021	0.005	23%	0.047	0.006	12%	0.040	0.005	13%
PM[a], mg/mile	0.53	0.12	23%	1.15	0.33	28%	1.72	0.24	14%	1.95	0.30	15%
Fuel Economy, mpg	21.5	0.5	2%	21.4	0.1	1%	21.1	0.2	1%	20.3	0.2	1%

[a] PM as determined from phase-by-phase filter samples collected during each test.

Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σ_{n-1}, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

TABLE 19. LIGHT-DUTY NORMAL PM EMTTER VEHICLE AT 20°F
(No Statistical Analyses Were Performed On These Data)

	20°F -- AVERAGE (AVG) OF 4 UDCS WITH EACH FUEL / LUBRICANT COMBINATION											
	GASOLINE						E10					
	FRESH OIL			AGED OIL			FRESH OIL			AGED OIL		
	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation
THC, g/mile	0.215	0.015	7%	0.242	0.020	8%	0.223	0.026	12%	0.290	0.009	3%
CO, g/mile	2.348	0.100	4%	2.647	0.096	4%	2.537	0.061	2%	2.778	0.078	3%
NOx, g/mile	0.049	0.003	6%	0.041	0.005	12%	0.046	0.004	8%	0.043	0.006	13%
PM[a], mg/mile	3.93	0.52	13%	4.25	0.52	12%	5.54	0.88	16%	4.98	0.73	15%
Fuel Economy, mpg	20.0	0.4	2%	19.2	0.4	2%	19.7	0.5	3%	18.6	0.1	0%

[a] PM as determined from phase-by-phase filter samples collected during each test.

Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σ_{n-1}, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

Tables 20 and 21 show the average results from the light-duty high PM emitter (HE) vehicle tests at 72°F and 20°F, respectively. A total of three UDCs were performed for each fuel, lubricant, and temperature combination in order to measure particulate counts and size distributions, but particulate filter sets sampled for later analyses were captured during only two of the three UDCs.

TABLE 20. LIGHT-DUTY HIGH PM EMITTER VEHICLE AT 72°F
(No Statistical Analyses Were Performed On These Data)

	72°F -- AVERAGE (AVG) OF 3 UDCS WITH EACH FUEL / LUBRICANT COMBINATION											
	GASOLINE						E10					
	FRESH OIL			AGED OIL			FRESH OIL			AGED OIL		
	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation
THC, g/mile	0.862	0.039	5%	0.777	0.029	4%	0.909	0.036	4%	0.698	0.017	2%
CO, g/mile	7.88	0.22	3%	7.47	0.33	4%	7.65	0.23	3%	6.73	0.14	2%
NOx, g/mile	0.904	0.051	6%	0.872	0.050	6%	0.955	0.097	10%	0.868	0.005	1%
PM[a], mg/mile	198	8.7	4%	172	9.6	6%	198	11.6	6%	122	10.0	8%
Fuel Economy, mpg	18.6	0.2	1%	19.2	0.5	2%	17.8	0.5	3%	18.9	0.8	4%

[a] PM as determined from phase-by-phase filter samples collected during each test.

Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

TABLE 21. LIGHT-DUTY HIGH PM EMITTER VEHICLE AT 20°F
(No Statistical Analyses Were Performed On These Data)

	20°F – AVERAGE (AVG) OF 3 UDCS WITH EACH FUEL / LUBRICANT COMBINATION											
	GASOLINE						E10					
	FRESH OIL			AGED OIL			FRESH OIL			AGED OIL		
	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation	AVG	Standard Deviation	Coefficient of Variation
THC, g/mile	0.998	0.038	4%	0.939	0.041	4%	0.953	0.037	4%	0.710	0.024	3%
CO, g/mile	9.73	0.17	2%	10.30	0.30	3%	8.48	0.42	5%	7.48	0.65	9%
NOx, g/mile	1.415	0.044	3%	1.434	0.050	4%	1.306	0.011	1%	1.300	0.072	6%
PM[a], mg/mile	178	4.5	3%	161	13.9	9%	194	10.8	6%	100	6.6	7%
Fuel Economy, mpg	17.1	0.1	1%	17.7	0.2	1%	16.8	0.3	2%	17.4	0.2	1%

[a] PM as determined from phase-by-phase filter samples collected during each test.

Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

Following the completion of testing of the light-duty normal emitter, NREL requested that a repeat test of this vehicle be conducted, at 72°F on non-oxygenated fuel with collection of composite PM samples for analyses by Desert Research Institute (DRI) using existing project methodologies. In addition, during the repeat test we collected samples using a MOUDI and nano-MOUDI and analyzed the samples for Ca, Zn, and other elements. MOUDI results are discussed in Section 7.5.2.10. Table 22 shows a comparison of the gaseous and PM emissions from the first two replicate tests alongside the repeat (third) test of the light-duty normal emitter on fresh oil with non-oxygenated fuel at 72°F.

During the third test, sequence average HC and CO emission results were slightly higher and NO_X emission results were slightly lower than the average results from the first two test sequences. This indicates that the engine may have run richer during the repeat tests. During the repeat test, PM emission rates were double those seen during the first two tests. For verification, SwRI re-weighed all the phase-by-phase PM filter samples from these tests and verified that the weights were correct.

TABLE 22. COMPARISON OF INITIAL AND REPEAT TEST OF LIGHT-DUTY NORMAL PM EMITTER
(No Statistical Analyses Were Performed On These Data)

	Gasoline With Fresh Oil at 72°F					
	First Two Tests			Third Test		
	Average of 16 UDCS			Average of 8 UDCS		
	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation
THC, g/mile	0.050	0.007	13%	0.071	0.006	8%
CO, g/mile	0.639	0.119	19%	0.863	0.081	9%
NOx, g/mile	0.023	0.004	15%	0.016	0.003	18%
PM[a], mg/mile	0.53	0.12	23%	1.09	0.14	12%
Fuel Economy, mpg	21.5	0.5	2%	21.6	0.4	2%

[a] PM as determined from phase-by-phase filter samples collected during each test.

Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

The reason for the nominal increase in PM rate is not known; however, the vehicle was tested at cold temperatures and on E10 fuel between the first two tests and the third test. Standard deviations within the respective data sets imply operation was comparably stable. Our records were inspected and dynamometer settings, fuel, engine oil, flushing procedures, and initial oil shear stabilization runs were repeated correctly for the third test.

Figures 7 through 13 graphically display the data in Tables 18 through 22.

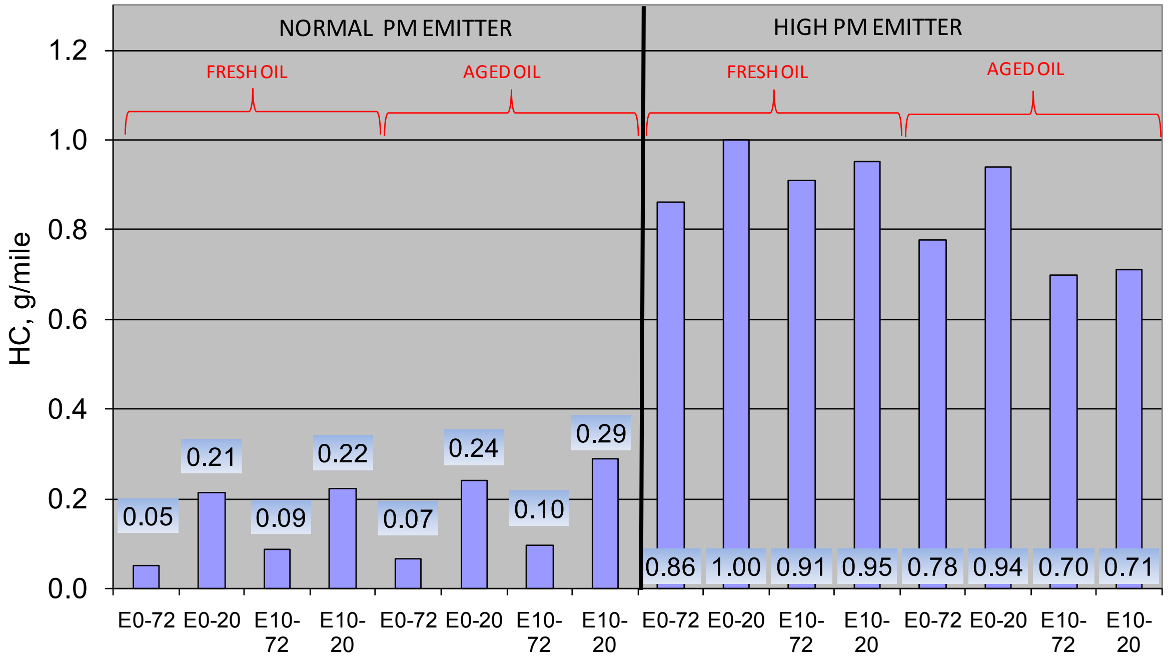

FIGURE 7. LIGHT-DUTY AVERAGE HYDROCARBON EMISSION RATES
(No Statistical Analyses Were Performed On These Data)

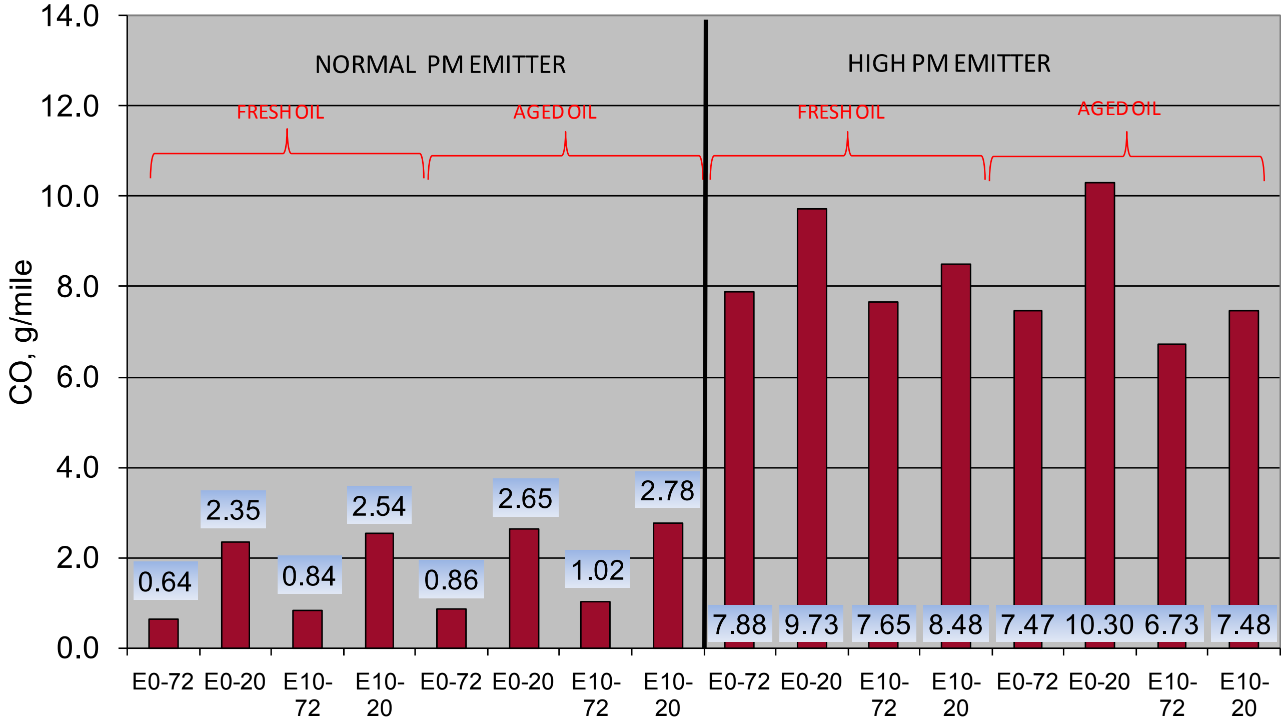

FIGURE 8. LIGHT-DUTY AVERAGE CARBON MONOXIDE EMISSION RATES (No Statistical Analyses Were Performed On These Data)

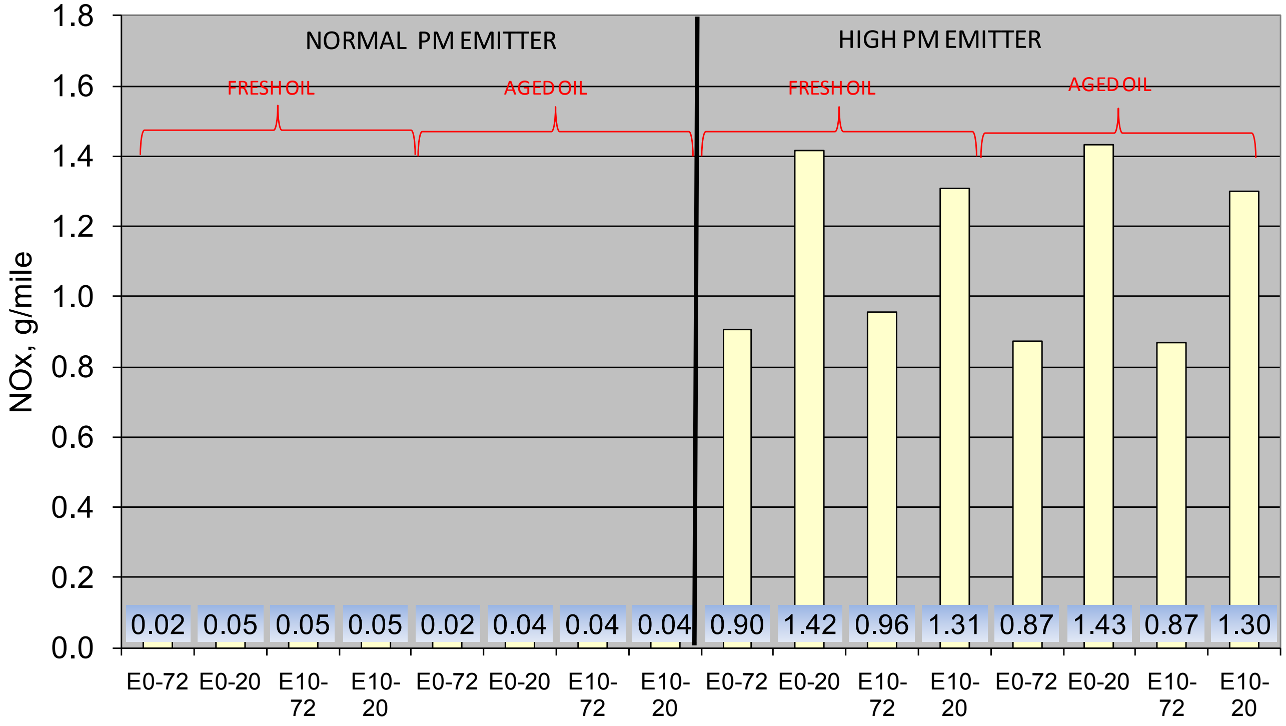

FIGURE 9. LIGHT-DUTY AVERAGE OXIDES OF NITROGEN EMISSION RATES (No Statistical Analyses Were Performed On These Data)

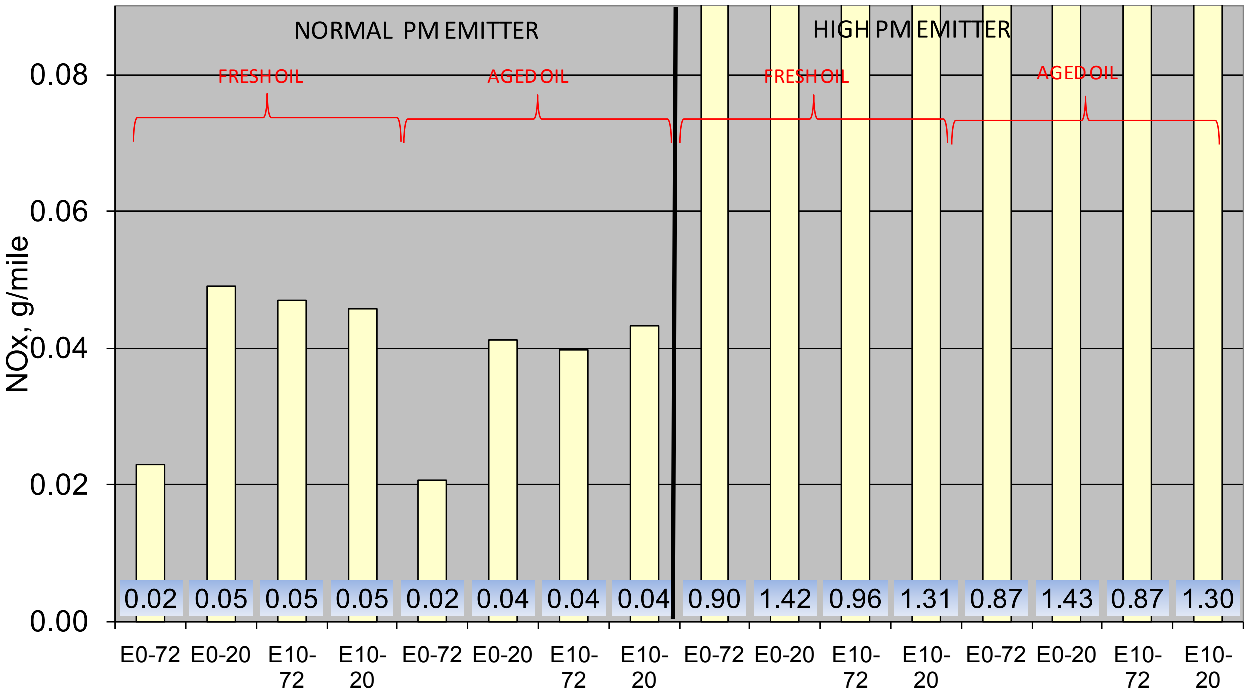

FIGURE 10. LIGHT-DUTY AVERAGE OXIDES OF NITROGEN EMISSION RATES – EXPANDED SCALE
(No Statistical Analyses Were Performed On These Data)

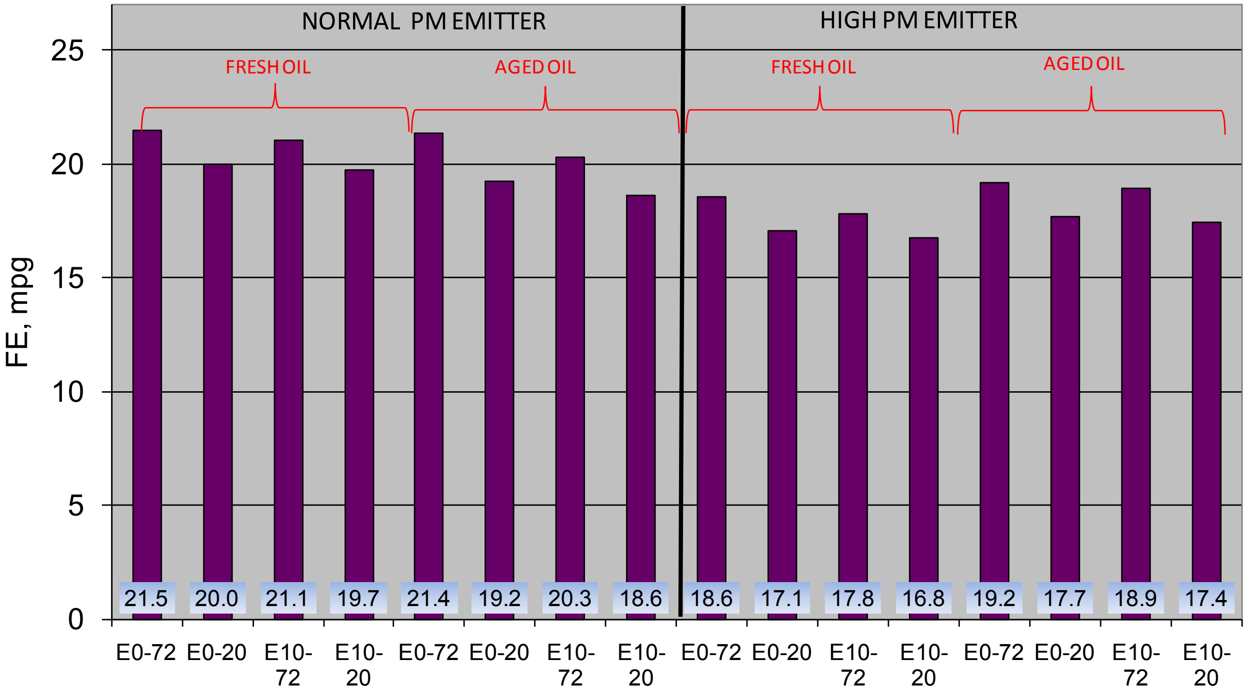

FIGURE 11. LIGHT-DUTY AVERAGE FUEL ECONOMY
(No Statistical Analyses Were Performed On These Data)

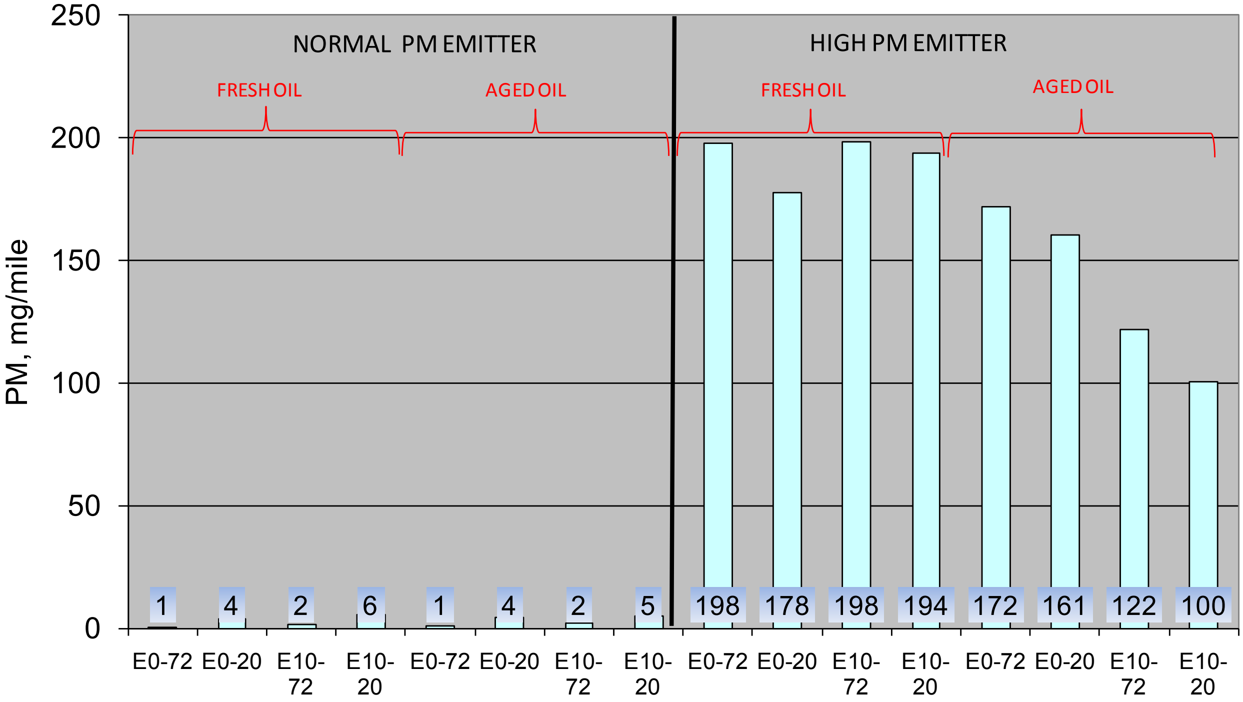

FIGURE 12. LIGHT-DUTY AVERAGE PARTICULATE MATTER EMISSION RATES
(No Statistical Analyses Were Performed On These Data)

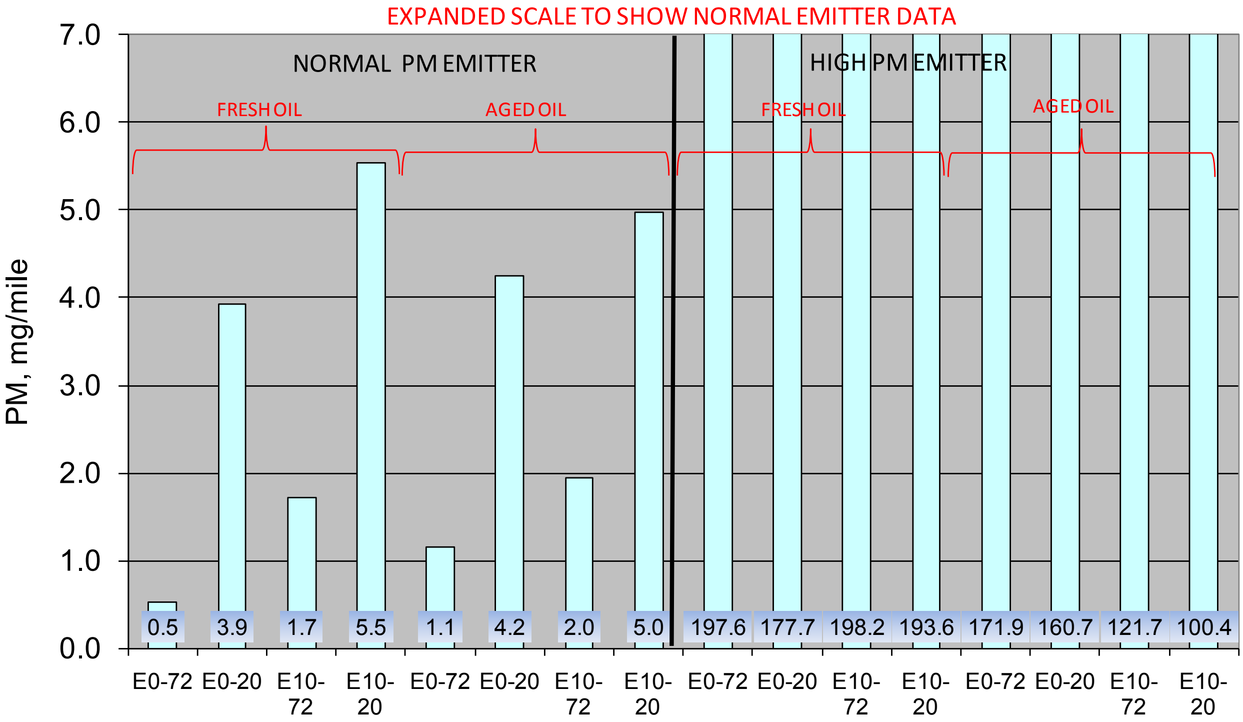

FIGURE 13. LIGHT-DUTY AVERAGE PARTICULATE MATTER EMISSION RATES – EXPANDED SCALE
(No Statistical Analyses Were Performed On These Data)

7.5.1.1 Discussion of Regulated Emission Results

This section discusses the results presented in Tables 18 through 22 and Figures 7 through 13. Note that long range precision was not thoroughly explored in the test design. Thus, statistical significance of comparisons across different temperatures, fuels, or lubricants cannot be rigorously verified.

Figure 7 shows the combined average hydrocarbon emission rates from both the normal and high PM emitter. The high emitter produced more hydrocarbons than the low emitter in all test cases. For the normal emitter, hydrocarbon emissions increased at cold temperatures in all tests, and with E10 increased at least nominally in all cases. Comparing fresh and aged oil tests with the normal emitter, it appears that the cold tests produced nominally higher hydrocarbons. But hydrocarbon emissions from the 72°F tests are not affected by the change from fresh to aged oil. For the high emitter, Figure 7 shows that hydrocarbon emissions tend to only nominally increase at cold temperatures, but there is no trend in hydrocarbon emissions when comparing E0 to E10 fuels.

Figure 8 shows the combined average carbon monoxide (CO) emission rates from both the normal and high PM emitter. The high emitter produced higher carbon monoxide emissions than the low emitter in all test cases. For the normal emitter, CO emissions increased nominally at cold temperatures, with E10 fuel, and increased nominally with aged oil in all tests. For the high emitter, Figure 8 shows that CO emissions increased nominally at cold temperatures.

Figures 9 and 10 show the combined average oxides of nitrogen (NO_X) emission rates from both the normal and high PM emitter. Figure 10 shows the same data as Figure 9 except that it is on an expanded scale to show the normal emitter's NO_X emissions. The high emitter produced much higher NO_X emissions than the low emitter in all test cases. As shown in Figure 9, the high emitter produced more NO_X at cold temperatures. The high emitter's NO_X emissions were not affected by changing from fresh to aged oils. On E0 fuel during the 72°F tests, in the NE vehicle NO_X emissions are nominally lower than all the other tests, but no other trends are apparent.

Figure 11 shows the average fuel economy of the light-duty vehicles. The high emitter had lower fuel economy than the normal emitter in all test cases but this is expected, because the high emitter is heavier, has a larger engine, and has older engine calibrations, hardware, and running gear. The cold (20°F) tests with both vehicles all produced nominally worse fuel economies than the room temperature tests. For the normal emitter, aged oil produced nominally lower fuel economy in three of the four configurations, but the high emitter had better fuel economy in all configurations with aged oil, which is not surprising. As expected due to its lower energy value, the average fuel economy was lower in all cases with E10 fuel compared to E0 fuel.

Figures 12 and 13 show the PM mass emissions from both light-duty vehicles. Figure 13 shows the same data as Figure 12 but with an expanded scale because the high emitter produced much higher emissions than the low emitter. From Figure 12 the PM rates for the higher emitter were nominally lower in cold (20°F) temperature tests compared to warm tests, which is opposite to the trend shown in Figure 13 for the normal emitter. During cold temperature starts, fuel rates are increased to enrich the air-fuel mixture to promote gasoline vaporization and enhance startability. The enriched mixture produces more unburned and partially burned hydrocarbons in the exhaust and thus an increase in hydrocarbon emissions, as shown in Figure 7. The richer combustion mixture also produces more soot. The soot and unburned hydrocarbons can also agglomerate together in the exhaust pipe and dilution tunnel and be collected as particulate. Thus, cold temperature starts typically produce higher PM emissions.

It is obvious in Figure 13 that the normal emitter's PM emissions with the low temperature starts trend as expected. It is also obvious in Figure 12 that even with fuel enrichment, the high emitter's PM emission rates during low temperature starts are determined by some means other than fuel enrichment, because its cold starts produced somewhat less PM emissions. Recall that the high emitter is a smoke emitter because it has a high rate of lubricant consumption. It appears the HE PM emissions are more influenced by lubricant consumption than air/fuel ratio changes caused by low temperature operation. Because at lower temperatures lubricants are more viscous and evaporate slower, we hypothesize that during low temperature starts less lubricant entered the combustion chamber, and may have remained on the cylinder, piston, and head surfaces for a longer period than during room temperature tests. Another hypothesis is that during low temperature starts the high emitter's catalytic converter and exhaust system and muffler collected more lubricant aerosols than during room temperature tests, and that at lower temperatures this oil was not released back into the exhaust stream.

Comparing the PM emission rate changes due to the use of fresh or aged oils, the low emitter does not show a change in PM emission rates, but the high emitter produced less PM with aged oil than fresh oil. Again, we hypothesize that, since the aged oil lost its lighter hydrocarbons as it aged, it is more viscous and evaporates slower than the fresh oil, or, since aged oil has more heavy hydrocarbons, more of the lubricant aerosols were collected in the vehicle's exhaust system.

From Figure 12, while it appears that PM emissions from the high emitter vehicle with aged oil tended to be lower with E10 fuel than E0 fuel, no such trend is apparent with fresh oil. From Figure 13, PM emissions from the NE were nominally higher with E10 than with E0 in every case. No reasons supporting these nominal changes are known.

7.5.2 PM and SVOC Analyses

PM emissions were characterized by analyzing them for elements, semi-volatile organic compounds (SVOC), elemental and organic compounds (EC/OC), sulfates, and soluble organic fraction (SOF). In the following PM characterization subsections, Tables 23 through 37 present the results of these particulate characterizations. Also included in Tables 23 through 37 are the results of the analyses of fuels and lubricants and code tables for the hydrocarbon species. PM analyses shown in these tables are averaged from a spreadsheet of PM analyses results devised by Dr. Eric Fujita of DRI for the apportionment analysis of the light-duty PM emissions. The spreadsheet includes the results from each test performed, and is posted at an ftp site at SwRI. Dr. Fujita used the spreadsheet data to identify elements of interest in his apportionment study which is included in Section 7.6. The third test of the light-duty normal emitter on regular E0 fuel, with fresh oil, at 72°F temperature is included in a separate column of data for comparison to the first two test's average.

These tables show results with emissions identified on the left of the tables and test configurations identified in the top row of the tables.

7.5.2.1 X-Ray Fluorescence (XRF)

PM sampled from the light-duty tests was analyzed by DRI for elements by XRF. Replicate emission tests were performed in each configuration. Table 23 shows the average results in µg/mile of the replicate tests performed in each configuration.

7.5.2.2 Inductively Coupled Plasma Mass Spectrometry (ICP-MS) Analysis

PM sampled from the light-duty tests was also analyzed by DRI for a subset of eighteen elements by ICP-MS. Table 24 shows the average results in µg/mile of the replicate tests performed in each configuration. The configurations are identified in the top rows of the table, and elements measured are shown in the left column. Table 25 shows the results of elemental analyses of the lubricants and one fuel. Replicate analyses were performed with three of the lubricants.

7.5.2.3 Polycyclic Aromatic Hydrocarbons

PM sampled from the light-duty tests was also analyzed by DRI for polycyclic aromatic hydrocarbons (PAH). Table 26 shows the average results in µg/mile of the replicate tests performed in each configuration. Table 27 shows the results of the lubricant and fuel analyses for PAHs. Table 28 shows the codes for the PAH species in Tables 26 and 27.

7.5.2.4 Alkanes

PM sampled from the light-duty tests was also analyzed by DRI for alkanes. Table 29 shows the average results in µg/mile of the replicate tests performed in each configuration. Table 30 shows the codes for the alkane species in Table 29.

Table 31 shows the results of alkane analyses of the fuels and lubricants from the light-duty vehicles. The first two columns are results from the fresh and aged oils as received from the suppliers. The following columns identified by a test number are lubricant analyses from samples taken from the engine crankcase after the tests in those configurations were completed. The last five columns show results of the light-duty fuel analyses for alkanes.

TABLE 23. AVERAGE RESULTS OF LIGHT-DUTY VEHICLE PM ELEMENTAL ANALYSIS BY XRF, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	**LD-NE-F-E0-72**	**LD-NE-F-E0-72-3a**	**LD-NE-F-E0-20**	**LD-NE-F-E10-72**	**LD-NE-F-E10-20**	**LD-NE-A-E0-72**	**LD-NE-A-E0-20**	**LD-NE-A-E10-72**	**LD-NE-A-E10-20**	**LD-HE-F-E0-72**	**LD-HE-F-E0-20**	**LD-HE-F-E10-72**	**LD-HE-F-E10-20**	**LD-HE-A-E0-72**	**LD-HE-A-E0-20**	**LD-HE-A-E10-72**	**LD-HE-A-E10-20**
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	E0	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10
Temp. °F	72	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Na	0.96	1.91	2.01	1.76	5.41	2.41	11.22	4.03	7.33	35.9	52.1	50.8	72.7	78.5	72.6	118	60.8
Mg	0.24	0.01	0.00	0.22	1.36	0.10	1.11	0.17	0.20	17.0	18.1	14.0	16.3	17.4	17.6	18.6	12.4
Al	1.39	0.84	4.82	0.87	4.32	0.86	2.79	0.59	1.14	12.1	8.17	7.57	6.79	10.5	12.4	9.3	10.9
Si	2.12	0.88	10.36	1.94	8.04	1.92	4.46	0.76	3.72	22.3	19.5	11.6	13.6	18.4	22.0	21.5	18.9
P	5.29	6.42	33.0	7.62	47.5	9.45	25.4	9.9	29.6	226	202	171	177	261	305	318	288
S	2.26	3.11	22.0	8.73	34.1	5.91	22.8	11.2	25.7	284	282	204	242	417	461	428	387
Cl	1.33	2.83	5.41	4.77	9.15	4.24	6.22	4.29	6.13	13.9	14.4	17.0	15.6	16.6	18.4	13.7	12.0
K	0.58	0.41	1.63	0.71	2.38	0.75	1.58	0.50	1.55	15.0	14.1	14.4	13.4	14.0	15.2	14.3	12.8
Ca	17.3	19.1	88.9	21.9	126.0	30.8	77.3	30.6	88.7	1273	1164	1214	1181	1182	1294	1252	1126
Sc	0.05	0.11	0.19	0.03	0.38	0.00	0.16	0.05	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.93	0.72	0.39	0.96	0.57	0.82	0.09	0.60	0.07	0.63	0.09	1.17	0.69	0.34	1.06	0.54	0.41
Va	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.18	0.00	0.03	0.02	0.03
Cr	0.50	0.27	1.43	0.63	2.12	0.34	0.97	0.22	1.04	3.03	4.00	0.98	0.91	0.73	1.09	2.09	1.58
Mn	0.13	0.10	0.80	0.09	1.11	0.12	0.72	0.09	0.63	0.96	0.78	0.34	0.40	0.71	0.88	1.40	1.06
Fe	5.34	3.40	18.9	4.62	25.10	5.15	14.81	2.90	17.2	35.8	33.2	12.4	14.1	13.8	20.6	46.5	27.1
Co	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.28	0.07	0.41	0.25	0.74	0.10	0.32	0.06	0.35	1.50	1.03	0.44	0.45	0.66	1.63	1.46	1.27
Cu	0.81	0.75	2.62	1.14	4.53	1.08	2.10	0.98	2.22	3.27	2.18	3.23	2.55	8.08	8.91	9.22	8.54
Zn	6.00	7.50	36.5	8.12	50.7	10.0	28.3	10.4	32.4	437	379	363	368	335	412	442	385
Ga	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.21	0.20	0.00	0.00	0.00	0.00	0.19
As	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00
Se	0.01	0.07	0.09	0.02	0.13	0.00	0.23	0.00	0.07	0.25	0.02	0.41	0.06	0.00	0.09	0.36	0.37
Br	0.01	0.09	0.20	0.16	0.20	0.02	0.05	0.12	0.03	0.61	0.30	0.76	0.95	0.32	0.57	0.63	0.84
Rb	0.02	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.04	0.11	0.01	0.11	0.14	0.00	0.04
Sr	0.01	0.01	0.40	0.07	0.14	0.08	0.11	0.13	0.11	2.25	2.14	2.27	2.07	2.09	2.58	2.34	2.23
Yt	0.03	0.00	0.13	0.03	0.21	0.03	0.11	0.05	0.15	0.01	0.14	0.02	0.17	0.05	0.26	0.15	0.10

TABLE 23 (CONT'D). AVERAGE RESULTS OF LIGHT-DUTY VEHICLE PM ELEMENTAL ANALYSIS BY XRF, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	**LD-NE-F-E0-72**	**LD-NE-F-E0-72-3a**	**LD-NE-F-E0-20**	**LD-NE-F-E10-72**	**LD-NE-F-E10-20**	**LD-NE-A-E0-72**	**LD-NE-A-E0-20**	**LD-NE-A-E10-72**	**LD-NE-A-E10-20**	**LD-HE-F-E0-72**	**LD-HE-F-E0-20**	**LD-HE-F-E10-72**	**LD-HE-F-E10-20**	**LD-HE-A-E0-72**	**LD-HE-A-E0-20**	**LD-HE-A-E10-72**	**LD-HE-A-E10-20**
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	E0	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10
Temp. °F	72	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Zr	0.49	0.38	1.25	0.38	1.87	0.54	0.97	0.34	1.56	0.18	0.30	0.43	1.20	0.04	0.18	0.70	0.61
Nb	0.00	0.00	0.03	0.00	0.08	0.00	0.05	0.00	0.04	0.00	0.05	0.24	0.08	0.00	0.15	0.21	0.17
Mo	0.42	0.53	2.32	0.62	2.81	0.92	2.24	1.08	2.66	40.6	38.4	29.1	30.2	42.4	48.6	48.7	42.6
Pd	0.00	0.00	0.19	0.02	0.16	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.00	0.00	0.00
Ag	0.00	0.00	0.00	0.00	0.05	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cd	0.04	0.00	0.00	0.00	0.18	0.05	0.00	0.00	0.10	0.48	0.00	0.00	0.33	0.00	0.00	0.00	0.00
In	0.03	0.03	0.03	0.02	0.00	0.01	0.09	0.02	0.08	0.18	0.00	0.00	0.00	0.06	0.00	0.00	0.00
Sn	0.02	0.00	0.01	0.03	0.00	0.00	0.05	0.00	0.00	0.00	0.41	0.00	0.00	0.00	0.00	0.00	0.12
Sb	0.00	0.00	0.11	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.72	0.00	0.00	0.00	0.00	0.00
Cs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00
La	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.04
Ce	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00
Sm	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.05	0.07	0.00	0.13	0.00	0.00	0.11	0.18	0.06
Eu	0.06	0.00	0.00	0.01	0.12	0.04	0.05	0.02	0.05	0.13	0.15	0.00	0.04	0.00	0.00	0.00	0.00
Tb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.06	0.09	0.00	0.00	0.00
Hf	0.09	0.00	0.42	0.06	0.68	0.00	0.27	0.05	0.05	1.52	1.56	0.68	0.00	1.53	1.38	2.81	2.60
Ta	0.21	0.05	0.45	0.08	0.26	0.10	0.00	0.06	0.21	0.89	0.08	1.05	0.92	0.45	0.97	2.02	0.08
Wo	0.00	0.19	0.56	0.00	0.42	0.00	0.23	0.04	0.33	1.56	2.45	2.19	3.39	0.77	0.00	0.00	0.80
Ir	0.04	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Au	0.13	0.00	0.00	0.00	0.16	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.35	0.00	0.00	0.00	0.00
Hg	0.00	0.00	0.00	0.02	0.00	0.02	0.05	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00
Tl	0.00	0.00	0.00	0.00	0.03	0.00	0.03	0.00	0.11	0.00	0.00	0.03	0.18	0.15	0.03	0.00	0.00
Tb	0.17	0.02	0.07	0.02	0.26	0.16	0.43	0.09	0.04	1.14	0.44	0.20	1.01	0.62	0.26	1.07	0.28
Ur	0.01	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.00	0.82	0.00	0.00	0.49	0.00	0.00

a The repeat test of the normal emitter after all other tests were run is included here but not as part of the first two test's averaged data.

TABLE 24. AVERAGE RESULTS OF LIGHT-DUTY VEHICLE PM ELEMENTAL ANALYSIS BY ICP-MS, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	**LD-NE-F-E0-72**	**LD-NE-F-E0-72-3**[a]	**LD-NE-F-E0-20**	**LD-NE-F-E10-72**	**LD-NE-F-E10-20**	**LD-NE-A-E0-72**	**LD-NE-A-E0-20**	**LD-NE-A-E10-72**	**LD-NE-A-E10-20**	**LD-HE-F-E0-72**	**LD-HE-F-E0-20**	**LD-HE-F-E10-72**	**LD-HE-F-E10-20**	**LD-HE-A-E0-72**	**LD-HE-A-E0-20**	**LD-HE-A-E10-72**	**LD-HE-A-E10-20**
Emitter	Normal	Normal	Norma	Norma	Norma	Norma	Norma	Norma	Norma	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	E0	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10
Temp, °F	72	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Mg	0.28	0.07	1.43	0.23	1.70	0.20	0.92	0.12	1.09	10.4	10.5	9.9	9.7	11.2	12.7	12.9	12.0
Al	2.53	0.42	9.24	1.42	7.13	1.16	4.10	0.80	4.00	10.7	9.5	5.5	7.0	6.6	8.1	10.4	7.6
Ca	15.9	16.3	80.0	19.0	110	26.8	68.9	26.6	79.3	1368	1418	1513	1392	1427	1468	1406	1271
Va	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.02	0.01	0.01	0.01	0.02	0.02	0.02
Cr	0.25	0.00	0.81	0.32	0.95	0.00	0.25	0.00	0.95	6.34	3.92	2.92	2.09	2.73	2.88	4.04	2.88
Mn	0.09	0.03	0.44	0.09	0.61	0.07	0.30	0.04	0.35	0.76	0.45	0.30	0.25	0.52	0.67	0.99	0.62
Fe	3.75	1.10	12.88	3.19	16.20	2.31	10.14	0.46	11.40	40.7	28.5	14.8	15.6	13.7	16.1	52.0	22.6
Ni	0.29	0.00	0.25	0.29	0.48	0.00	0.12	0.00	0.22	3.28	1.60	1.02	0.68	0.74	1.13	2.02	1.41
Cu	0.72	0.51	1.87	0.82	2.97	0.80	1.33	0.71	1.34	2.83	1.45	2.80	3.05	7.11	8.08	8.19	7.31
Zn	4.90	5.50	28.5	6.03	39.3	7.46	21.2	7.4	24.4	376	365	358	355	324	361	392	352
Mo	0.34	0.34	1.47	0.40	1.83	0.58	1.40	0.61	1.51	35.9	34.6	26.7	28.3	38.6	40.6	41.3	37.4
Ag	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.08	0.60	0.25	0.46	0.01	0.00	0.03	0.00
Cd	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sn	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.28	0.32	0.13	0.18	0.35	0.39	0.47	0.45
Ba	0.58	0.28	0.39	0.50	0.41	0.37	0.08	0.24	0.12	2.28	0.63	3.25	0.86	2.79	1.12	2.66	0.84
Ce	0.05	0.04	0.33	0.05	0.53	0.08	0.25	0.06	0.34	0.04	0.04	0.02	0.02	0.05	0.29	0.21	0.12
Hg	0.01	0.00	0.01	0.01	0.02	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pb	0.04	0.00	0.00	0.00	0.00	0.03	0.21	0.00	0.00	0.81	0.60	0.29	0.37	0.35	0.49	0.80	0.57

[a] The repeat test of the normal emitter after all other tests were run is included here but not as part of the first two test's averaged data.

TABLE 25. LIGHT-DUTY VEHICLE ELEMENTAL ANALYSIS OF FUELS AND LUBRICANTS BY ICP-MS, ng/g

(No Statistical Analyses Were Performed On These Data)

SAMPLE CODE	ELEMENTS CONCENTRATIONS, ng/gram							
	COLD E10 FUEL	LD-NE-F-E0 REP 1	LD-NE-F-E0 REP 2	LD-NE-A-E0 REP 1	LD-NE-A-E0 REP 2	LD-NE-F-E10	LD-NE-A-E10 REP 1	LD-NE-A-E10 REP 2
Sample Type	Fuel	Oil	Oil	Oil	Oil	Oil	Oil	Oil
Emitter	Both	Normal	Normal	Normal	Normal	Normal	Normal	Normal
Oil	NA	Fresh	Fresh	Aged	Aged	Fresh	Aged	Aged
Fuel	EM-6856-F	E0	E0	E0	E0	E10	E10	E10
Temp, °F	20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20
Tracer	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Mg	<LOD[a]	14143	13903	16260	15829	13919	15184	16181
Al	<LOD	1820	1254	7194	7164	1802	6874	6517
Ca	<LOD	1940847	1918484	2089479	2071293	1948107	2050272	2034966
Va	<LOD	7	5	9	9	7	9	11
Cr	<LOD	135	55	345	350	110	337	345
Mn	<LOD	429	158	827	827	298	768	771
Fe	59	6183	1887	10412	10430	3393	9382	9519
Ni	<LOD	92	32	223	193	103	154	151
Cu	8	5285	2121	15671	15458	3722	15171	15478
Zn	<LOD	863385	856665	876769	886816	917314	838830	875179
Mo	<LOD	72391	71602	78782	78456	71357	81899	80284
Ag	<LOD	<LOD	<LOD	6	5	<LOD	8	8
Ba	<LOD	58	17	65	55	32	42	48
Pb	2	243	109	398	401	147	392	387
W	<LOD	3	<LOD	4	3	<LOD	3	3
P	<LOD	721877	716541	654430	632582	722491	631292	652123
S	28362	2169961	2081068	2189573	2159864	2221592	2140706	2153047
Ti	<LOD	26	<LOD	26	34	28	31	43
Sr	<LOD	3109	3128	3134	3168	3130	3326	3080

[a] Less than Level of Detection

TABLE 26. POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	**LD-NE-F-E0-72**	**LD-NE-F-E0-72-3**	**LD-NE-F-E0-20**	**LD-NE-F-E10-72**	**LD-NE-F-E10-20**	**LD-NE-A-E0-72**	**LD-NE-A-E0-20**	**LD-NE-A-E10-72**	**LD-NE-A-E10-20**	**LD-HE-F-E0-72**	**LD-HE-F-E0-20**	**LD-HE-F-E10-72**	**LD-HE-F-E10-20**	**LD-HE-A-E0-72**	**LD-HE-A-E0-20**	**LD-HE-A-E10-72**	**LD-HE-A-E10-20**
Source	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	E0	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10
Temp, °F	72	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media[b]	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction[c]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
naphth	51.2	34.5	552.8	70.6	228.1	28.8	590.0	56.9	186.0	851.5	1360.4	1501.1	1361.3	1149.0	771.3	1327.2	560.1
quinoline	0.0	0.2	0.5	0.7	0.9	0.2	0.7	1.7	1.9	20.9	27.6	50.3	44.4	36.3	51.3	45.5	36.0
mnaph2	16.9	18.5	72.8	67.2	74.3	22.1	73.3	89.7	122.4	432.8	192.3	1117.4	325.0	715.0	381.8	1075.3	293.3
mnaph1	10.3	11.0	49.4	43.4	46.7	13.9	50.2	55.3	81.8	239.4	125.3	555.8	196.0	392.5	243.5	537.0	167.6
biphen	1.5	1.6	15.3	4.9	11.9	1.9	16.7	6.0	23.4	31.3	31.5	47.5	34.9	49.4	51.3	41.3	28.6
m_2bph	1.1	0.7	2.7	0.1	5.4	0.4	2.9	0.5	9.1	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0
dmn267	1.5	1.3	4.2	6.7	5.1	2.3	4.2	10.0	7.4	54.2	28.7	108.0	52.9	90.7	62.1	104.7	44.5
dm1367	2.9	2.3	9.5	10.4	9.9	3.9	8.9	15.5	15.7	98.1	59.3	171.2	93.5	156.3	116.5	155.6	75.8
d14523	1.0	0.7	3.6	2.8	3.8	1.2	3.8	4.0	6.3	34.1	24.3	50.0	36.0	54.1	46.7	42.7	26.7
enap12	1.6	2.0	20.7	7.5	17.6	2.7	22.0	11.5	37.2	69.6	44.0	131.7	67.4	105.9	82.5	121.5	54.3
acnapy	1.7	1.3	49.3	3.7	21.8	1.4	42.0	4.2	44.0	35.6	102.2	41.3	91.0	45.4	157.3	32.8	69.8
dmn12	0.4	0.3	1.8	1.1	1.8	0.5	2.1	1.7	3.5	16.2	18.8	23.4	25.1	29.0	42.9	18.9	15.9
dmn18	0.0	0.0	0.2	0.0	0.2	0.0	0.1	0.2	0.2	0.0	0.3	0.4	0.4	0.4	0.8	0.3	0.4
acnape	0.0	0.1	36.3	0.3	30.4	0.2	46.6	0.4	79.8	3.4	9.2	4.9	8.7	5.1	15.8	4.1	6.0
m_3bph	2.4	1.6	2.9	2.0	1.3	1.4	2.0	2.1	0.7	9.0	2.1	1.9	1.5	18.1	12.3	0.8	0.3
m_4bph	0.6	0.5	1.6	0.7	1.8	0.5	2.2	0.8	3.9	5.3	1.8	2.2	1.4	9.5	6.2	0.9	0.5
dbzfur	1.0	0.1	2.5	1.2	2.2	0.5	2.4	1.2	2.4	7.9	8.8	9.9	10.0	14.3	15.5	9.4	8.5
em_12n	1.0	0.4	2.3	2.3	1.1	0.3	0.6	1.1	1.3	9.7	8.0	11.5	10.3	15.7	13.7	8.0	6.7
tmi235n	0.4	0.2	0.6	0.5	0.8	0.4	0.5	0.4	0.7	13.3	5.9	7.0	8.3	16.9	8.6	6.4	3.3
btmnap	0.5	0.5	0.5	0.6	1.0	0.5	0.3	1.3	0.8	21.3	15.7	22.4	15.0	31.6	27.0	18.5	13.9
atmnap	0.6	0.7	0.9	1.9	0.8	1.1	0.0	2.2	4.8	32.7	23.3	38.8	28.0	50.0	38.5	33.8	21.7
ctmnap	0.5	0.4	0.6	0.7	1.0	0.5	0.4	1.2	1.3	17.4	12.6	17.5	15.1	26.4	22.2	14.9	5.5
em_21n	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	2.3	2.2	2.3	2.6	3.7	3.9	1.9	1.5
etmnap	0.3	0.2	0.5	0.4	0.5	0.3	0.5	0.6	0.7	9.7	6.5	9.1	7.2	13.7	11.3	7.8	4.9
tm245n	0.0	0.1	0.5	0.1	0.2	0.1	0.1	0.1	0.2	3.5	2.6	3.5	4.0	4.6	6.0	1.4	2.2
ftmnap	0.3	0.2	0.3	0.4	0.4	0.3	0.4	0.6	0.5	9.2	6.9	8.9	7.5	13.4	12.2	7.1	5.9

TABLE 26 (CONT'D). POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	LD-NE-F-E0-72	LD-NE-F-E0-72-3	LD-NE-F-E0-20	LD-NE-F-E10-72	LD-NE-F-E10-20	LD-NE-A-E0-72	LD-NE-A-E0-20	LD-NE-A-E10-72	LD-NE-A-E10-20	LD-HE-F-E0-72	LD-HE-F-E0-20	LD-HE-F-E10-72	LD-HE-F-E10-20	LD-HE-A-E0-72	LD-HE-A-E0-20	LD-HE-A-E10-72	LD-HE-A-E10-20
Source	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	E0	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10
Temp, °F	72	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media[b]	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction[c]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
fluore	0.8	0.7	5.4	1.4	3.4	0.9	6.0	1.7	7.9	17.7	26.6	17.0	26.1	24.1	38.9	15.5	21.2
tm145n	0.0	0.0	0.2	0.1	0.1	0.1	0.1	0.1	0.2	1.4	1.8	2.9	1.7	2.8	3.8	1.7	1.7
jtmnap	0.0	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.2	4.0	1.7	3.0	3.8	5.0	5.8	1.7	1.2
a_mfluo	0.1	0.3	0.1	0.4	0.6	0.3	0.5	0.4	0.8	8.0	8.7	4.2	7.0	10.1	8.2	4.1	5.3
b_mfluo	0.0	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.2	1.4	1.3	0.9	1.5	1.8	3.1	1.4	1.5
m_1fluo	0.0	0.1	0.6	0.4	0.7	0.1	0.7	0.5	0.8	6.3	6.1	4.9	4.9	6.8	8.9	4.8	5.4
fl9one	0.8	1.0	2.2	2.5	2.7	1.2	2.5	2.5	3.4	15.2	14.1	14.2	13.1	15.2	17.6	13.2	11.1
phenan	0.9	1.3	9.9	3.1	8.5	1.6	11.6	3.5	16.9	27.3	39.7	23.7	35.6	31.9	59.2	25.8	30.3
anthra	0.3	0.4	1.9	0.8	1.6	0.5	2.1	1.0	3.0	6.4	10.7	5.5	9.3	8.3	15.2	5.7	7.6
xanone	0.1	0.1	0.1	0.2	0.1	0.2	0.0	0.2	0.1	0.4	0.3	0.2	0.2	0.3	0.5	0.6	0.5
acquone	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
m_2phen	0.1	0.1	0.3	0.2	0.4	0.2	0.3	0.3	0.5	10.9	9.0	6.1	6.6	8.3	10.0	6.3	6.0
m_3phen	0.2	0.2	0.4	0.3	0.4	0.3	0.3	0.4	0.6	11.2	9.9	6.7	7.2	9.4	10.7	6.6	4.8
pnapone	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.2	0.2	0.4	0.3	0.5	0.5	0.1	0.6	0.4	0.1
m_2anth	0.1	0.1	0.4	0.1	0.4	0.1	0.3	0.2	0.6	1.1	2.2	0.8	1.3	2.0	2.8	1.2	1.6
m_45phen	0.0	0.1	0.9	0.2	0.8	0.1	0.9	0.2	1.2	1.5	2.7	0.9	2.4	1.5	2.3	0.7	2.6
m_9phen	0.1	0.1	0.2	0.1	0.3	0.1	0.2	0.1	0.3	4.3	4.0	3.1	3.3	4.0	1.8	1.1	2.4
mpht_1	0.1	0.2	0.1	0.2	0.1	0.1	0.2	0.3	0.5	4.3	4.3	2.2	3.0	3.0	3.3	2.9	2.1
anthron	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.5	0.6	0.7	0.5	0.5	0.5	0.4
m_9ant	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.1
nap2phen	0.1	0.1	0.5	0.3	0.6	0.2	0.5	0.3	0.8	6.2	6.7	3.4	4.5	4.4	8.2	4.4	3.8
anrquone	0.2	0.1	0.1	0.3	0.2	0.2	0.1	0.2	0.1	2.7	1.6	1.8	1.2	2.3	2.2	1.4	0.6
a_dmph	0.1	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	5.6	5.0	3.3	2.9	3.5	4.5	2.9	2.4
b_dmph	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	2.1	1.0	1.5	2.1	2.5	1.6	1.1
dm17ph	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	3.5	2.8	2.0	1.8	2.1	2.6	1.7	1.0
dm36ph	0.0	0.0	0.2	0.0	0.3	0.0	0.0	0.1	0.1	3.5	3.5	2.7	2.1	2.6	3.3	2.2	1.4

TABLE 26 (CONT'D). POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	LD-NE-F-E0-72	LD-NE-F-E0-72-3	LD-NE-F-E0-20	LD-NE-F-E10-72	LD-NE-F-E10-20	LD-NE-A-E0-72	LD-NE-A-E0-20	LD-NE-A-E10-72	LD-NE-A-E10-20	LD-HE-F-E0-72	LD-HE-F-E0-20	LD-HE-F-E10-72	LD-HE-F-E10-20	LD-HE-A-E0-72	LD-HE-A-E0-20	LD-HE-A-E10-72	LD-HE-A-E10-20
Source	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	E0	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10
Temp, °F	72	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media^b	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction^c	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
d_dmph	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	2.1	1.9	1.5	1.5	1.7	1.7	1.2	1.4
e_dmph	0.0	0.1	0.0	0.0	0.1	0.0	0.1	0.0	0.1	1.9	3.4	2.1	1.3	2.4	2.6	2.2	1.6
c_dmph	0.1	0.1	0.0	0.1	0.0	0.1	0.1	0.1	0.1	6.8	6.1	4.1	4.1	4.8	5.7	3.9	3.2
fluora	0.3	0.3	2.5	0.8	2.2	0.3	2.8	0.8	3.5	12.1	18.5	10.4	13.0	8.2	21.2	10.3	10.0
pyrene	0.3	0.7	2.6	0.9	2.5	0.4	3.1	1.1	4.0	17.5	23.2	16.2	17.4	11.3	23.7	13.9	12.4
antal9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	1.0	0.5	0.5	0.4	0.7	0.5	0.4
retene	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
bafluo	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.8	2.5	0.9	0.8	0.4	0.8	0.4	0.3
bbfluo	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.2	0.2	0.1	0.2	0.1	0.3	0.2	0.1
bmpyfl	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	2.5	3.5	1.1	1.4	1.5	3.2	1.2	1.2
c1mflpy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.8	4.5	1.8	1.8	2.5	4.3	2.5	1.2
m_13fl	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	1.6	1.3	1.3	1.2	0.7	2.0	1.3	1.2
m_4pyr	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	5.1	5.4	4.7	4.0	2.8	4.3	3.3	1.7
cmpyfl	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.1	0.3	0.2	0.2	0.3	0.2	0.4	0.2	0.1
dmpyfl	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	5.8	5.5	5.2	4.1	2.8	5.0	4.4	2.8
m_1pyr	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	2.3	2.6	1.7	1.6	0.5	1.9	1.5	1.1
bntiop	0.0	0.0	0.3	0.0	0.1	0.0	0.0	0.1	0.0	0.4	0.2	0.2	0.3	0.3	0.6	0.3	0.2
bzcphen	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.6	1.7	0.6	0.2	0.4	0.8	0.3	0.5
bghifl	0.0	0.3	0.9	0.3	0.9	0.2	1.3	0.4	1.5	3.8	8.0	0.7	0.2	0.1	3.6	2.2	2.9
phant9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
cp_cdpyr	0.0	0.0	0.4	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.2	0.1	0.1	0.1	0.2	0.3	0.2
baanth	0.0	0.0	0.1	0.1	0.1	0.0	0.2	0.1	0.2	0.9	1.6	0.3	0.1	0.1	0.9	1.3	0.9
chr_tr	0.0	0.1	0.3	0.1	0.3	0.1	0.4	0.1	0.5	5.5	6.5	3.9	4.4	3.9	6.7	3.5	2.4
bzanthr	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.2	1.3	1.7	0.4	0.2	0.4	1.0	1.2	0.5
baa7_12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.2	0.8	0.2	0.5	0.6	0.4	0.2
m_3chr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.0	0.8	0.5	0.5	0.7	0.7	0.5

TABLE 26 (CONT'D). POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST, μg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	**LD-NE-F-E0-72**	**LD-NE-F-E0-72-3**	**LD-NE-F-E0-20**	**LD-NE-F-E10-72**	**LD-NE-F-E10-20**	**LD-NE-A-E0-72**	**LD-NE-A-E0-20**	**LD-NE-A-E10-72**	**LD-NE-A-E10-20**	**LD-HE-F-E0-72**	**LD-HE-F-E0-20**	**LD-HE-F-E10-72**	**LD-HE-F-E10-20**	**LD-HE-A-E0-72**	**LD-HE-A-E0-20**	**LD-HE-A-E10-72**	**LD-HE-A-E10-20**
Source	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	E0	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10
Temp, °F	72	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media[b]	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction[c]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
chry56m	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.8	0.1	0.5	0.1	0.5	0.0	0.1
m_7baa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.1	0.1	0.1	0.1	0.1	0.1
dmban712	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.3	0.0	0.3	0.2	0.3	0.2	0.1	0.1
bbjkfl	0.0	0.0	0.1	0.0	0.1	0.0	0.2	0.0	0.2	0.2	0.6	1.1	0.6	0.4	0.4	0.4	0.2
bafl	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
bepyrn	0.0	0.0	0.2	0.0	0.2	0.0	0.3	0.0	0.3	2.4	2.4	0.9	0.9	1.2	2.4	1.6	1.1
bapyrn	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1
peryle	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
m_7bpy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.1	0.1
bpy910dih	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.0	0.0	0.1	0.0
incdfl	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
dbahacr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0
dbajacr	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
in123pyr	0.0	0.0	0.3	0.0	0.2	0.0	0.5	0.0	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0
dbahacan	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
dbajan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0
bbchr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
pic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0
bghipe	0.0	0.0	0.5	0.0	0.4	0.0	0.8	0.0	1.0	0.1	0.5	0.2	0.1	0.2	1.9	0.7	0.8
anthan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
dbalpyr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
corone	0.0	0.0	0.2	0.0	0.1	0.0	0.2	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
dbaepyr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
dbaipyr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
dbahpyr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
dbbkfl	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[a] The repeat test of the normal emitter after all other tests were run is included here but not as part of the first two test's averaged data.

[b] Filter XAD cartridge samples

[c] Test samples were corrected by subtracting the many tunnel blank measurements

TABLE 27. LIGHT-DUTY VEHICLE FUELS AND LUBRICANTS POLYCYCLIC AROMATIC HYDROCARBONS, µg/g
(No Statistical Analyses Were Performed On These Data)

Test Number	**LO-221459**	**LO-223292**	**LD-NE-F-E0**	**LD-NE-F-E0-REP**	**LD-NE-F-E10**	**LD-NE-A-E0**	**LD-NE-A-E10**	**LD-HE F-E0**	**LD-HE-F-E10**	**LD-HE-A-E0**	**LD-HE-A-E10**	**EM-6314-F**	**EM-6391-F**	**EM-5574-F**	**EM-6378-F**	**EM-6802-F**
Emitter	Oil as received	Oil as received	Normal	Normal	Normal	Normal	Normal	High	High	High	High	NE & HE	NE & HE	NE & HE	NE & HE	NE & HE
Oil	Fresh	Aged	Fresh	Fresh	Fresh	Aged	Aged	Fresh	Fresh	Aged	Aged	F&A	F&A	F&A	F&A	F&A
Fuel	NA	NA	E0	E0	E10	E0	E10	E0	E10	E0	E10	E0	E10	Cold CO	Cold E10	New Cold CO (E0)
Temp	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72	72	20	20	20
Media	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Fuel	Fuel	Fuel	Fuel	Fuel
naphth	0.0	129.6	322.9	231.3	390.5	418.9	347.3	508.9	537.0	276.7	48.4	2077.1	3724.2	2514.5	2596.1	1608.7
quinoline	0.0	3.2	0.0	0.0	0.5	0.2	0.3	0.2	0.3	0.4	0.8	1.3	54.9	0.1	0.0	0.0
mnaph2	0.0	201.7	89.9	299.4	311.3	93.4	303.7	201.5	307.4	210.1	111.7	1190.4	3932.9	4.9	6.5	91.3
mnaph1	0.0	105.2	55.3	162.5	156.7	50.8	152.3	120.4	171.9	120.4	67.2	577.4	1672.8	0.1	1.2	44.0
biphen	0.0	0.5	1.6	5.3	7.9	2.3	8.0	2.2	6.3	6.0	2.0	16.8	45.2	0.0	0.1	0.6
m_2bph	0.0	0.3	0.8	3.2	0.8	1.5	2.9	3.0	2.3	1.2	0.0	4.5	12.0	0.0	0.0	0.0
dmn267	0.0	22.8	31.0	62.6	74.6	24.7	75.5	30.4	45.4	32.2	17.3	122.0	364.8	0.0	0.3	5.7
dm1367	0.1	37.3	57.9	108.4	122.1	49.1	121.0	59.5	94.4	63.7	33.0	206.2	504.1	0.0	0.6	11.4
d14523	0.8	64.6	20.1	34.8	29.8	16.7	35.8	107.5	150.8	121.2	52.0	64.7	116.9	0.0	0.0	21.4
enap12	0.0	16.4	15.0	35.1	44.0	12.0	43.9	34.3	44.4	38.4	15.3	69.4	210.5	0.0	0.0	5.3
acnapy	0.0	0.1	0.2	0.9	0.2	1.5	0.2	2.1	1.3	1.2	0.0	1.4	1.6	0.0	0.0	0.0
dmn12	0.0	7.7	8.8	19.3	9.7	7.3	11.2	14.7	13.6	17.7	2.7	27.2	41.2	0.0	0.0	2.6
dmn18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
acnape	0.3	0.5	1.0	1.7	0.3	0.2	0.4	0.2	1.0	0.4	0.3	3.6	4.1	0.0	0.0	0.0
m_3bph	0.2	5.3	15.3	22.2	10.9	12.4	7.7	28.2	13.6	24.5	4.5	30.6	14.2	0.0	0.0	0.3
m_4bph	0.0	1.4	7.0	9.6	1.9	5.0	2.9	11.4	5.4	12.8	1.6	13.0	4.9	0.0	0.0	0.1
dbzfur	0.0	0.0	0.1	0.0	0.4	0.0	0.0	2.2	0.4	1.7	0.0	0.0	1.2	0.0	0.0	0.0
em_12n	0.2	3.0	8.2	11.6	3.7	6.9	5.2	12.8	7.2	11.5	1.1	11.0	9.7	0.0	0.0	0.4
tmi235n	0.1	13.2	34.7	37.5	22.4	29.7	27.4	54.2	25.0	48.4	11.4	36.5	21.7	0.0	0.0	1.3
btmnap	0.4	10.8	33.3	42.1	27.8	29.5	29.4	51.2	37.6	50.1	9.4	45.8	42.7	0.0	0.0	3.3
atmnap	0.6	15.8	36.0	46.2	32.8	27.5	32.1	54.2	48.9	51.2	11.3	57.9	61.1	0.0	0.0	0.8
ctmnap	0.6	12.4	28.7	40.0	21.8	26.2	28.7	48.1	28.4	45.2	8.4	37.4	34.2	0.0	0.0	3.6
em_21n	0.0	0.7	0.8	2.0	0.3	0.9	1.6	0.2	0.5	1.4	0.0	0.9	1.5	0.0	0.0	0.1
etmnap	0.1	7.7	19.3	27.2	15.8	18.9	15.7	31.6	19.6	33.1	5.2	22.4	19.6	0.0	0.0	2.2
tm245n	0.1	2.1	9.8	0.7	1.4	8.5	4.5	9.4	5.2	8.4	0.4	0.8	0.2	0.0	0.0	0.2
ftmnap	0.2	6.8	18.8	24.2	16.0	17.8	18.3	33.4	22.2	30.9	6.7	23.4	19.6	0.0	0.0	2.2
fluore	0.2	3.6	13.8	1.2	14.9	12.9	12.6	21.0	11.3	19.0	3.2	1.3	10.7	0.0	0.0	0.1

TABLE 27 (CONT'D). LIGHT-DUTY VEHICLE FUELS AND LUBRICANTS POLYCYCLIC AROMATIC HYDROCARBONS, µg/g
(No Statistical Analyses Were Performed On These Data)

Test Number	LO-221459	LO-223292	LD-NE-F-E0	LD-NE-F-E0-REP	LD-NE-F-E10	LD-NE-A-E0	LD-NE-A-E10	LD-HE F-E0	LD-HE-F-E10	LD-HE-A-E0	LD-HE-A-E10	EM-6314-F	EM-6391-F	EM-5574-F	EM-6378-F	EM-6802-F
Emitter	Oil as received	Oil as received	Normal	Normal	Normal	Normal	Normal	High	High	High	High	NE & HE	NE & HE	NE & HE	NE & HE	NE & HE
Oil	Fresh	Aged	Fresh	Fresh	Fresh	Aged	Aged	Fresh	Fresh	Aged	Aged	F&A	F&A	F&A	F&A	F&A
Fuel	NA	NA	E0	E0	E10	E0	E10	E0	E10	E0	E10	E0	E10	Cold CO	Cold E10	New Cold CO (E0)
Temp	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72	72	20	20	20
Media	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Fuel	Fuel	Fuel	Fuel	Fuel
tm145n	0.2	2.5	8.5	8.3	0.9	6.8	0.3	5.5	1.7	4.2	0.3	7.1	1.3	0.0	0.0	0.2
jtmnap	0.1	1.4	10.2	11.8	6.7	8.0	7.2	16.1	9.5	16.5	1.0	8.4	0.4	0.0	0.0	0.0
a_mfluo	0.3	8.7	38.5	29.9	31.2	31.7	29.3	53.3	20.0	37.2	7.4	20.5	1.5	0.0	0.0	0.0
b_mfluo	0.1	0.5	6.1	4.7	4.9	6.2	5.3	11.7	2.0	4.5	0.3	4.0	0.7	0.0	0.0	0.0
m_1fluo	0.3	0.3	11.5	15.2	16.1	14.4	14.2	34.3	1.7	21.3	5.2	9.0	2.7	0.0	0.0	0.0
fl9one	0.0	0.3	1.8	1.7	1.5	1.4	1.5	1.2	0.5	0.8	0.3	0.5	0.2	0.0	0.0	0.0
phenan	0.3	12.7	28.6	26.2	26.9	29.2	26.3	59.6	31.3	44.2	10.0	12.5	8.7	0.0	0.0	0.0
anthra	0.0	4.4	11.9	9.6	4.3	12.4	7.7	25.0	6.4	14.6	4.7	4.3	1.0	0.0	0.0	0.0
xanone	0.2	0.8	3.3	1.9	3.0	3.0	2.0	11.0	0.7	6.2	1.1	0.5	0.2	0.0	0.0	0.0
acquone	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
m_2phen	0.4	25.8	44.1	31.7	32.9	51.3	39.9	82.0	37.8	63.8	18.4	11.2	6.5	0.0	0.1	0.0
m_3phen	0.2	17.9	40.0	31.7	45.9	51.8	46.6	86.4	45.9	66.3	21.2	11.4	4.2	0.0	0.0	0.0
pnapone	0.8	0.8	4.0	1.1	2.0	1.6	2.3	1.6	4.6	4.3	0.6	0.1	0.2	0.0	0.1	0.0
m_2anth	0.1	11.3	18.4	10.9	4.6	18.8	12.6	29.6	7.9	29.4	8.3	3.1	0.2	0.0	0.0	0.0
m_45phen	0.3	2.4	3.9	2.5	1.5	4.0	1.2	11.1	3.6	7.9	1.4	0.1	0.1	0.0	0.0	0.0
m_9phen	0.1	11.5	13.3	13.5	9.8	15.4	9.6	18.2	14.7	29.8	13.5	3.5	0.2	0.0	0.0	0.0
mpht_1	0.2	7.9	15.5	10.8	15.0	26.6	15.3	41.9	17.0	26.2	6.9	2.4	3.4	0.0	0.0	0.0
anthron	1.5	2.3	4.9	4.6	2.0	8.8	0.9	33.5	10.9	9.9	9.0	0.5	0.4	0.0	0.6	0.0
m_9ant	0.2	1.0	0.9	0.3	0.4	0.3	0.4	1.2	0.9	1.2	0.2	0.1	0.0	0.0	0.0	0.0
nap2phen	0.1	5.4	9.4	4.4	4.6	11.7	9.3	23.0	4.0	17.6	6.2	0.7	0.0	0.0	0.0	0.0
anrquone	1.0	0.8	0.3	2.6	0.3	0.9	0.6	1.2	0.3	0.7	0.6	0.0	0.2	0.0	0.0	0.0
a_dmph	0.5	21.6	27.2	15.7	25.7	33.0	28.8	45.3	23.8	40.1	13.5	5.8	4.1	0.0	0.0	0.0
b_dmph	0.6	8.5	14.4	8.6	14.3	18.1	13.7	24.0	18.6	21.9	7.2	2.4	1.5	0.0	0.0	0.0
dm17ph	0.8	6.2	25.5	14.0	16.0	14.7	15.3	12.3	20.9	32.0	12.1	1.2	1.8	0.0	0.0	0.0
dm36ph	0.2	14.2	15.8	10.2	20.7	19.0	17.4	28.4	17.2	28.4	9.2	2.6	1.9	0.0	0.0	0.0
d_dmph	0.6	6.2	8.2	6.1	12.1	9.8	20.5	17.9	10.5	16.3	13.5	1.3	0.9	0.0	0.0	0.0
e_dmph	0.8	12.3	15.3	10.4	10.2	21.4	16.0	29.4	13.2	29.3	10.9	0.9	0.6	0.0	0.0	0.0

TABLE 27 (CONT'D). LIGHT-DUTY VEHICLE FUELS AND LUBRICANTS POLYCYCLIC AROMATIC HYDROCARBONS, µg/g
(No Statistical Analyses Were Performed On These Data)

Test Number	LO-221459	LO-223292	LD-NE-F-E0	LD-NE-F-E0-REP	LD-NE-F-E10	LD-NE-A-E0	LD-NE-A-E10	LD-HE F-E0	LD-HE-F-E10	LD-HE-A-E0	LD-HE-A-E10	EM-6314-F	EM-6391-F	EM-5574-F	EM-6378-F	EM-6802-F
Emitter	Oil as received	Oil as received	Normal	Normal	Normal	Normal	Normal	High	High	High	High	NE & HE	NE & HE	NE & HE	NE & HE	NE & HE
Oil	Fresh	Aged	Fresh	Fresh	Fresh	Aged	Aged	Fresh	Fresh	Aged	Aged	F&A	F&A	F&A	F&A	F&A
Fuel	NA	NA	E0	E0	E10	E0	E10	E0	E10	E0	E10	E0	E10	Cold CO	Cold E10	New Cold CO (E0)
Temp	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72	72	20	20	20
Media	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Fuel	Fuel	Fuel	Fuel	Fuel
c_dmph	0.4	35.1	39.0	22.4	31.0	60.5	45.5	66.6	32.3	69.5	25.9	7.4	1.1	0.0	0.0	0.0
fluora	0.9	9.2	13.0	9.4	10.1	14.9	13.6	21.6	11.1	18.0	6.8	2.1	1.0	0.0	0.0	0.0
pyrene	5.7	15.4	23.8	19.8	28.3	30.6	28.5	55.9	50.6	52.1	15.6	2.3	2.5	0.0	0.0	0.0
antal9	2.3	3.6	4.6	2.1	3.8	3.7	3.1	3.7	5.2	8.0	1.9	0.0	0.2	0.0	0.0	0.0
retene	0.2	0.1	0.2	0.2	0.1	0.2	0.2	0.3	0.2	0.2	0.1	0.0	0.0	0.0	0.0	0.0
bafluo	0.4	4.0	11.8	6.9	10.6	18.1	14.6	11.5	6.8	30.6	4.8	0.9	0.6	0.0	0.0	0.0
bbfluo	0.9	5.5	9.2	0.8	7.9	10.9	8.7	16.0	8.4	12.3	4.7	0.9	0.6	0.0	0.0	0.0
bmpyfl	1.5	15.4	10.1	10.2	14.9	24.3	14.1	35.3	13.4	35.3	7.8	1.1	0.8	0.0	0.0	0.0
c1mflpy	0.6	9.8	12.0	12.0	12.1	20.2	21.4	33.1	14.2	28.9	8.9	1.5	0.5	0.0	0.0	0.0
m_13fl	1.7	7.4	8.5	3.1	4.6	10.6	14.3	35.4	13.2	35.4	7.7	0.3	0.8	0.0	0.0	0.0
m_4pyr	15.7	17.4	23.1	18.1	23.6	24.5	17.3	40.3	42.2	44.0	15.0	0.3	0.2	0.0	0.0	0.0
cmpyfl	1.7	10.4	15.7	9.4	15.0	20.7	18.2	29.8	15.7	22.9	8.7	1.8	1.1	0.0	0.0	0.0
dmpyfl	13.2	17.6	24.2	19.6	26.9	23.5	20.9	52.6	63.3	59.0	14.4	0.7	0.3	0.0	0.0	0.0
m_1pyr	11.4	14.3	15.0	12.2	13.2	18.4	13.2	34.8	30.2	36.2	11.8	0.2	0.2	0.0	0.0	0.0
bntiop	0.8	0.8	0.4	1.0	2.0	1.0	0.3	0.9	1.2	0.8	0.8	0.0	0.0	0.0	0.0	0.0
bzcphen	0.6	0.4	1.1	1.9	1.0	1.5	0.3	0.9	1.2	1.7	0.3	0.0	0.0	0.0	0.0	0.0
bghifl	3.3	2.2	0.5	3.0	1.7	0.9	0.7	0.8	0.5	1.3	2.3	0.0	0.0	0.0	0.0	0.0
phant9	1.0	0.3	0.2	0.5	0.4	0.1	0.3	0.2	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0
cp_cdpyr	1.1	0.8	0.6	0.6	0.4	0.3	0.5	2.4	1.0	0.5	0.3	0.1	0.0	0.0	0.0	0.0
baanth	0.2	7.1	8.2	4.3	4.4	10.2	7.7	16.3	8.8	17.1	8.9	0.5	0.6	0.0	0.3	0.0
chr_tr	0.2	5.6	6.5	8.5	4.2	9.0	7.8	15.7	10.9	16.0	6.9	0.1	0.2	0.0	0.0	0.0
bzanthr	2.3	1.6	3.3	2.5	1.2	2.4	4.2	8.7	0.9	9.3	1.3	0.4	5.8	0.0	2.5	0.0
baa7_12	4.7	3.0	9.9	1.9	5.1	11.7	11.3	3.5	3.6	0.0	3.9	0.2	0.1	0.0	0.0	0.0
m_3chr	0.2	7.4	6.3	2.2	4.5	12.7	6.0	14.0	12.3	19.1	7.0	0.2	0.1	0.0	0.0	0.0
chry56m	0.3	6.3	0.0	0.0	0.0	0.0	0.0	10.3	7.3	13.2	0.3	0.0	0.0	0.0	0.0	0.0
m_7baa	0.9	1.3	3.0	2.6	2.7	3.6	2.6	4.1	0.9	1.1	1.4	0.0	0.0	0.0	0.0	0.0
dmban712	0.4	1.4	0.2	1.1	0.6	1.2	0.3	0.0	1.8	0.3	0.1	0.4	0.1	0.0	0.0	0.1

TABLE 27 (CONT'D). LIGHT-DUTY VEHICLE FUELS AND LUBRICANTS POLYCYCLIC AROMATIC HYDROCARBONS, µg/g

(No Statistical Analyses Were Performed On These Data)

Test Number	**LO-221459**	**LO-223292**	**LD-NE-F-E0**	**LD-NE-F-E0-REP**	**LD-NE-F-E10**	**LD-NE-A-E0**	**LD-NE-A-E10**	**LD-HE F-E0**	**LD-HE-F-E10**	**LD-HE-A-E0**	**LD-HE-A-E10**	**EM-6314-F**	**EM-6391-F**	**EM-5574-F**	**EM-6378-F**	**EM-6802-F**
Emitter	Oil as received	Oil as received	Normal	Normal	Normal	Normal	Normal	High	High	High	High	NE & HE	NE & HE	NE & HE	NE & HE	NE & HE
Oil	Fresh	Aged	Fresh	Fresh	Fresh	Aged	Aged	Fresh	Fresh	Aged	Aged	F&A	F&A	F&A	F&A	F&A
Fuel	NA	NA	E0	E0	E10	E0	E10	E0	E10	E0	E10	E0	E10	Cold CO	Cold E10	New Cold CO (E0)
Temp	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72	72	20	20	20
Media	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Fuel	Fuel	Fuel	Fuel	Fuel
bbjkfl	0.8	0.8	0.6	0.8	0.3	1.7	1.4	0.9	0.9	1.4	1.2	0.2	0.2	0.0	0.0	0.1
bafl	0.3	0.3	0.4	0.6	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.0	0.0	0.0	0.0	0.0
bepyrn	0.6	6.4	5.3	2.5	3.2	8.7	6.8	6.3	0.8	7.1	4.1	0.0	0.1	0.0	0.0	0.0
bapyrn	0.5	5.0	5.8	3.3	2.7	8.4	6.1	6.9	0.8	13.1	5.6	0.1	0.1	0.0	0.0	0.0
peryle	0.2	0.5	1.1	0.5	0.3	1.5	1.8	0.5	0.3	1.9	0.3	0.1	0.0	0.1	0.0	0.0
m_7bpy	0.3	1.4	1.7	0.3	0.9	1.5	1.7	0.5	0.4	1.2	0.3	0.0	0.0	0.0	0.0	0.0
bpy910dih	0.8	1.4	0.6	0.9	0.4	1.0	3.6	0.5	0.9	1.0	0.0	0.0	0.0	0.0	0.0	0.0
incdfl	0.4	1.4	0.3	0.5	1.0	1.0	0.4	0.6	0.7	0.3	0.0	0.0	0.0	0.0	0.0	0.0
dbahacr	0.6	0.6	0.8	4.5	0.8	0.9	1.0	0.7	0.8	0.0	0.7	0.0	0.1	0.0	0.0	0.0
dbajacr	0.4	0.3	0.6	0.9	1.1	0.3	0.6	0.3	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
in123pyr	0.6	0.4	0.9	1.5	0.7	1.2	0.5	0.4	0.4	2.0	0.1	0.0	0.0	0.0	0.0	0.0
dbahacan	2.8	1.6	0.8	2.3	0.8	0.8	1.2	2.4	1.3	0.0	1.4	0.0	0.0	0.0	0.0	0.0
dbajan	0.6	0.8	1.0	1.1	0.7	0.8	0.8	0.5	0.5	0.0	0.2	0.0	0.0	0.0	0.0	0.0
bbchr	0.8	0.5	0.3	1.2	1.4	0.7	0.4	0.4	1.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0
pic	0.6	0.4	0.6	1.3	1.5	0.8	0.5	0.9	1.2	0.0	0.4	0.0	0.0	0.0	0.0	0.0
bghipe	0.6	9.1	8.5	4.6	1.8	15.5	13.3	10.2	2.7	19.3	3.2	0.1	0.1	0.0	0.0	0.0
anthan	0.3	0.4	0.4	0.6	0.7	0.5	0.4	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
dbalpyr	0.3	0.4	0.3	0.6	0.1	0.3	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
corone	0.2	0.5	1.0	0.0	0.2	2.0	0.6	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.1	0.0
dbaepyr	0.3	0.2	0.2	0.0	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
dbaipyr	0.1	0.1	0.1	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
dbahpyr	0.1	0.3	0.0	0.0	0.2	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
dbbkfl	0.1	1.1	0.3	0.3	0.1	0.6	0.3	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 28. POLYCYCLIC AROMATIC HYDROCARBONS SPECIES CODES

CODE	SPECIE
NAPHTH	naphthalene
QUINOLINE	Quinoline
MNAPH2	2-methylnaphthalene
MNAPH1	1-methylnaphthalene
BIPHEN	Biphenyl
M_2BPH	2-methylbiphenyl
DMN267	2,6+2,7-dimethylnaphthalene
DM1367	1,3+1,6+1,7dimethylnaphth
D14523	1,4+1,5+2,3-dimethylnaphth
ENAP12	1+2ethylnaphthalene
ACNAPY	Acenaphthylene
DMN12	1,2-dimethylnaphthalene
DMN18	1,8-dimethylnaphthalene
ACNAPE	Acenaphthene
M_3BPH	3-methylbiphenyl
M_4BPH	4-methylbiphenyl
DBZFUR	Dibenzofuran
EM_12N	1-ethyl-2-methylnaphthalene
TMI235N	2,3,5+I-trimethylnaphthalene
BTMNAP	B-trimethylnaphthalene
ATMNAP	A-trimethylnaphthalene
CTMNAP	C-trimethylnaphthalene
EM_21N	2-ethyl-1-methylnaphthalene
ETMNAP	E-trimethylnaphthalene
TM245N	2,4,5-trimethylnaphthalene
FTMNAP	F-trimethylnaphthalene
FLUORE	Fluorene
TM145N	1,4,5-trimethylnaphthalene
JTMNAP	J-trimethylnaphthalene
A_MFLUO	A-Methylfluorene
B_MFLUO	B-Methylfluorene
M_1FLUO	1-Methylfluorene
FL9ONE	9-fluorenone
DBTH	Dibenzothiophene
PHENAN	Phenanthrene
ANTHRA	Anthracene
XANONE	Xanthone
ACQUONE	Acenaphthenequinone
M_2PHEN	3-methylphenanthrene
M_3PHEN	2-methylphenanthrene
PNAPONE	Perinaphthenone
M_2ANTH	2-methylanthracene
M_45PHEN	4,5-methylenephenanthrene
M_9PHEN	9-methylphenanthrene
MPHT_1	1-methylphenanthrene
ANTHRON	Anthrone
M_9ANT	9-methylanthracene
NAP2PHEN	2-phenylnaphthalene
ANRQUONE	Anthraquinone
A_DMPH	A-dimethylphenanthrene
B_DMPH	B-dimethylphenanthrene
DM17PH	1,7-dimethylphenanthrene
DM36PH	3,6-dimethylphenanthrene
D_DMPH	D-dimethylphenanthrene
E_DMPH	E-dimethylphenanthrene
C_DMPH	C-dimethylphenanthrene
FLUORA	Fluoranthene
PYRENE	Pyrene
ANTAL9	9-Anthraaldehyde
RETENE	Retene
BAFLUO	benzo(a)fluorene
BBFLUO	benzo(b)fluorene
BMPYFL	B-MePy/MeFl
C1MFLPY	1-MeFl+C-MeFl/Py
M_13FL	1+3-methylfluoranthene
M_4PYR	4-methylpyrene
CMPYFL	C-MePy/MeFl
DMPYFL	D-MePy/MeFl
M_1PYR	1-methylpyrene
BNTIOP	Benzonaphthothiophene
BZCPHEN	benzo(c)phenanthrene
BGHIFL	Benzo(ghi)fluoranthene
PHANT9	9-phenylanthracene
CP_CDPYR	Cyclopenta(c,d)pyrene
BAANTH	Benz(a)anthracene
CHR_TR	Chrysene-Triphenylene
BZANTHR	Benzanthrone
BAA7_12	Benz(a)anthracene-7,12-dione
M_3CHR	3-methylchrysene
CHRY56M	5+6-methylchrysene
M_7BAA	7-methylbenz(a)anthracene
DMBAN712	7,12-dimethylbenz(a)anthracene
BBJKFL	Benzo(b+j+k)fluoranthene
BAFL	Benzo(a)fluoranthene
BEPYRN	BeP
BAPYRN	BaP
PERYLE	Perylene
M_7BPY	7-methylbenzo(a)pyrene
BPY910DIH	9,10-dihydrobenzo(a)pyrene-7(8H)-one
INCDFL	Indeno[123-cd]fluoranthene
DBAHACR	dibenz(a,h)acridine
DBAJACR	dibenz(a,j)acridine
IN123PYR	Indeno[123-cd]pyrene
DBAHACAN	Dibenzo(ah+ac)anthracene
DBAJAN	Dibenzo(a,j)anthracene
BBCHR	Benzo(b)chrysene
PIC	Picene
BGHIPE	Benzo(ghi)perylene
ANTHAN	Anthanthrene
DBALPYR	Dibenzo(a,l)pyrene
CORONE	Coronene
DBAEPYR	Dibenzo(a,e)pyrene
DBAIPYR	Dibenzo(a,i)pyrene
DBAHPYR	Dibenzo(a,h)pyrene
DBBKFL	Dibenzo(b,k)fluoranthene

TABLE 29. LIGHT-DUTY VEHICLE AVERAGE ALKANES IN EXHAUST, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	**LD-NE-F-E0-72**	**LD-NE-F-E0-72-3a**	**LD-NE-F-E0-20**	**LD-NE-F-E10-72**	**LD-NE-F-E10-20**	**LD-NE-A-E0-72**	**LD-NE-A-E0-20**	**LD-NE-A-E10-72**	**LD-NE-A-E10-20**	**LD-HE-F-E0-72**	**LD-HE-F-E0-20**	**LD-HE-F-E10-72**	**LD-HE-F-E10-20**	**LD-HE-A-E0-72**	**LD-HE-A-E0-20**	**LD-HE-A-E10-72**	**LD-HE-A-E10-20**
Source	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	E0	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10
Temp, °F	72	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media[b]	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction[c]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
dodec	0	0	6	3	19	0	12	9	5	15	15	73	22	22	42	79	30
norfarn	0	0	0	1	1	0	0	4	0	4	3	31	7	5	7	34	9
tridec	0	0	1	0	1	0	2	1	2	14	11	53	24	21	25	58	23
hpycyhx	0	0	0	0	1	0	0	0	0	7	3	2	5	3	5	2	2
farnes	0	0	0	0	1	0	0	0	0	1	2	4	2	2	9	4	4
tdec	0	0	2	0	7	0	1	0	0	17	15	25	19	18	26	26	17
ocycyhx	0	0	0	0	0	0	0	0	0	1	2	1	1	1	2	1	3
pentad	0	0	1	0	2	0	1	0	0	11	14	14	15	17	20	10	10
noycyhx	0	0	0	0	0	0	0	0	0	3	2	3	4	5	4	3	3
hexad	0	0	1	0	2	0	2	0	1	32	30	30	31	28	30	25	20
norprst	0	0	0	0	1	0	0	0	0	4	3	4	3	3	4	1	1
decyhx	0	0	0	0	0	0	0	0	0	2	2	1	1	1	2	1	1
heptad	0	0	1	0	2	0	2	0	1	23	22	23	26	19	26	14	11
heptdpris	0	0	1	0	1	0	1	0	0	10	11	10	11	9	8	6	4
dec1yhx	0	0	0	0	0	0	0	0	0	3	3	4	7	3	3	2	2
octad	0	0	1	0	1	0	1	0	0	41	52	56	48	43	52	38	29
phytan	0	0	0	0	1	0	0	0	0	15	13	15	15	8	9	2	3
dec2yhx	0	0	0	0	0	0	0	0	0	3	3	3	3	1	2	1	2
nonad	0	0	1	0	1	0	1	0	0	24	23	24	26	18	22	12	9
dec3yhx	0	0	0	0	1	0	0	0	0	2	3	3	5	2	3	2	0
eicosa	0	0	2	0	1	0	1	0	1	46	63	65	60	54	66	47	36
dec4yhx	0	0	0	0	0	0	0	0	0	6	7	7	7	3	4	1	2
heneic	0	0	7	0	4	0	6	0	3	29	32	40	31	28	31	17	18
dec5yhx	0	0	0	0	0	0	0	0	0	19	18	21	20	15	16	12	6
docosa	0	0	17	0	9	0	15	0	9	49	78	96	72	63	70	51	44

TABLE 29 (CONT'D). LIGHT-DUTY VEHICLE AVERAGE ALKANES IN EXHAUST, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	**LD-NE-F-E0-72**	**LD-NE-F-E0-72-3a**	**LD-NE-F-E0-20**	**LD-NE-F-E10-72**	**LD-NE-F-E10-20**	**LD-NE-A-E0-72**	**LD-NE-A-E0-20**	**LD-NE-A-E10-72**	**LD-NE-A-E10-20**	**LD-HE-F-E0-72**	**LD-HE-F-E0-20**	**LD-HE-F-E10-72**	**LD-HE-F-E10-20**	**LD-HE-A-E0-72**	**LD-HE-A-E0-20**	**LD-HE-A-E10-72**	**LD-HE-A-E10-20**
Source	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate	Particulate
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	E0	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10
Temp, °F	72	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media[b]	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction[c]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
dec6yhx	0	0	0	0	0	0	0	0	0	2	3	21	16	2	3	2	2
tricosa	0	0	44	1	26	0	40	1	25	60	102	140	93	63	51	36	40
dec7yhx	0	0	5	0	4	2	6	1	11	35	47	57	55	52	50	32	30
tetcos	1	0	91	1	49	0	81	0	47	112	191	270	179	124	98	76	86
dec8yhx	0	0	0	0	0	0	0	0	0	8	10	11	29	12	9	7	3
pencos	1	0	179	1	98	0	161	0	92	98	255	350	230	52	74	72	71
hexcos	2	0	250	6	145	0	119	2	133	140	302	488	97	161	65	94	107
dec9yhx	0	0	0	0	0	0	0	0	0	1	37	61	42	26	21	8	19
hepcos	0	0	249	0	142	0	236	0	134	351	588	932	665	470	180	296	219
cyhxeic	0	0	0	0	0	0	0	0	0	17	18	2	18	15	13	16	2
octcos	1	0	257	0	146	0	231	0	136	251	478	772	517	412	138	197	155
noncos	1	0	272	0	154	0	225	0	139	211	397	685	482	341	83	171	130
cyhxhen	0	0	3	0	1	0	2	0	1	10	19	21	21	17	23	14	14
tricont	2	0	218	2	126	0	187	2	114	130	323	451	255	131	76	68	78
htricont	2	0	221	1	123	0	158	0	112	103	305	419	221	97	54	49	59
dtricont	0	0	140	0	80	0	78	0	67	45	185	260	136	62	22	23	30
ttricont	0	0	88	0	53	0	34	0	43	32	124	154	96	35	15	12	15
tetricont	0	0	42	0	28	0	8	0	22	19	62	85	50	14	6	5	14
ptricont	0	0	22	0	17	0	0	0	13	8	46	50	28	9	1	1	2
hxtricont	0	0	10	1	10	0	0	0	7	7	30	39	25	10	0	0	2
hptricont	0	0	4	0	5	0	0	0	4	6	25	32	18	3	0	0	1
otricont	0	0	2	0	2	0	0	0	1	1	12	17	10	1	0	0	0
ntricont	0	0	2	0	1	0	0	0	1	0	7	10	1	0	0	0	0
tecont	0	0	1	0	0	0	0	0	1	0	1	8	1	0	0	0	0
hxtric74	0.03	0.02	0.17	0.02	0.05	0.01	0.03	0.02	0.07	220	219	408	482	411	574	402	420
UCM	1852	0	1721	123	344	0	273	126	250	41877	39787	43084	41254	35579	42630	33152	29508

[a] The repeat test of the normal emitter after all other tests were run is included here but not as part of the first two test's averaged data.
[b] Filter and XAD cartridge samples
[c] Test samples were corrected by subtracting a tunnel blank measurement

TABLE 30. ALKANES SPECIES CODES

CODE	SPECIE
Alkanes	
DODEC	Dodecane
NORFARN	norfarnesane
TRIDEC	Tridecane
HPYCYHX	Heptylcyclohexane
FARNES	farnesane
TDEC	Tetradecane
OCYCYHX	Octylcyclohexane
PENTAD	pentadecane
NOYCYHX	Nonylcyclohexane
HEXAD	Hexadecane
NORPRST	Norpristane
DECYHX	Decylcyclohexane
HEPTAD	Heptadecane
HEPTDPRIS	Pristane
DEC1YHX	Undecylcyclohexane
OCTAD	octadecane
PHYTAN	phytane
DEC2YHX	Dodecylcyclohexane
NONAD	nonadecane
DEC3YHX	Tridecylcyclohexane
EICOSA	eicosane
DEC4YHX	Tetradecylcyclohexane
HENEIC	heneicosane
DEC5YHX	Pentadecylcyclohexane
DOCOSA	docosane
DEC6YHX	Hexadecylcyclohexane
TRICOSA	tricosane
DEC7YHX	Heptadecylcyclohexane
TETCOS	tetracosane
DEC8YHX	Octadecylcyclohexane
PENCOS	Pentacosane
HEXCOS	Hexacosane
DEC9YHX	Nonadecylcyclohexane
HEPCOS	Heptacosane
CYHXEIC	Eicosylcyclohexane
OCTCOS	Octacosane
NONCOS	Nonacosane
CYHXHEN	Heneicosylcyclohexane
TRICONT	Triacontane
HTRICONT	Hentriacontane
DTRICONT	Dotriacontane
TTRICONT	Tritriacontane
TETRICONT	Tetratriacontane
PTRICONT	Pentatriacontane
HXTRICONT	Hexatriacontane
HPTRICONT	Heptatriacontane
OTRICONT	Octatriacontane
NTRICONT	Nonatriacontane
TECONT	Tetracontane
HXTRIC74	Hexatriacontane-d74
UCM	Unresolved Complex Mixture

TABLE 31. LIGHT-DUTY VEHICLE ALKANES IN FUELS AND LUBRICANTS
(No Statistical Analyses Were Performed On These Data)

Test Number	LO-221459	LO-223292	LD-NE-F-E0	LD-NE-F-E0-REP	LD-NE-F-E10	LD-NE-A-E0	LD-NE-A-E10	LD-HE-F-E0	LD-HE-F-E10	LD-HE-A-E0	LD-HE-A-E10	EM_6314_F	EM_6391_F	EM_5574_F	EM_6378_F	EM_6802_F
Sample Type	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Fuel	Fuel	Fuel	Fuel	Fuel
Emitter	NA	NA	Normal	Normal	Normal	Normal	Normal	High	High	High	High	NE & HE	NE & HE	NE & HE	NE & HE	NE & HE
Oil	Fresh	Aged	Fresh	Fresh	Fresh	Aged	Aged	Fresh	Fresh	Aged	Aged	F&A	F&A	F&A	F&A	F&A
Fuel	NA	NA	E0	E0	E10	E0	E10	E0	E10	E0	E10	E0	E10	Cold CO	Cold E10	New Cold CO (E0)
Temp, °F	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72	72	20	20	20
Tracer[a]	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No
dodec	0	40	4	3	13	13	20	37	12	15	16	47	320	29	33	58
norfarn	0	6	1	1	4	0	2	1	0	2	8	5	167	0	1	4
tridec	2	59	10	18	55	19	45	12	24	17	24	35	292	6	7	23
hpycyhx	0	2	0	0	1	0	1	0	1	0	0	0	9	0	0	0
farnes	0	1	0	0	2	0	1	0	2	2	3	0	4	0	0	2
tdec	1	25	8	7	47	7	21	6	19	16	17	6	52	1	3	16
ocycyhx	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0
pentad	13	16	7	13	43	7	9	5	8	15	6	2	6	1	1	10
noycyhx	4	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0
hexad	49	17	32	41	86	24	15	20	21	23	13	11	9	5	5	12
norprst	31	4	7	14	18	3	1	8	9	5	5	0	0	0	0	0
decyhx	10	0	4	3	2	1	0	1	2	1	0	0	0	0	0	0
heptad	121	36	71	116	154	36	14	47	51	32	23	1	1	1	0	2
heptdpris	41	11	21	31	56	7	9	25	27	13	9	1	0	1	0	1
dec1yhx	26	3	15	18	13	1	2	10	6	2	1	2	1	0	1	0
octad	173	60	109	131	154	61	45	76	75	50	39	14	6	8	7	10
phytan	96	26	63	81	74	17	19	57	63	28	19	0	0	0	0	2
dec2yhx	49	7	20	22	27	3	2	23	17	3	2	0	0	0	0	0
nonad	157	115	100	107	160	81	79	95	101	72	65	0	4	1	1	0
dec3yhx	42	13	31	35	36	5	3	26	20	7	11	1	0	0	0	0
eicosa	181	176	118	106	159	119	101	103	117	99	99	8	7	6	6	8
dec4yhx	28	9	15	14	19	19	5	34	32	19	25	0	0	0	0	0
heneic	153	196	119	114	156	156	119	111	112	122	121	0	1	0	0	0
dec5yhx	216	141	130	116	131	108	93	107	94	79	98	1	0	0	0	0
docosa	280	213	179	73	161	173	190	140	152	174	158	8	5	7	7	5
dec6yhx	27	15	70	74	34	74	52	13	10	11	53	0	0	0	0	0

TABLE 31 (CONT'D). LIGHT-DUTY VEHICLE ALKANES IN FUELS AND LUBRICANTS
(No Statistical Analyses Were Performed On These Data)

Test Number	**LO-221459**	**LO-223292**	**LD-NE-F-E0**	**LD-NE-F-E0-REP**	**LD-NE-F-E10**	**LD-NE-A-E0**	**LD-NE-A-E10**	**LD-HE-F-E0**	**LD-HE-F-E10**	**LD-HE-A-E0**	**LD-HE-A-E10**	**EM_6314_F**	**EM_6391_F**	**EM_5574_F**	**EM_6378_F**	**EM_6802_F**
Sample Type	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Fuel	Fuel	Fuel	Fuel	Fuel
Emitter	NA	NA	Normal	Normal	Normal	Normal	Normal	High	High	High	High	NE & HE	NE & HE	NE & HE	NE & HE	NE & HE
Oil	Fresh	Aged	Fresh	Fresh	Fresh	Aged	Aged	Fresh	Fresh	Aged	Aged	F&A	F&A	F&A	F&A	F&A
Fuel	NA	NA	E0	E0	E10	E0	E10	E0	E10	E0	E10	E0	E10	Cold CO	Cold E10	New Cold CO (E0)
Temp, °F	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72	72	20	20	20
Tracer[a]	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No
tricosa	265	197	221	221	186	204	254	172	251	284	269	3	1	2	0	0
dec7yhx	629	90	304	336	45	305	270	290	11	239	272	0	0	0	0	0
tetcos	425	63	397	405	361	369	276	279	357	163	348	7	4	6	4	7
dec8yhx	273	29	3	34	35	122	34	37	85	50	53	0	0	0	0	0
pencos	177	77	693	661	866	843	443	997	443	357	839	3	1	1	2	0
hexcos	303	222	78	123	152	998	281	397	602	361	417	5	5	3	3	2
dec9yhx	107	11	10	90	10	199	30	4	17	15	211	1	1	1	0	0
hepcos	72	90	253	187	133	1195	1004	1059	1310	1500	802	1	1	1	1	1
cyhxeic	60	7	57	193	80	41	199	116	28	21	29	0	0	0	0	0
octcos	199	160	143	973	744	1106	852	1113	671	723	696	4	5	1	2	1
noncos	226	162	623	777	678	997	662	450	113	208	408	1	1	3	2	0
cyhxhen	16	40	20	173	67	83	66	206	7	136	201	0	0	0	0	0
tricont	153	165	536	463	499	372	503	170	202	143	125	4	3	3	2	1
htricont	113	169	133	316	296	202	87	106	74	143	88	1	0	1	3	0
dtricont	49	256	101	57	37	15	39	20	51	34	32	1	5	2	3	2
ttricont	38	53	45	15	25	64	4	14	5	4	8	2	2	1	1	0
tetricont	139	22	4	21	8	14	4	8	9	10	14	3	2	1	1	1
ptricont	11	8	4	3	7	3	8	2	1	1	3	2	1	1	0	0
hxtricont	6	9	20	14	11	11	11	1	1	1	3	6	6	3	4	0
hptricont	3	3	4	2	4	9	2	1	3	1	3	5	3	7	5	1
otricont	1	1	2	3	5	2	3	1	0	0	1	5	5	4	5	0
ntricont	6	7	3	4	7	2	4	3	2	1	1	3	4	4	7	0
tecont	5	2	3	2	2	3	3	2	1	1	2	4	0	1	2	1
hxtric74	1	2	523	2042	702	714	570	387	874	725	2451	0	0	0	0	0
UCM	742508	451766	537779	634536	660285	527735	553354	208139	219961	218711	211950	1525	1307	1342	1516	493

[a] Tracer refers to whether the Hexatriaconte tracer was added to the lubricant.

7.5.2.5 Hopanes and Steranes

PM and SVOCs sampled from the light-duty tests were also analyzed by DRI for hopanes and steranes. Table 32 shows the average results in µg/mile of the replicate tests performed in each configuration. Table 33 shows the codes for the hopanes and steranes species in Table 32.

Hopanes and steranes were also measured by DRI in the fuels and lubricants used in the study. These data are shown in Table 34 in units of µg/gram of lubricant or fuel. The first two columns of data in Table 34 are results of the analyses of the fresh and aged lubricants before mixing with the hexatriacontane tracer. The following nine columns of data are from lubricant samples taken after the replicate emission tests were performed. The final seven columns are data from fuel analyses and two replicate analyses.

Because higher levels of hopanes and steranes were found in the light-duty fuels than expected, NREL funded a small study to measure hopanes and steranes in additional commercial fuels. DRI was tasked to collect samples of regular gasoline, premium gasoline, and diesel fuels from three locations in Reno, Nevada. DRI then analyzed the fuel samples for hopanes and steranes. The results are shown in Appendix D. The Reno fuels are compared to the CLOSE Project fuels in Figures D1 and D2 for gasoline and diesel fuels, respectively. Figure D1 shows that the CLOSE Project light-duty fuels are very different in hopane and sterane content than the commercial gasolines from Nevada. The differences between the CLOSE and Reno gasolines may be because the CLOSE fuels are blended to meet stringent specifications with a variety of blend fuels that are not expected in commercial fuels. Figure D2 shows that the TxLED diesel and B20 diesel are similar to the Nevada diesels.

7.5.2.6 Particulate-Phase Elemental and Organic Carbon

PM sampled from the light-duty tests were also analyzed by DRI for elemental carbon and organic carbon (EC/OC). Table 35 shows the average results in µg/mile of the replicate tests performed in each configuration. The configurations are identified in the five left columns of the table, and EC/OC results are shown in the three right columns. In Table 35, EC is elemental carbon measured, OC is organic carbon, and TC is total carbon.

7.5.2.7 Particulate-Phase Sulfates

PM sampled from the light-duty tests were also analyzed by DRI for sulfates. Table 36 shows the average results in µg/mile of the replicate tests performed in each configuration.

7.5.2.8 Particulate-Phase Soluble Organic Fraction

PM sampled from the light-duty tests were also analyzed by DRI for soluble organic fraction (SOF). Table 37 shows the average results for the normal emitter and high emitter, in percent SOF, of the replicate tests performed in each configuration.

TABLE 32. LIGHT-DUTY VEHICLE HOPANES AND STERANES IN EXHAUST, μg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	LD-NE-F-E0-72	LD-NE-F-E0-72-3a	LD-NE-F-E0-20	LD-NE-F-E10-72	LD-NE-F-E10-20	LD-NE-A-E0-72	LD-NE-A-E0-20	LD-NE-A-E10-72	LD-NE-A-E10-20	LD-HE-F-E0-72	LD-HE-F-E0-20	LD-HE-F-E10-72	LD-HE-F-E10-20	LD-HE-A-E0-72	LD-HE-A-E0-20	LD-HE-A-E10-72	LD-HE-A-E10-20
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	E0	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10	E0	E0	E10	E10
Temp, °F	72	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media[b]	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction[c]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
hop15	0.002	0.009	0.107	0.022	0.086	0.014	0.141	0.008	0.206	3.182	2.278	1.976	1.979	2.348	2.136	1.636	1.710
hop17	0.015	0.014	0.115	0.020	0.032	0.020	0.187	0.024	0.094	21.172	16.408	14.874	14.299	15.123	12.865	10.211	10.355
hop19	0.008	0.000	0.104	0.013	0.021	0.004	0.129	0.007	0.053	9.037	7.049	6.271	6.036	6.361	5.401	4.307	4.303
hop20	0.003	0.000	0.047	0.005	0.004	0.011	0.041	0.011	0.024	0.227	0.256	0.079	0.148	0.515	0.288	0.292	0.348
hop21	0.011	0.000	0.072	0.003	0.038	0.002	0.077	0.003	0.062	6.184	4.735	4.034	4.095	4.274	3.377	2.885	3.024
hop22	0.000	0.000	0.057	0.001	0.018	0.000	0.047	0.001	0.052	4.896	4.308	3.207	3.414	3.613	2.834	2.479	2.471
hop23	0.003	0.000	0.003	0.001	0.004	0.000	0.004	0.000	0.000	0.333	0.474	0.366	0.186	0.375	0.323	0.154	0.183
hop24	0.003	0.000	0.015	0.004	0.000	0.000	0.043	0.000	0.000	3.161	2.735	2.239	2.248	2.169	1.869	1.534	1.636
hop25	0.005	0.000	0.022	0.005	0.000	0.000	0.021	0.001	0.009	1.991	1.585	1.279	1.331	1.425	1.245	0.918	1.157
hop26	0.003	0.000	0.013	0.003	0.012	0.001	0.016	0.001	0.012	1.718	1.259	1.002	1.049	1.057	0.845	0.836	0.790
hop27	0.003	0.000	0.015	0.002	0.002	0.000	0.043	0.006	0.008	0.828	0.809	0.495	0.479	0.493	0.367	0.420	0.446
ster42	0.008	0.001	0.038	0.005	0.016	0.002	0.034	0.003	0.006	1.373	1.077	0.856	0.892	0.970	0.975	0.776	0.715
ster43	0.006	0.001	0.025	0.006	0.018	0.003	0.082	0.006	0.010	5.237	3.977	3.482	3.405	3.393	3.146	2.442	2.337
ster44	0.002	0.002	0.057	0.005	0.007	0.002	0.004	0.004	0.028	2.301	1.773	1.535	1.590	1.689	1.573	1.202	1.050
ster45_40	0.001	0.000	0.102	0.002	0.200	0.003	0.315	0.001	0.106	4.671	3.623	3.106	3.259	2.690	2.503	2.416	1.389
ster46	0.005	0.000	0.021	0.000	0.011	0.000	0.024	0.000	0.006	1.044	0.873	0.622	0.697	0.638	0.620	0.465	0.434
ster47	0.002	0.001	0.038	0.002	0.013	0.001	0.049	0.002	0.020	1.416	1.112	0.763	0.879	1.099	1.166	0.915	0.844
ster48_41	0.004	0.001	0.060	0.003	0.064	0.006	0.069	0.004	0.030	3.698	2.948	2.430	2.403	2.755	2.075	1.397	1.819
ster49	0.007	0.021	0.013	0.006	0.045	0.004	0.027	0.006	0.020	0.694	0.529	0.230	0.425	0.666	0.515	0.371	0.200
ster50	0.000	0.000	0.020	0.002	0.001	0.000	0.018	0.002	0.000	0.708	0.469	0.444	0.445	0.255	0.303	0.401	0.442
ster51	0.001	0.000	0.034	0.003	0.006	0.000	0.035	0.001	0.016	1.798	1.404	1.123	1.098	1.197	1.017	0.766	0.811
ster52	0.001	0.000	0.022	0.002	0.006	0.001	0.028	0.003	0.013	1.330	0.946	0.834	0.803	0.935	0.773	0.722	0.607
ster53	0.002	0.000	0.021	0.000	0.000	0.000	0.025	0.001	0.011	0.873	0.764	0.550	0.575	0.604	0.540	0.429	0.470

[a] The repeat test of the normal emitter after all other tests were run is included here but not as part of the first two test's averaged data.
[b] Filter and XAD cartridge samples
[c] Test samples were corrected by subtracting a tunnel blank measurement

TABLE 33. HOPANES AND STERANES SPECIES CODES

Code	Specie
hop15	17α(H)-22,29,30-Trisnorhopane
hop17	17α(H),21ß(H)-29-Norhopane
hop19	17α(H),21ß(H)-Hopane
hop20	17ß(H),21α(H)-Hopane
hop21	22S-17α(H),21ß(H)-30-Homohopane
hop22	22R-17α(H),21ß(H)-30-Homohopane
hop23	17ß(H),21ß(H)-Hopane
hop24	22S-17α(H),21ß(H)-30,31-Bishomohopane
hop25	22R-17α(H),21ß(H)-30,31-Bishomohopane
hop26	22S-17α(H),21ß(H)-30,31,32-Trishomohopane
hop27	22R-17α(H),21ß(H)-30,31,32-Trishomohopane
ster42	20S-5α(H),14α(H),17α(H)-cholestane
ster43	20R-5α(H),14ß(H),17ß(H)-cholestane
ster44	20S-5α(H),14ß(H),17ß(H)-cholestane
ster45_40	20R-5α(H),14α(H),17α(H)-cholestane & 20S-13ß(H),17α(H)-diastigmastane
ster46	20S-5α(H),14α(H),17α(H)-ergostane
ster47	20R-5α(H),14ß(H),17ß(H)-ergostane
ster48_41	20S-5α(H),14ß(H),17ß(H)-ergostane & 20R-13α(H),17ß(H)-diastigmastane
ster49	20R-5α(H),14α(H),17α(H)-ergostane
ster50	20S-5α(H),14α(H),17α(H)-stigmastane
ster51	20R-5α(H),14ß(H),17ß(H)-stigmastane
ster52	20S-5α(H),14ß(H),17ß(H)-stigmastane
ster53	20R-5α(H),14α(H),17α(H)-stigmastane

TABLE 34. LIGHT-DUTY VEHICLE HOPANES AND STERANES IN FUELS AND LUBRICANTS, µg/g
(No Statistical Analyses Were Performed On These Data)

Sample Code	**LO-221459**	**LO-223292**	**LD-NE-F-E0**	**LD-NE-F-E0-REP**	**LD-NE-F-E10**	**LD-NE-A-E0**	**LD-NE-A-E10**	**LD-HE-F-E0**	**LD-HE-F-E10**	**LD-HE-A-E0**	**LD-HE-A-E10**	**EM_6314_F**	**EM_6391_F**	**EM_5574_F**	**EM_6378_F**	**EM_6802_F**	**EM_5574_F**	**EM_6378_F**
Sample Type	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel, replicate	Fuel, replicate
Emitter	NA	NA	Normal	Normal	Normal	Normal	Normal	High	High	High	High	NE & HE	NE & HE	NE & HE	NE & HE	NE & HE	NE & HE	NE & HE
Oil	Fresh	Aged	Fresh	Fresh	Fresh	Aged	Aged	Fresh	Fresh	Aged	Aged	F&A	F&A	F&A	F&A	F&A	F&A	F&A
Fuel	NA	NA	E0	E0	E10	E0	E10	E0	E10	E0	E10	E0	E10	Cold CO	Cold E10	New Cold CO (E0)	Original Cold CO	Cold E10
Temp, °F	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72	72	20	20	20	20	20
Tracer[a]	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No
hop15	3.89	4.63	5.03	6.17	6.61	5.57	4.89	6.64	7.68	5.73	5.76	0.04	0.03	0.00	0.00	0.02	0.00	0.00
hop17	19.27	20.96	25.22	26.25	31.84	24.89	23.03	29.57	34.29	24.27	26.33	0.09	0.18	0.13	0.14	0.10	0.13	0.13
hop19	8.63	9.02	11.57	11.45	14.32	11.57	10.70	13.96	15.18	11.12	12.47	0.12	0.13	0.08	0.06	0.07	0.08	0.07
hop20	0.48	0.31	0.67	0.71	1.24	0.62	0.55	0.57	1.16	0.49	0.54	0.03	0.04	0.00	0.00	0.08	0.00	0.00
hop21	6.05	6.12	7.73	8.44	10.02	8.10	7.54	9.81	10.36	7.94	8.35	0.20	0.21	0.00	0.14	0.20	0.00	0.14
hop22	4.90	5.51	6.38	7.16	8.54	6.82	5.98	8.02	9.02	6.00	7.42	0.00	0.15	0.00	0.00	0.14	0.00	0.00
hop23	0.00	0.32	0.12	0.00	0.00	0.00	0.00	0.36	0.10	0.00	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00
hop24	3.27	3.94	4.63	5.25	5.70	5.36	4.35	6.18	6.35	4.70	5.30	0.00	0.06	0.00	0.00	0.00	0.00	0.00
hop25	2.51	2.55	3.46	3.38	4.02	3.18	2.97	4.27	4.67	3.09	3.27	0.16	0.00	0.00	0.00	0.00	0.00	0.00
hop26	1.87	1.91	2.36	2.63	3.02	2.83	2.48	3.42	3.00	2.40	2.97	0.00	0.00	0.09	0.00	0.00	0.09	0.00
hop27	1.15	1.16	1.47	1.72	1.58	1.53	1.51	2.07	1.88	1.45	1.75	0.00	0.00	0.00	0.15	0.00	0.00	0.15
ster42	1.95	2.17	2.57	2.12	2.80	2.07	1.77	2.79	2.78	2.17	2.85	0.09	0.09	0.09	0.11	0.02	0.10	0.10
ster43	6.33	6.22	6.12	5.86	8.64	6.33	5.99	8.22	9.72	7.17	7.79	0.02	0.04	0.02	0.04	0.01	0.02	0.03
ster44	2.65	2.72	2.63	3.15	3.96	3.04	2.89	3.19	3.90	3.03	2.42	0.01	0.10	0.05	0.05	0.00	0.04	0.05
ster45_40	4.89	4.00	5.29	5.16	6.95	4.62	4.55	5.84	7.26	5.68	5.09	0.06	0.05	0.07	0.12	0.00	0.10	0.09
ster46	1.53	1.53	1.56	1.50	1.86	1.58	1.37	1.94	1.89	2.12	1.92	0.02	0.00	0.00	0.00	0.00	0.00	0.00
ster47	1.52	1.40	1.80	1.53	1.96	1.63	1.48	1.88	2.18	2.41	1.92	0.02	0.02	0.01	0.03	0.00	0.02	0.03
ster48_41	5.74	6.13	6.74	6.04	7.08	5.44	5.29	6.68	8.22	6.81	7.20	0.03	0.11	0.05	0.00	0.00	0.05	0.00
ster49	1.25	1.27	1.59	1.60	1.88	1.42	1.36	1.60	1.88	1.56	1.81	0.03	0.02	0.02	0.00	0.00	0.02	0.00
ster50	1.54	1.48	1.51	1.64	2.03	1.63	1.49	1.77	1.93	1.96	1.80	0.00	0.05	0.00	0.00	0.03	0.00	0.00
ster51	2.31	2.36	2.25	2.36	3.07	2.44	2.17	2.81	3.63	2.89	3.19	0.02	0.09	0.00	0.05	0.02	0.00	0.06
ster52	1.66	1.73	2.54	1.80	2.39	2.23	1.68	2.69	2.57	2.37	2.18	0.03	0.03	0.02	0.02	0.00	0.02	0.02
ster53	1.15	1.22	1.29	1.10	1.46	1.14	1.15	1.40	1.65	1.26	1.49	0.04	0.04	0.01	0.03	0.02	0.01	0.03

[a] Tracer refers to whether the Hexatriaconte tracer was added to the lubricant.

TABLE 35. LIGHT-DUTY ELEMENTAL CARBON AND ORGANIC CARBON (No Statistical Analyses Were Performed On These Data)

Test Number	Emitter	Oil	Fuel	Temp, °F	EC µg/mile	OC µg/mile	TC µg/mile
LD-NE-F-E0-72	Normal	Fresh	E0	72	142	39	181
LD-NE-F-E0-72-3a	Normal	Fresh	E0	72	599	61	660
LD-NE-F-E0-20	Normal	Fresh	E0	20	2254	409	2663
LD-NE-F-E10-72	Normal	Fresh	E10	72	1100	104	1204
LD-NE-F-E10-20	Normal	Fresh	E10	20	3710	473	4184
LD-NE-A-E0-72	Normal	Aged	E0	72	668	52	720
LD-NE-A-E0-20	Normal	Aged	E0	20	3095	388	3483
LD-NE-A-E10-72	Normal	Aged	E10	72	1361	118	1478
LD-NE-A-E10-20	Normal	Aged	E10	20	3455	377	3832
LD-HE-F-E0-72	High	Fresh	E0	72	1487	79095	80582
LD-HE-F-E0-20	High	Fresh	E0	20	2172	71723	73895
LD-HE-F-E10-72	High	Fresh	E10	72	953	63304	64257
LD-HE-F-E10-20	High	Fresh	E10	20	7823	68629	76452
LD-HE-A-E0-72	High	Aged	E0	72	1527	55760	57286
LD-HE-A-E0-20	High	Aged	E0	20	7429	73217	80646
LD-HE-A-E10-72	High	Aged	E10	72	2141	50997	53138
LD-HE-A-E10-20	High	Aged	E10	20	2606	44587	47193

a The repeat test of the normal emitter after all other tests were run is included here but not as part of the first two test's averaged data.

TABLE 36. AVERAGE SULFATE EMISSIONS FROM LIGHT-DUTY VEHICLES (No Statistical Analyses Were Performed On These Data)

Test Number	Emitter	Oil	Fuel	Temp	Average Sulfate (µg/mile)
LD-NE-F-E0-72	Normal	Fresh	E0	72	5.02
LD-NE-F-E0-72-3a	Normal	Fresh	E0	72	7.88
LD-NE-F-E0-20	Normal	Fresh	E0	20	30.9
LD-NE-F-E10-72	Normal	Fresh	E10	72	40.3
LD-NE-F-E10-20	Normal	Fresh	E10	20	51.5
LD-NE-A-E0-72	Normal	Aged	E0	72	5.91
LD-NE-A-E0-20	Normal	Aged	E0	20	32.4
LD-NE-A-E10-72	Normal	Aged	E10	72	17.5
LD-NE-A-E10-20	Normal	Aged	E10	20	32.9
LD-HE-F-E0-72	High	Fresh	E0	72	571
LD-HE-F-E0-20	High	Fresh	E0	20	682
LD-HE-F-E10-72	High	Fresh	E10	72	428
LD-HE-F-E10-20	High	Fresh	E10	20	464
LD-HE-A-E0-72	High	Aged	E0	72	928
LD-HE-A-E0-20	High	Aged	E0	20	1003
LD-HE-A-E10-72	High	Aged	E10	72	887
LD-HE-A-E10-20	High	Aged	E10	20	878

a The repeat test of the normal emitter after all other tests were run is included here but not as part of the first two test's averaged data.

TABLE 37. LIGHT DUTY VEHICLE AVERAGE SOLUBLE ORGANIC FRACTION (No Statistical Analyses Were Performed On These Data)

Test Number	Vehicle	Lubricant	Fuel	Temp, F	SOF, %
LD-NE-F-E0-72	Normal Emitter	Fresh	E0	72	47%
LD-NE-F-E0-72-3 a	Normal Emitter	Fresh	E0	72	16%
LD-NE-F-E0-20	Normal Emitter	Fresh	E0	20	38%
LD-NE-F-E10-72	Normal Emitter	Fresh	E10	72	10%
LD-NE-F-E10-20	Normal Emitter	Fresh	E10	20	33%
LD-NE-A-E0-72	Normal Emitter	Aged	E0	72	19%
LD-NE-A-E0-20	Normal Emitter	Aged	E0	20	25%
LD-NE-A-E10-72	Normal Emitter	Aged	E10	72	11%
LD-NE-A-E10-20	Normal Emitter	Aged	E10	20	26%
LD-HE-F-E0-72	High Emitter	Fresh	E0	72	96%
LD-HE-F-E0-20	High Emitter	Fresh	E0	20	95%
LD-HE-F-E10-72	High Emitter	Fresh	E10	72	96%
LD-HE-F-E10-20	High Emitter	Fresh	E10	20	96%
LD-HE-A-E0-72	High Emitter	Aged	E0	72	95%
LD-HE-A-E0-20	High Emitter	Aged	E0	20	94%
LD-HE-A-E10-72	High Emitter	Aged	E10	72	92%
LD-HE-A-E10-20	High Emitter	Aged	E10	20	92%

a The repeat test of the normal emitter after all other tests were run is included here but not as part of the first two test's averaged data.

7.5.2.9 Particle Number and Size Distributions

Due to the limited number of repeats taken with the particle number and size data (two runs using total particle number (PN) measurement and one run using solid PN measurement), it is important to highlight only major differences observed between fresh and aged oil and between NE and HE vehicles. Figures 14 and 15 show the exhaust PN concentration for the light-duty normal emitter (NE). The data are shown for the fresh and aged oil using E0 and E10 at 72°F and 20°F. The data are plotted as an average concentration for the cold-start (Bags 1 and 2) and the hot-start (Bags 3 and 4) portions of the UDC. The exhaust PN concentration ranged from about 0.05×10^6 part./cm³ to 5×10^6 part./cm³. The combination of cold-start and cold ambient temperature operation resulted in the highest PN emissions. The NE vehicle with fresh oil emitted a higher number of solid and volatile particles, compared to emissions with the aged oil. This was observed at the cold-start and the hot-start portion of the drive cycle. E10 resulted in higher particle emissions, compared to E0, particularly at 72°F. At 20°F, there was not a consistent trend between E10 and E0. The repeated test with the NE using E0 and fresh oil after all other testing at 72°F and 20°F gave much higher PN emissions, compared to the original test performed. This was consistent with the trend observed earlier with the PM mass data. This also suggests a shift in the PM emissions performance of the NE vehicle. Figures 16 and 17 show the percent ratio of solid and volatile PN concentration to total PN concentration. Over 70 percent of the number of particles emitted from the NE were solid in nature. This is generally consistent with the trend observed with the OC/EC mass and with the SOF results reported earlier on a mass basis.

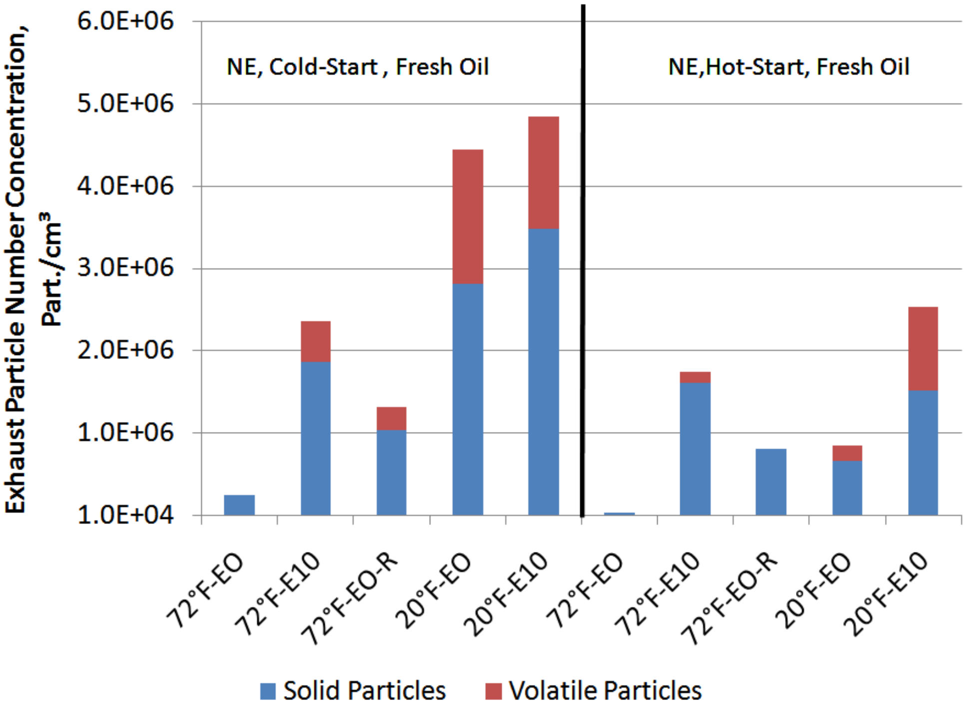

FIGURE 14. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (LIGHT-DUTY, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

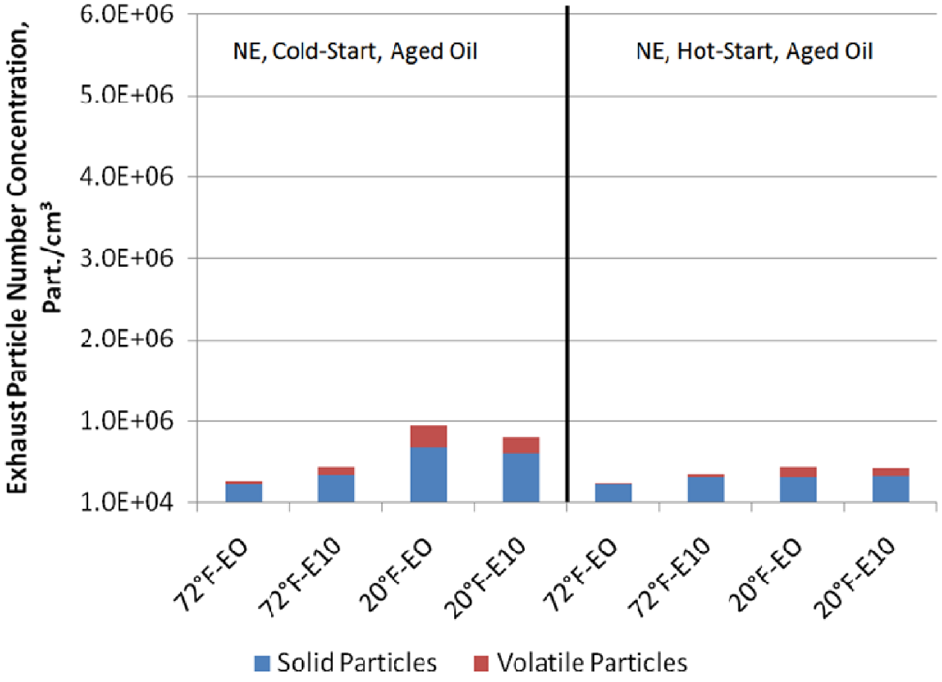

FIGURE 15. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (LIGHT-DUTY, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

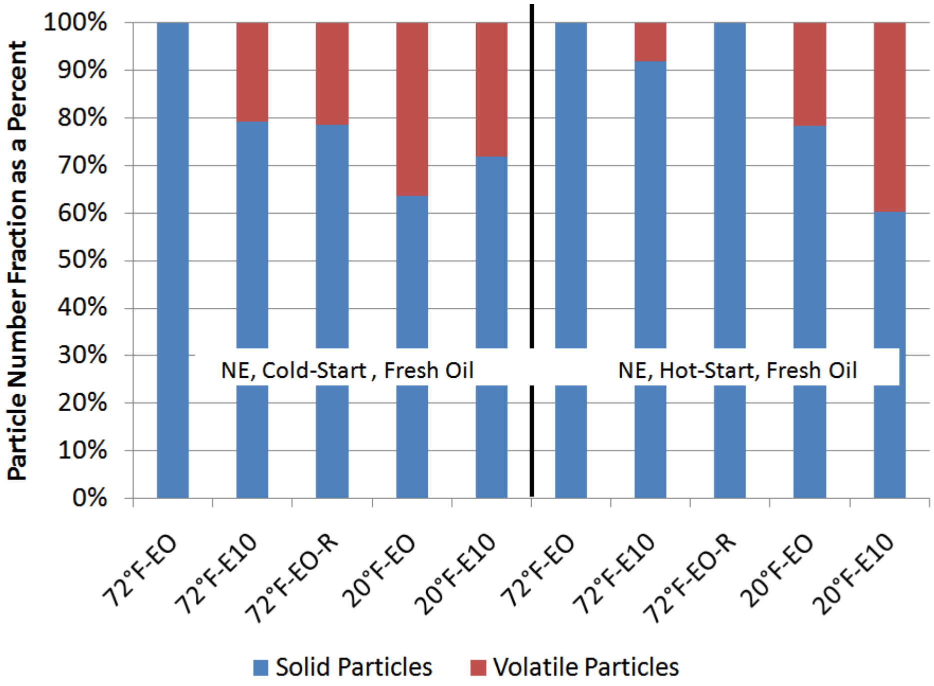

FIGURE 16. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (LIGHT-DUTY, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

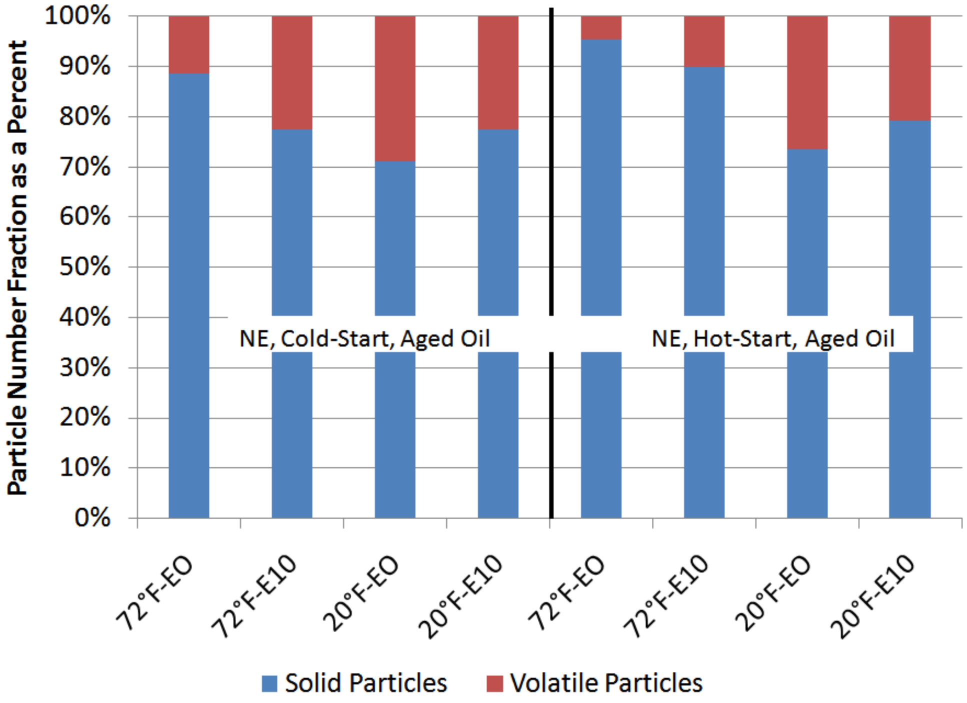

FIGURE 17. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (LIGHT-DUTY, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

Figures 18 and 19 show the exhaust PN concentration for the light-duty high emitter (HE). The exhaust PN concentration ranged from 5x10^6 part./cm³ to 150 x 10^6 part./cm³. The highest PN concentration observed with the high emitter are a factor of 3000 and 30 higher than the lowest and highest concentration observed with the NE, respectively. For the HE, there was not a difference in the emissions between the cold-start and the hot-start PN emissions using the fresh oil. For the aged oil, the hot-start produced about 50 percent higher PN emissions. Contrary to what was observed with the NE, the HE with the aged oil showed much higher particle number emissions, compared to that with the fresh oil. The HE number emissions were dominated by volatile particles. With the fresh oil, as shown in Figure 20, more than 65 percent of the particles were volatile in nature. With the aged oil, as shown in Figure 21, the number of volatile particles represents more than 85 percent of total particle number. The volatile fraction observed with the HE is consistent with the OC/EC and SOF trends reported earlier on a mass basis. However, this trend is opposite to what was observed with the NE, where solid particle number and mass dominate total PN and PM composition.

Figures 22 through Figure 30 show the size distributions for the light-duty NE using the fresh and aged oil with E0 and E10 at 72°F and 20°F. The total and solid particle size distributions are shown for the cold-start and hot-start portions of the test. The total and solid distributions seem to exhibit a similar bimodal lognormal structure that consists of a nuclei mode <20 nm, and an accumulation mode. For the fresh oil, the accumulation mode peaked at about 50 nm to 60 nm and the nuclei mode peaked at 10 nm. The accumulation mode for the aged oil was lower than the fresh oil in concentration and it was at least 20 nm smaller in diameter than that for the fresh oil. Since the accumulation mode consists mainly of solid particles, the fresh oil seems to contribute to the formation and growth by coagulation of solid particles leading to a higher concentration and a larger particle size, compared with the aged oil. Filter measurements and OC/EC were inconsistent with these findings. Filter measurements showed higher PM with the aged oil, compared to the fresh oil. However, the reader should keep in mind that the size distribution data were taken for a limited number of tests, while the PM data were based on an interval of 16 different tests spanned over 16 days. The size distribution data were collected at a constant dilution ratio from vehicle tailpipe and were reported as averages for the entire cold-start (Phase 1 and Phase 2) and hot-start portions (Phase 3 & Phase 4) of the UDC. These differences can contribute to differences in observations, particularly in case of vehicle emissions performance shift, as evidenced in Figure 30. The data plotted in Figure 30 represent the same conditions as those plotted in Figure 22, but it is a repeat after all the testing performed using E0, E10, 72°F, 20°F, with the fresh and aged oil. Figure 30 shows a much higher concentration than that observed in Figure 22. However, the size distribution characteristic, particularly the size location of the accumulation mode between 50 nm and 60 nm is consistent with that observed with the fresh oils, compared to the smaller diameter observed with the aged oils.

Figures 31 through Figure 38 show the size distributions for the light-duty HE using the fresh and aged oil with E0 and E10 at 72°F and 20°F. The size distributions are monomodal lognormal distributions. The accumulation mode for total particles peaks between 30 nm and 50 nm and is volatile in nature. This is different from the NE, where the accumulation mode was composed mainly of solid particles. For solid particle emissions from the HE, the distribution has a nuclei mode at 10 nm similar to that observed with the normal emitter, but with the higher concentration. It is speculated that the source of nuclei mode solid particles is the ash inherently

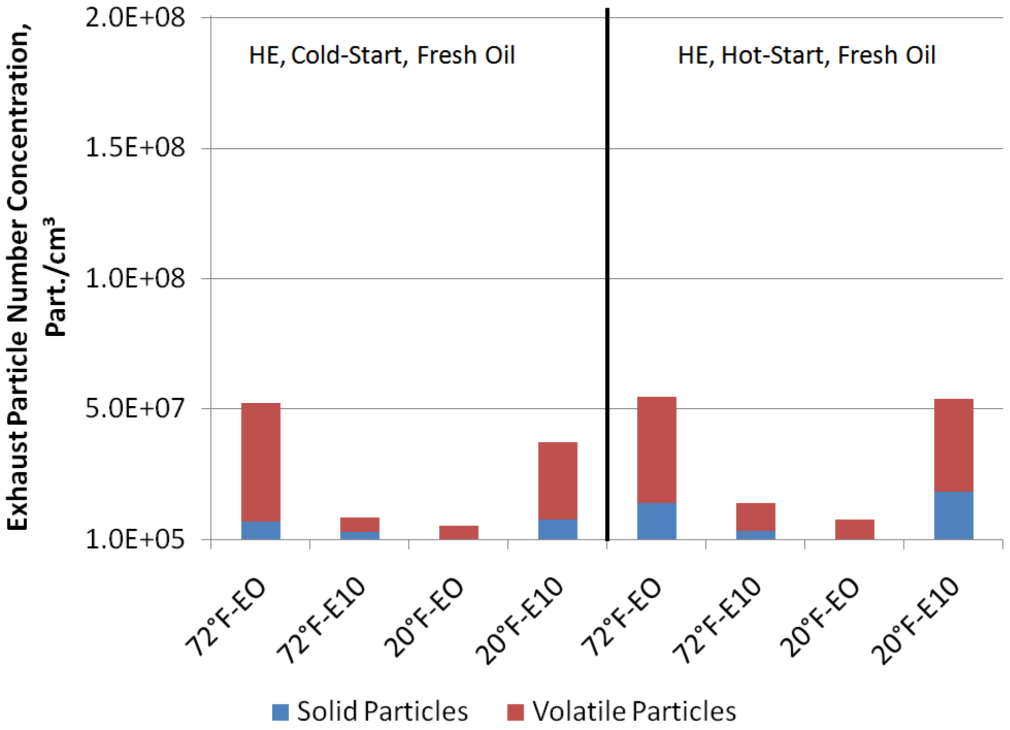

FIGURE 18. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (LIGHT-DUTY, HIGH EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

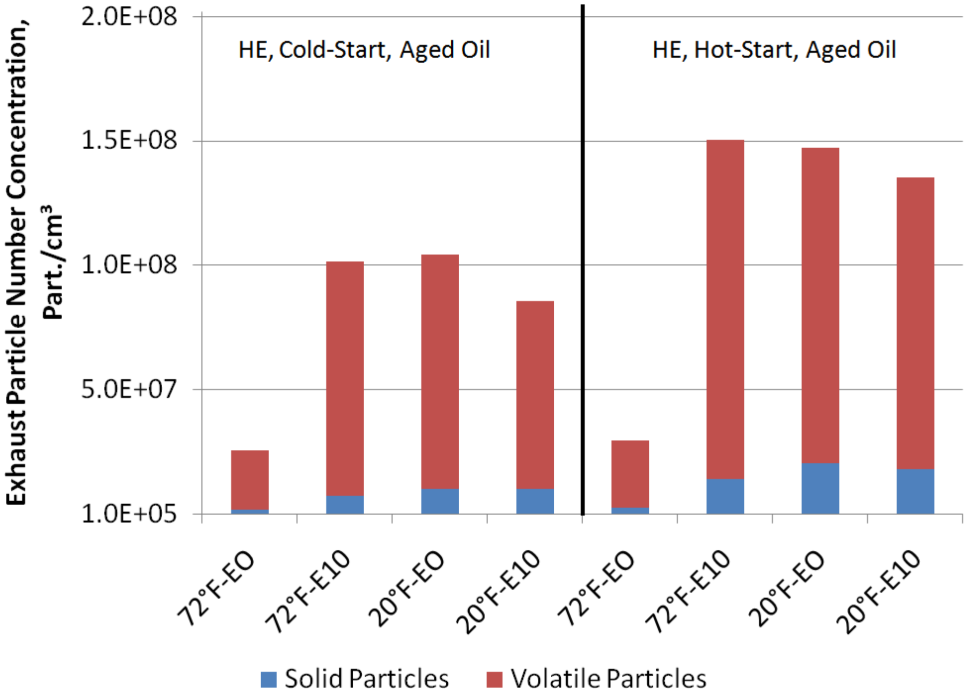

FIGURE 19. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (LIGHT-DUTY, HIGH EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

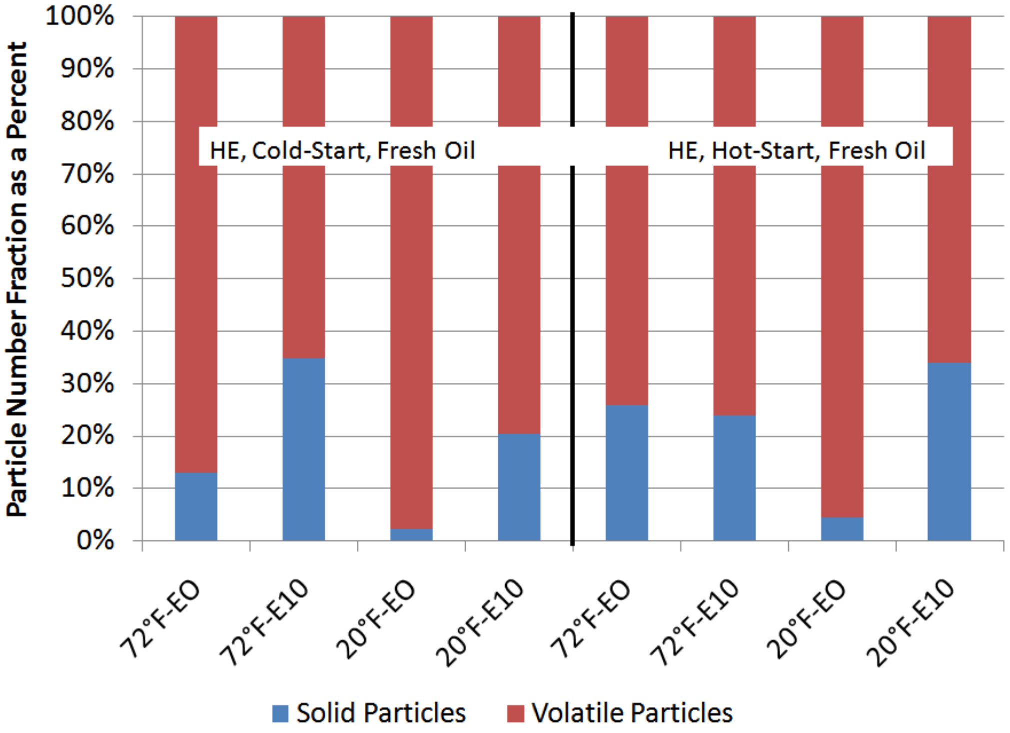

FIGURE 20. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (LIGHT-DUTY, HIGH EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

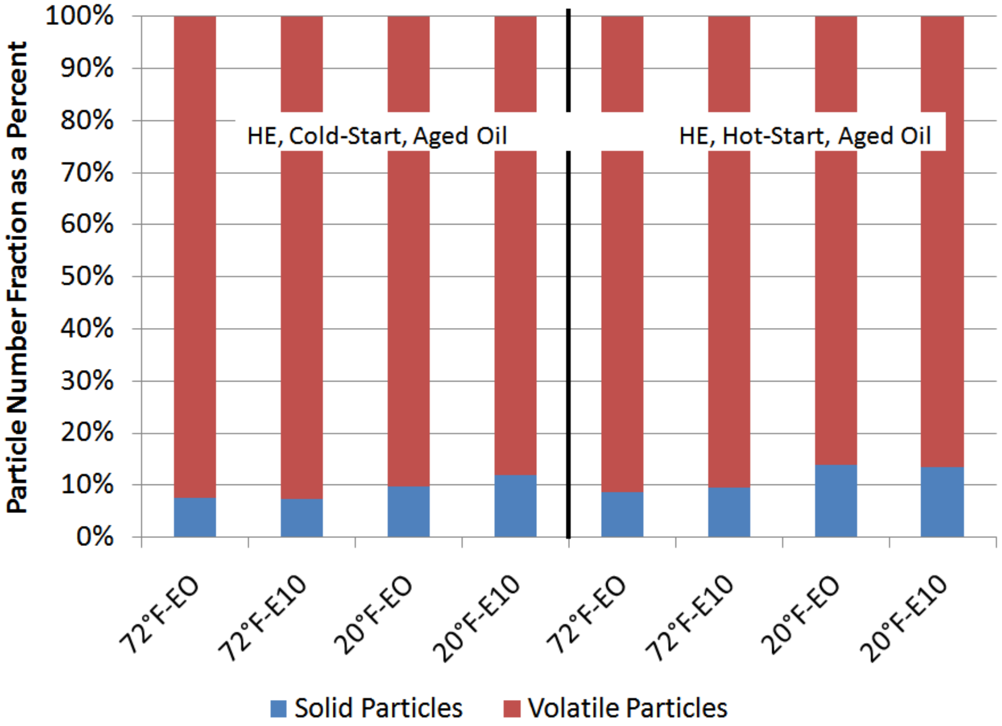

FIGURE 21. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (LIGHT-DUTY, HIGH EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

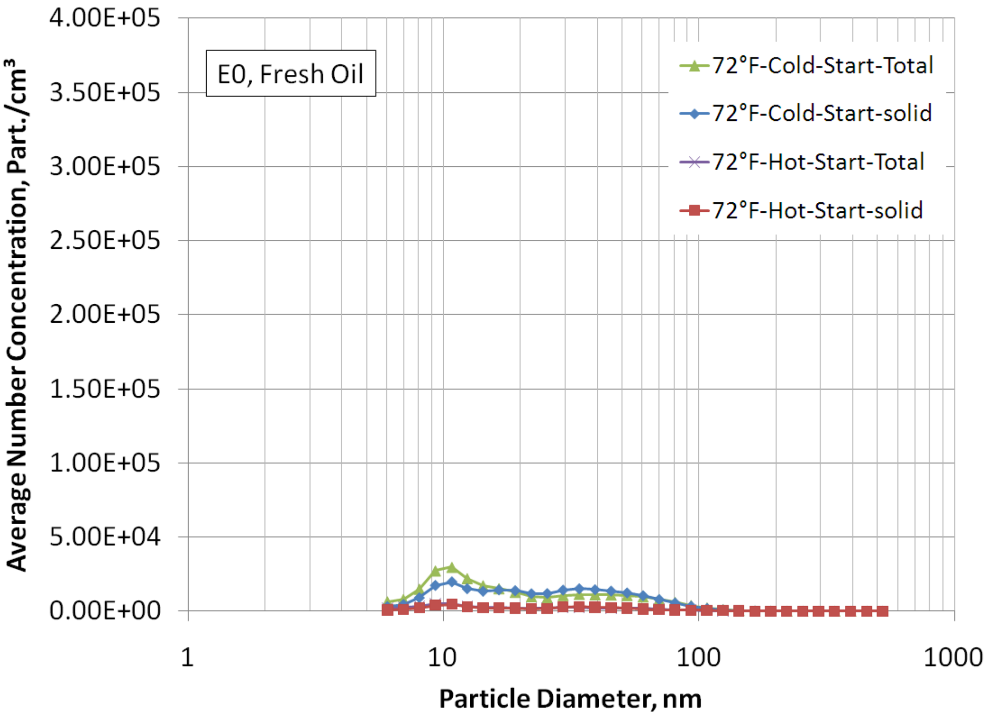

FIGURE 22. NUMBER-WEIGHTED SIZE DISTRIBUTION (E0, 72°F, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

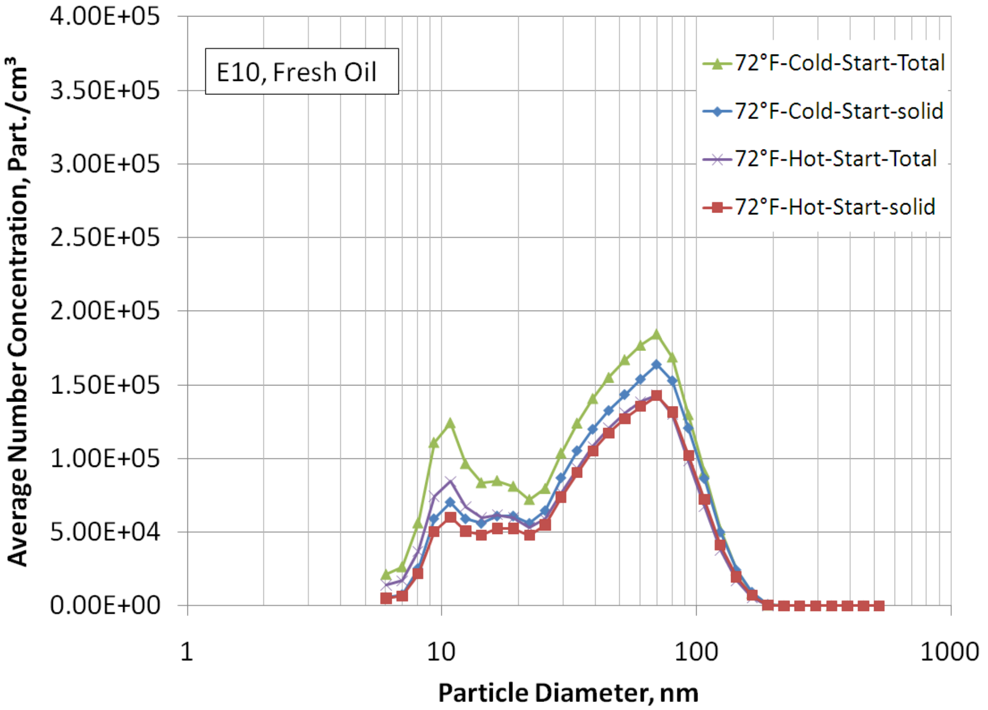

FIGURE 23. NUMBER-WEIGHTED SIZE DISTRIBUTION (E10, 72°F, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

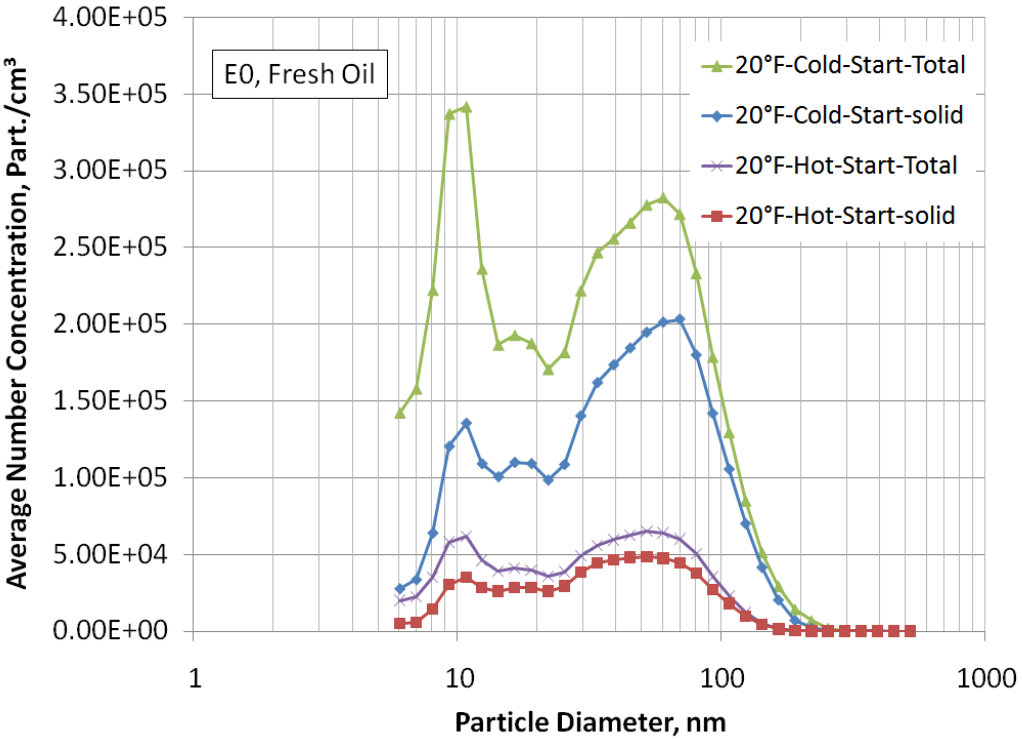

FIGURE 24. NUMBER-WEIGHTED SIZE DISTRIBUTION (E0, 20°F, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

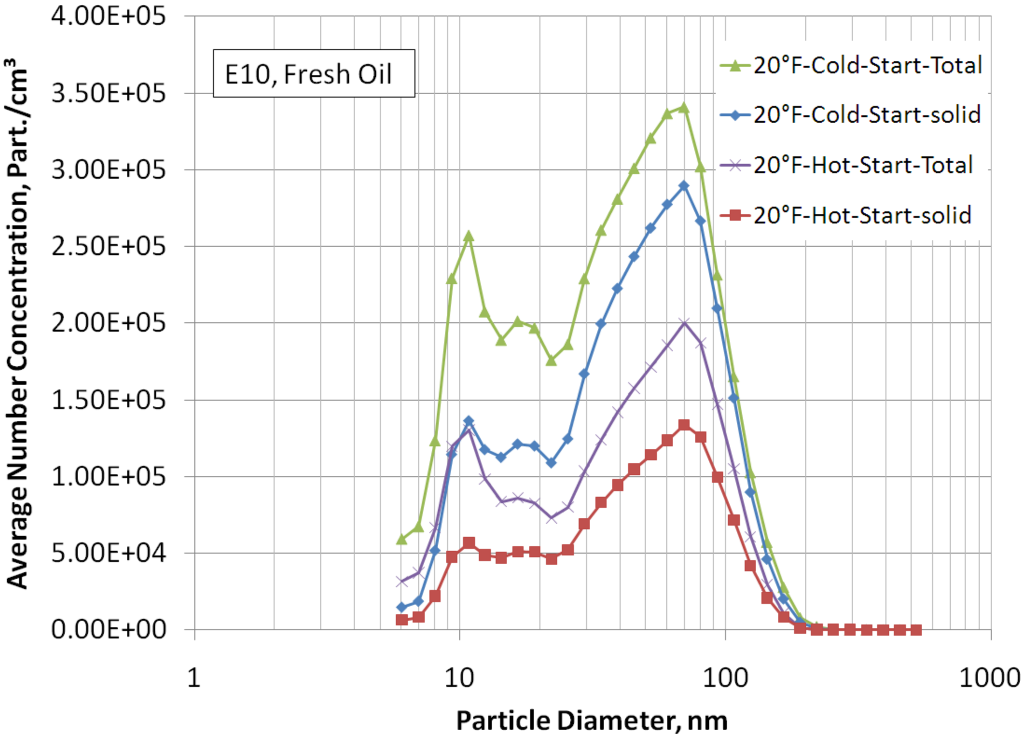

FIGURE 25. NUMBER-WEIGHTED SIZE DISTRIBUTION (E10, 20°F, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

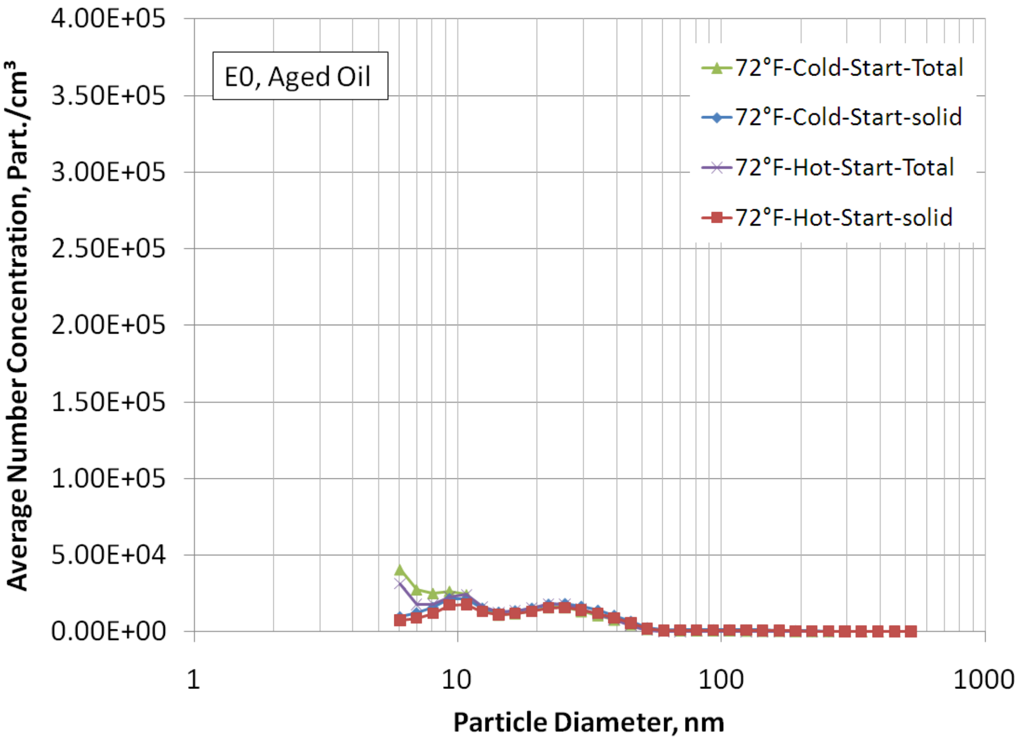

FIGURE 26. NUMBER-WEIGHTED SIZE DISTRIBUTION (E0, 72°F, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

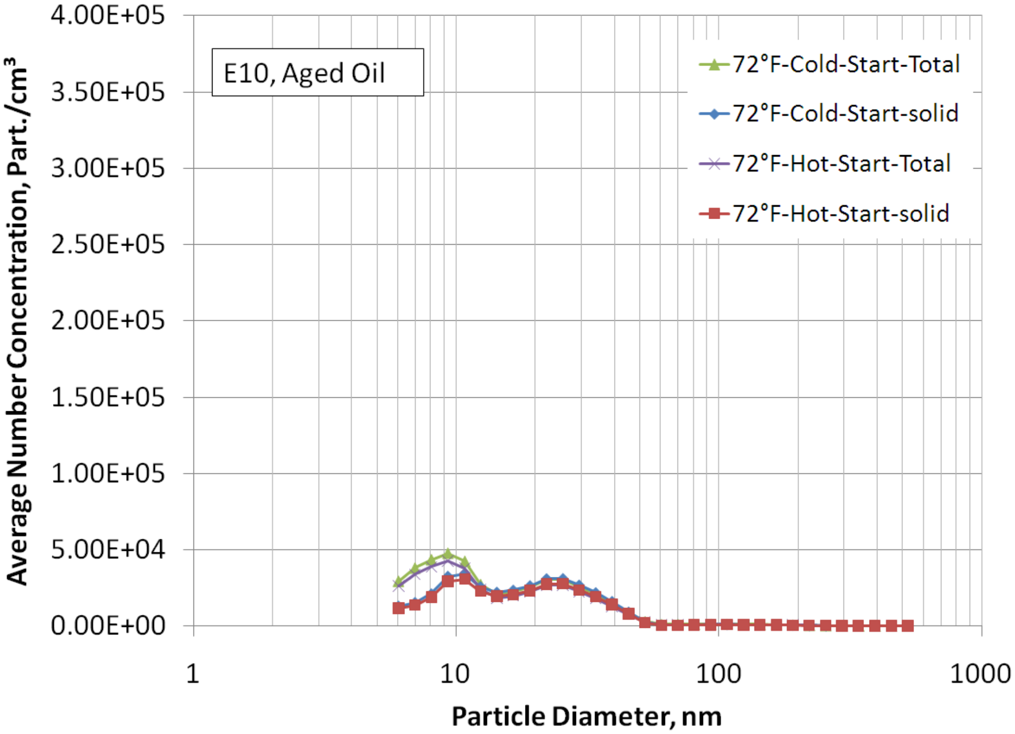

FIGURE 27. NUMBER-WEIGHTED SIZE DISTRIBUTION (E10, 72°F, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

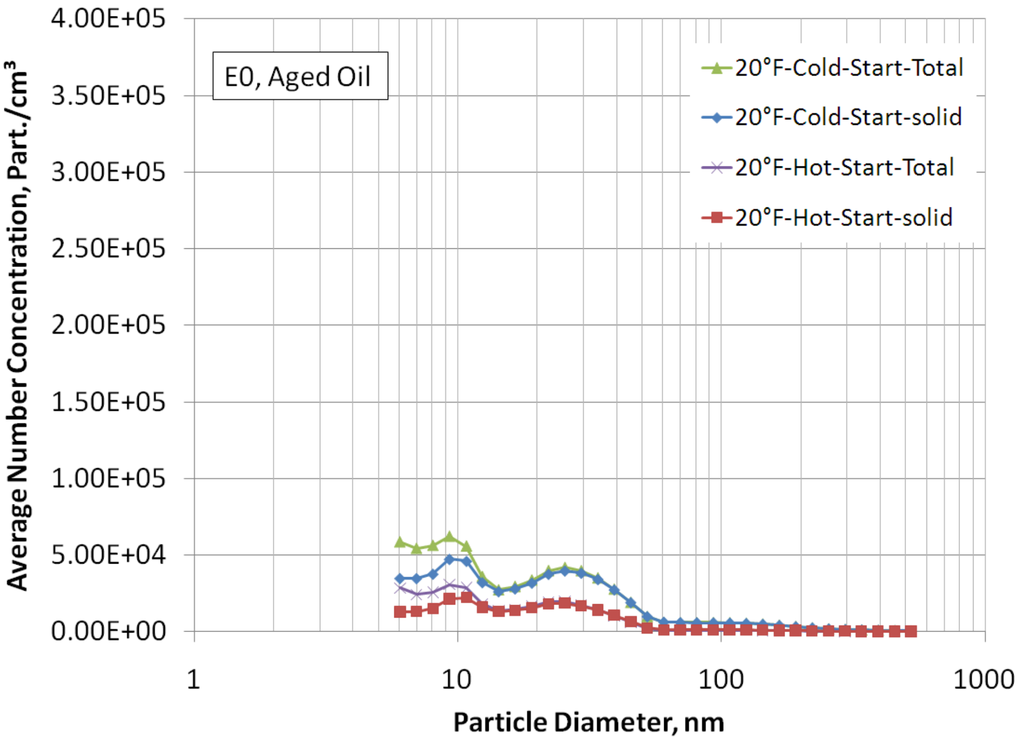

FIGURE 28. NUMBER-WEIGHTED SIZE DISTRIBUTION (E0, 20°F, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

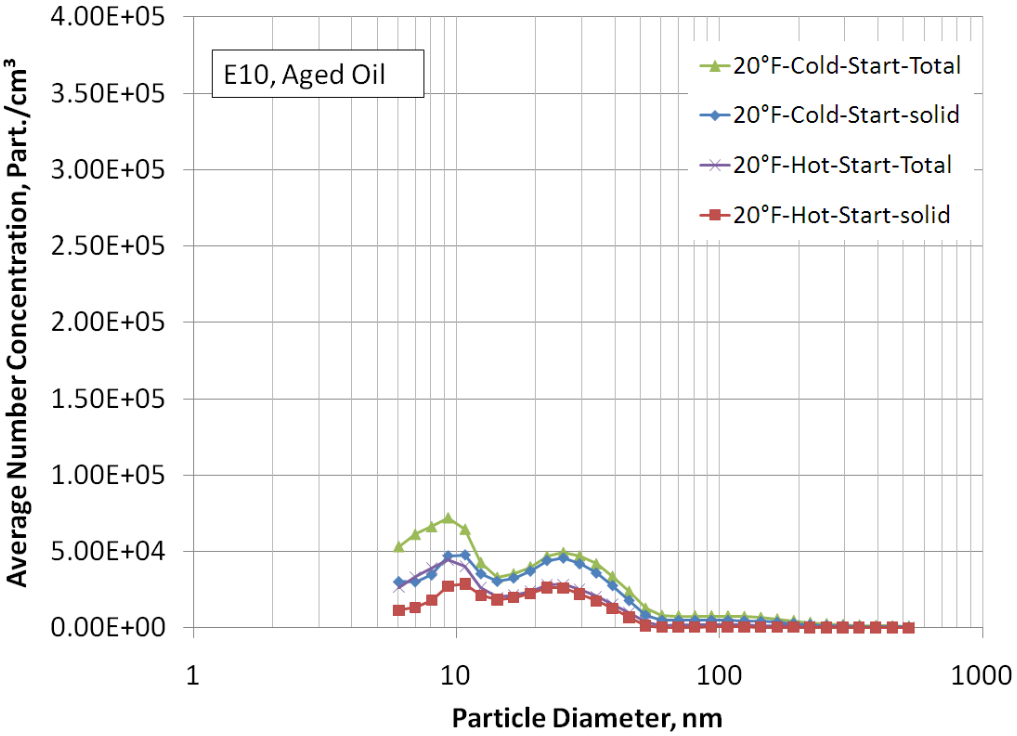

FIGURE 29. NUMBER-WEIGHTED SIZE DISTRIBUTION (E10, 20°F, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

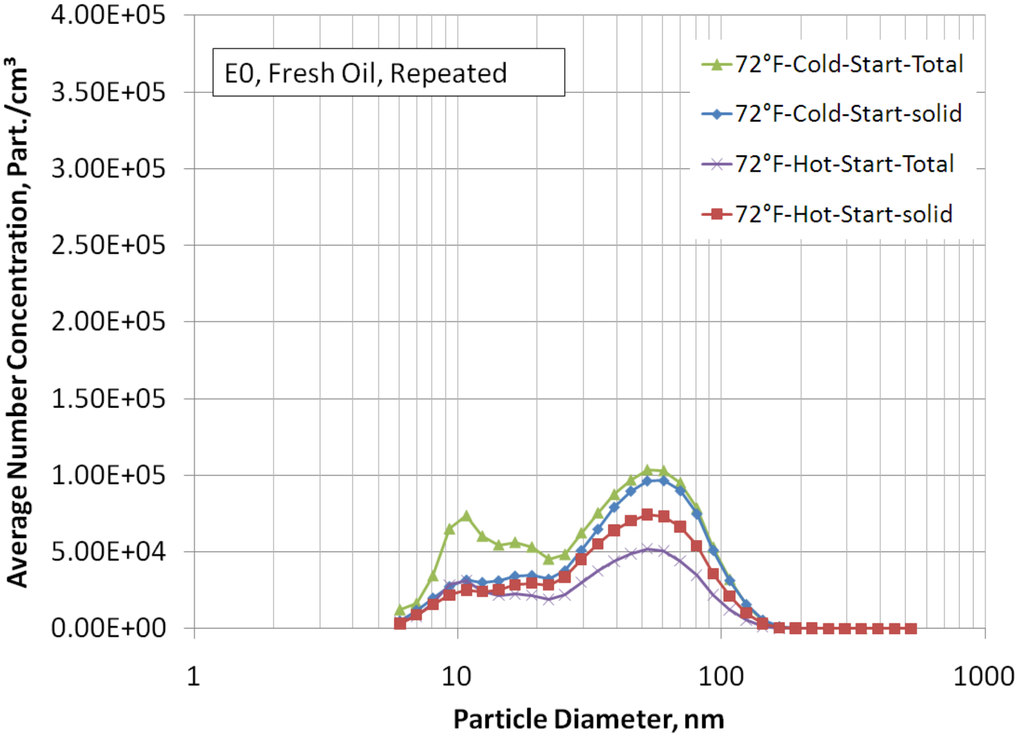

FIGURE 30. NUMBER-WEIGHTED SIZE DISTRIBUTION (E0, 72°F, NORMAL EMITTER, FRESH OIL, REPEATED TEST AFTER E0, E10 WITH FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

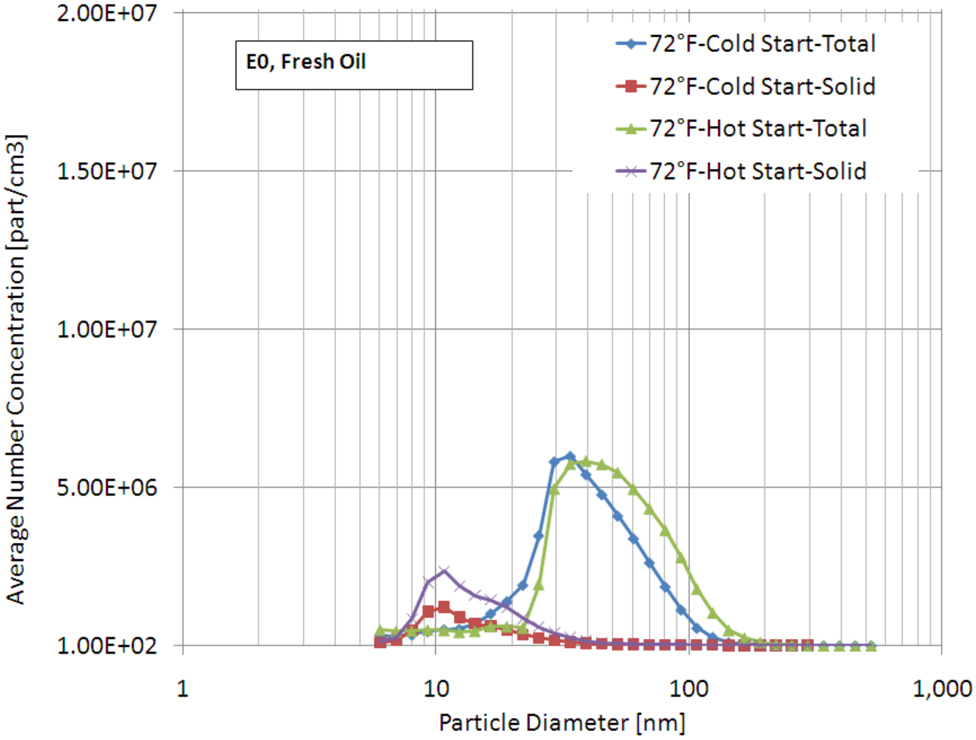

FIGURE 31. NUMBER-WEIGHTED SIZE DISTRIBUTION (E0, 72°F, HIGH EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

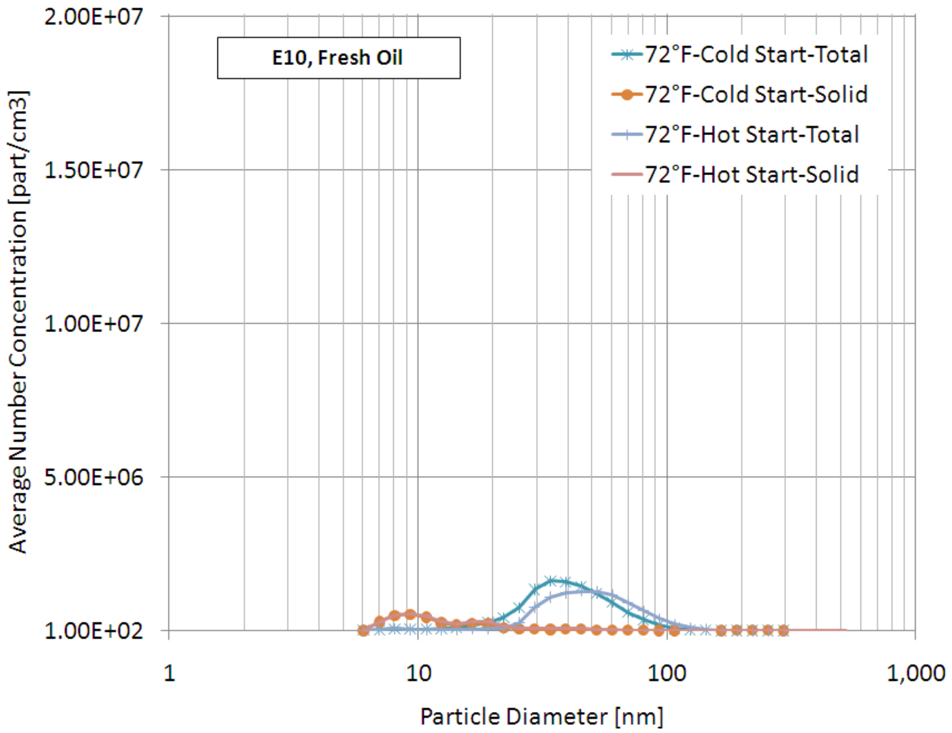

FIGURE 32. NUMBER-WEIGHTED SIZE DISTRIBUTION (E10, 72°F, HIGH EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

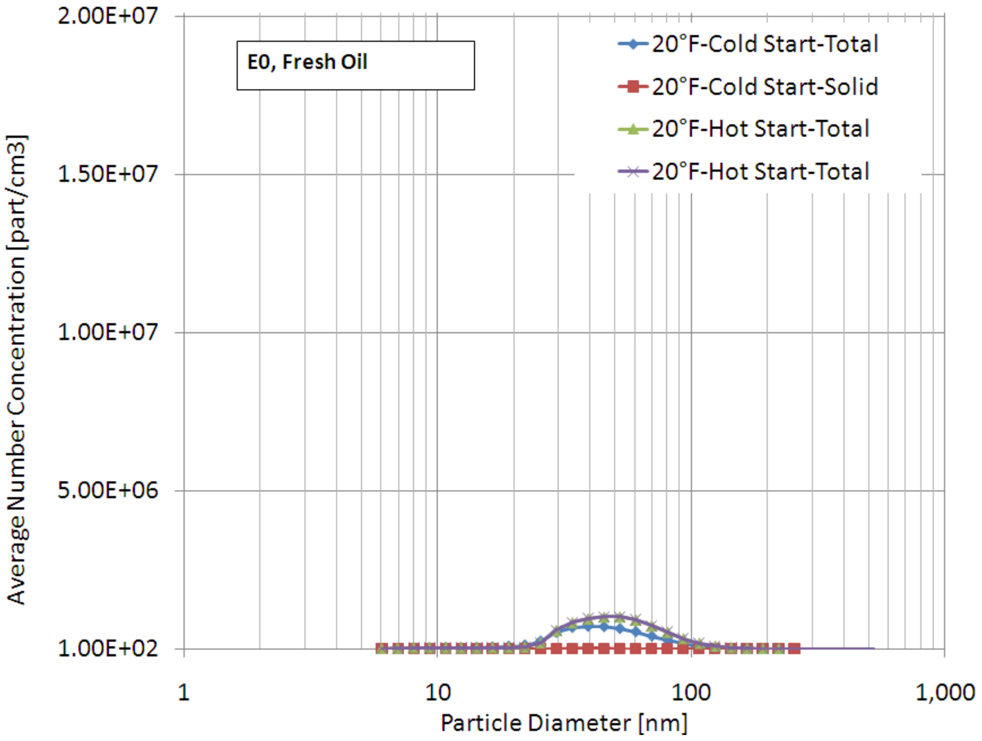

FIGURE 33. NUMBER-WEIGHTED SIZE DISTRIBUTION (E0, 20°F, HIGH EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

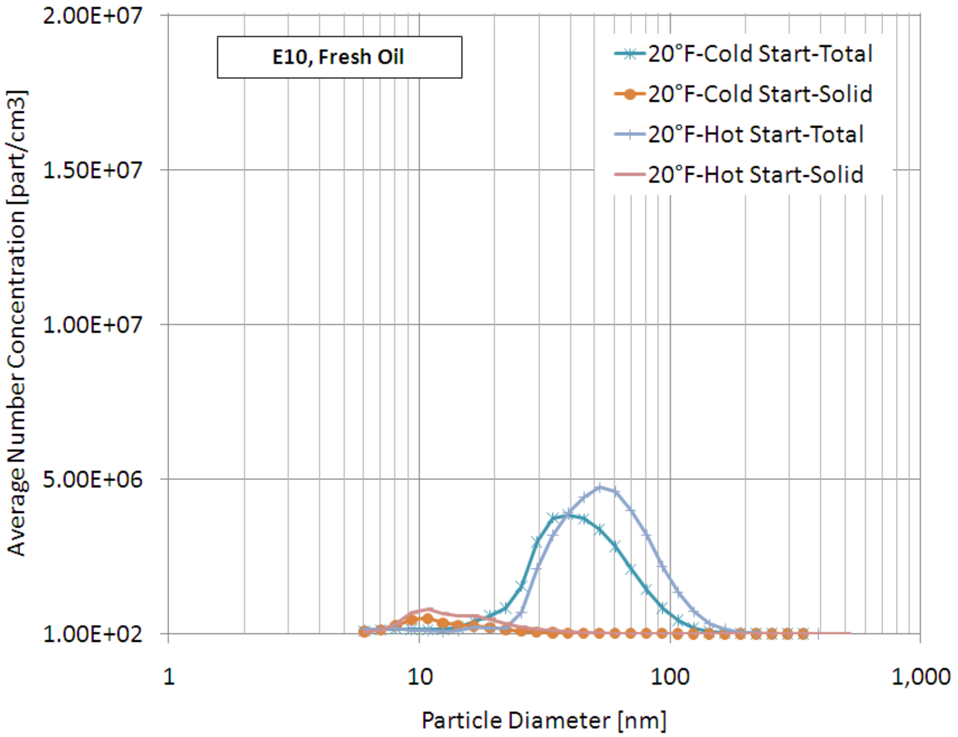

FIGURE 34. NUMBER-WEIGHTED SIZE DISTRIBUTION (E10, 20°F, HIGH EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

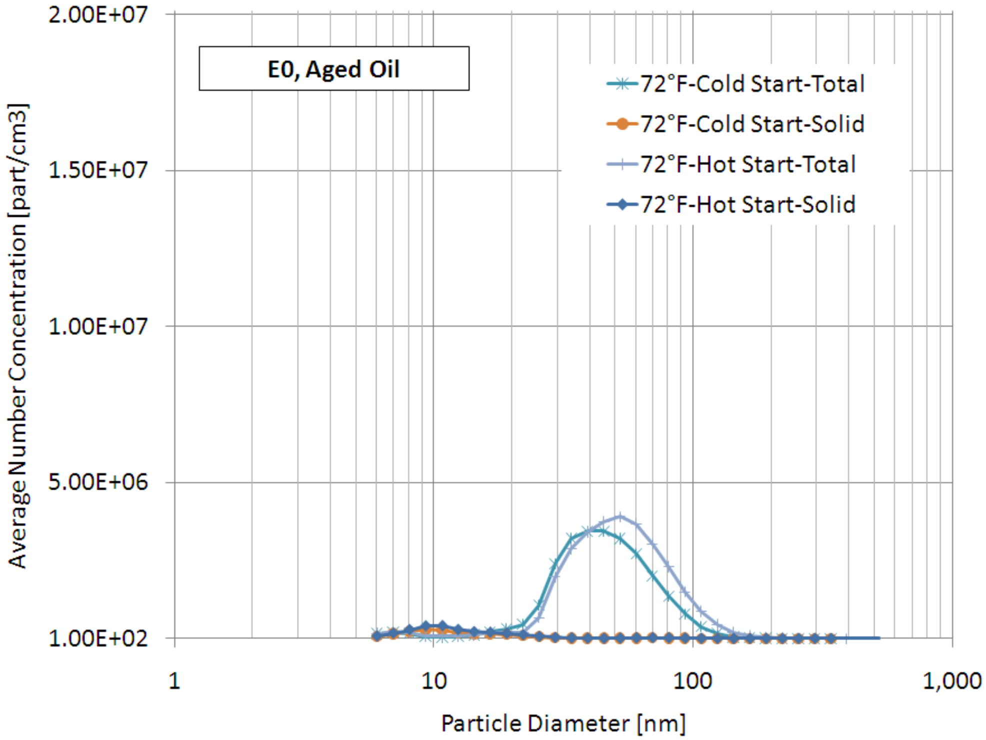

FIGURE 35. NUMBER-WEIGHTED SIZE DISTRIBUTION (E0, 72°F, HIGH EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

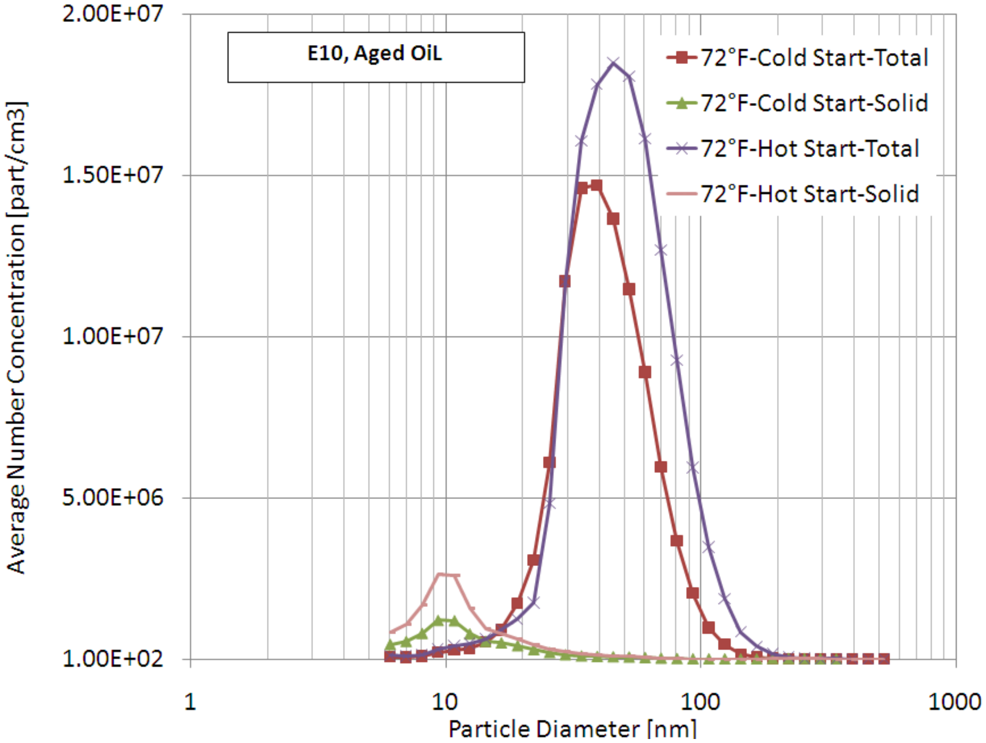

FIGURE 36. NUMBER-WEIGHTED SIZE DISTRIBUTION (E10, 72°F, HIGH EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

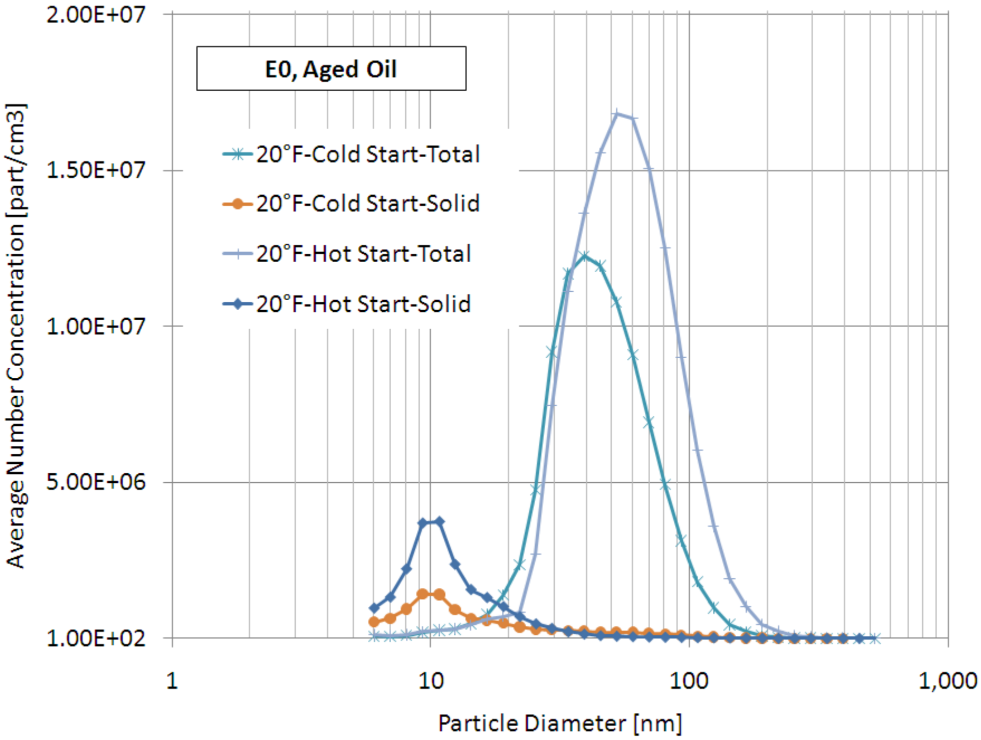

FIGURE 37. NUMBER-WEIGHTED SIZE DISTRIBUTION (E0, 20°F, HIGH EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

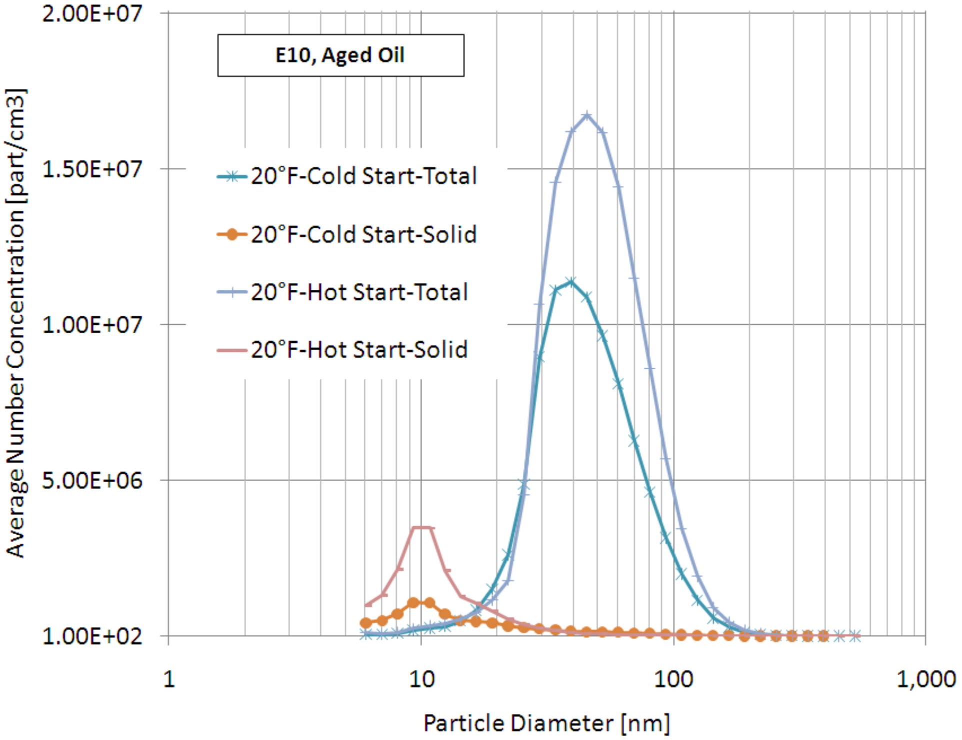

FIGURE 38. NUMBER-WEIGHTED SIZE DISTRIBUTION (E10, 20°F, HIGH EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

present in fresh lube oil and ash and wear particles present in aged oil, but no chemical analysis was performed to quantify the chemical composition of sub-20 nm particles from the high emitter. This could be of interest in future work, similar to what was done for the NE as shown in the next section. The higher volatile accumulation mode observed with aged oil, compared to fresh oil could be related to the lower vapor pressure of the bulk aged oil compared to fresh oil. Lower vapor pressure promotes particle nucleation and growth of particles during dilution and cooling. Another possibility for the enhanced volatile particle formation with the aged oil, compared to fresh oil, is the higher presence of solid wear particles that may act as condensation/nucleation site during dilution and cooling of the hot exhaust. More systematic future research efforts are needed to better understand these phenomena.

7.5.2.10 MOUDI Test Results

It is hypothesized that the nuclei mode solid particles consist of ash particles derived from the lube oil. The ash particles form later in combustion during the expansion stroke creating nuclei mode particles that do not have enough time to coagulate with the accumulation mode. To prove this hypothesis, we used a MOUDI and nano-MOUDI impactors for size-specific mass collection and elemental analysis. The idea was to show that particles in the sub-30 nm size range are dominated by lube-related ash particles including P, S, Ca, and Zn.

Figure 39 shows the PM mass cumulative fraction as a function of particle diameter. More than 80 percent of the particle mass is in the ultrafine range below 0.1 µm in aerodynamic diameter and more than 50 percent is in the nanoparticle size range below 0.05 µm in diameter. Figure 40 shows the size-specific elemental mass as a percent of size-specific total PM mass. The limited MOUDI elemental analysis performed in this work showed that the percent of elemental mass relative to total PM mass is very low (<0.5%) and similar across the size range between 0.01 µm and 0.3 µm. Thus, the measured elements do not dominate the PM mass even in the sub-30 nm size range, as suspected, where solid nuclei are present on a number basis, as shown in Figures 22 and 23. However, if one looks at particles larger than 0.3 µm in diameter, the percent elemental mass (particularly Ca) increased to a level reaching 23 percent. This high percentage of elements at the upper stages can possibly be due to the diffusion of small metallic ash particles to the upper stages of the MOUDI. Due to the high solid fraction of particles observed with the NE, as shown in Figures 16 and 17, it is likely that the sub-30 nm solid particles are dominated by soot or some other metallic elements that are different from Ca and Zn. Future efforts should focus on using the MOUDI for both elemental analysis and particle morphology. Particle morphology coupled with energy dispersion X-ray spectroscopy should help determine the physical characteristics and elemental composition of small particles depositing on the upper stages of the MOUDI, if any. Figure 41 shows P, S, Ca, and Zn as a percent of total PM. S, P, Ca, and Zn, represent 0.5%, 0.2%, 0.15%, and 0.15% of total PM of 1.44 mg/mi. The sum of measured elements represents one percent of the total PM emissions or 14.4 µg/mi.

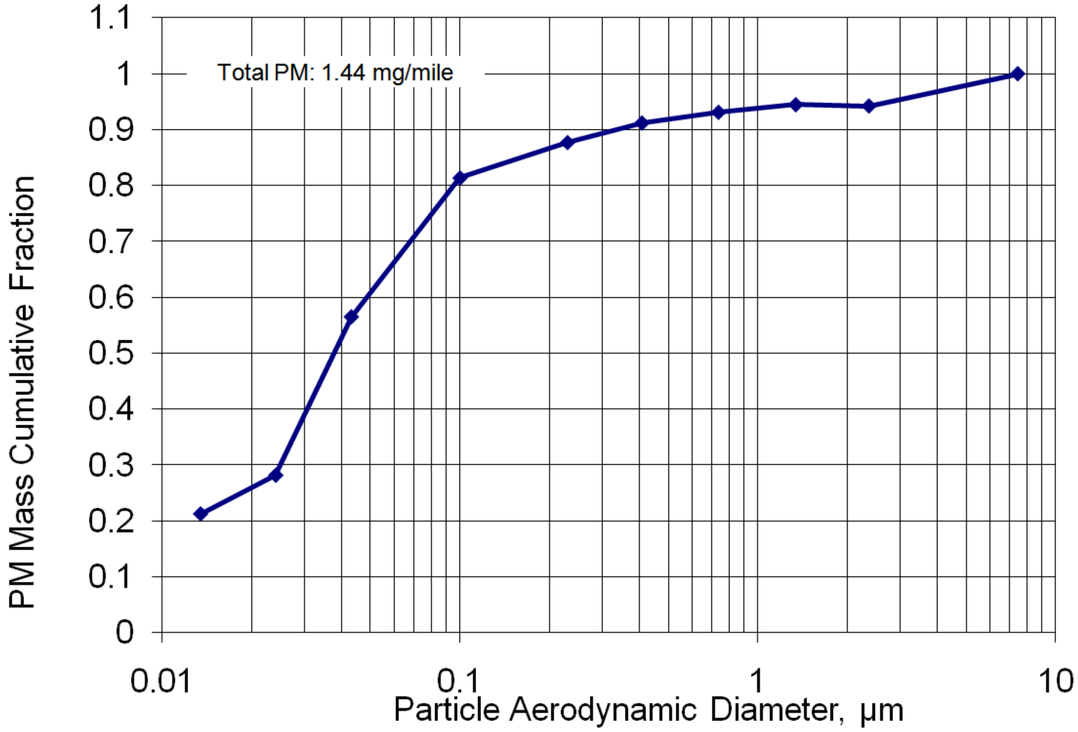

FIGURE 39. SIZE SPECIFIC CUMULATIVE MASS FRACTION (No Statistical Analyses Were Performed On These Data)

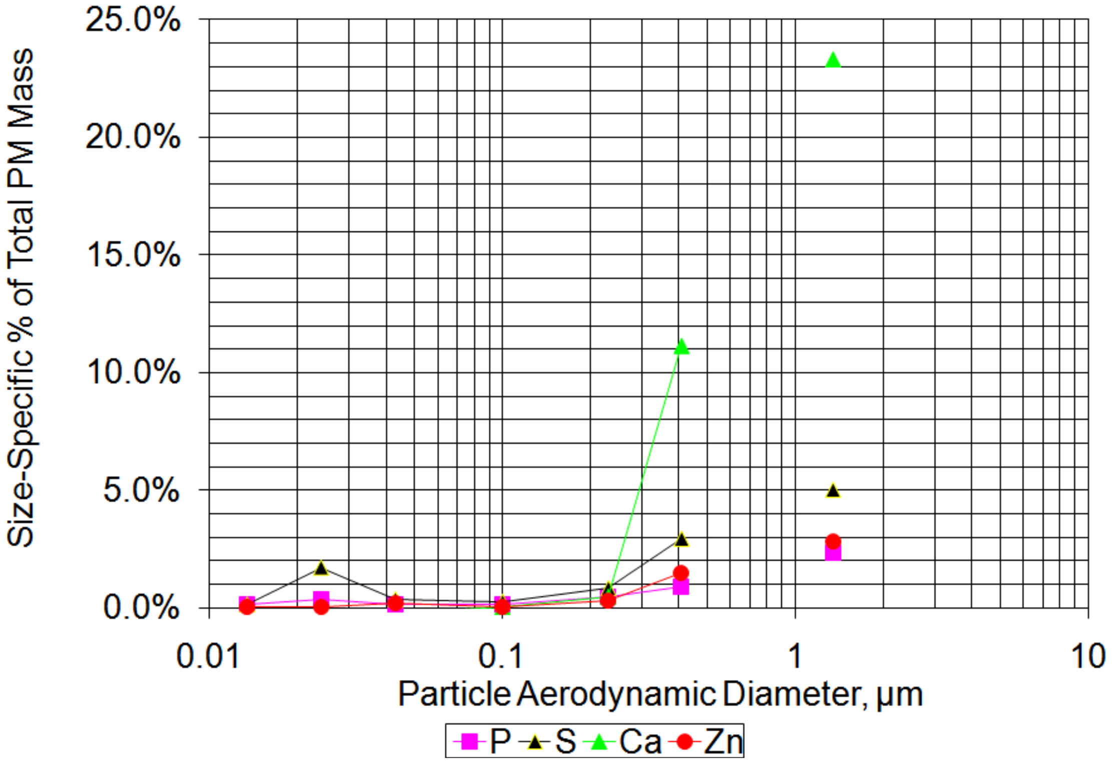

FIGURE 40. SIZE-SPECIFIC ELEMENTS AS A PERCENT OF TOTAL PM
(No Statistical Analyses Were Performed On These Data)

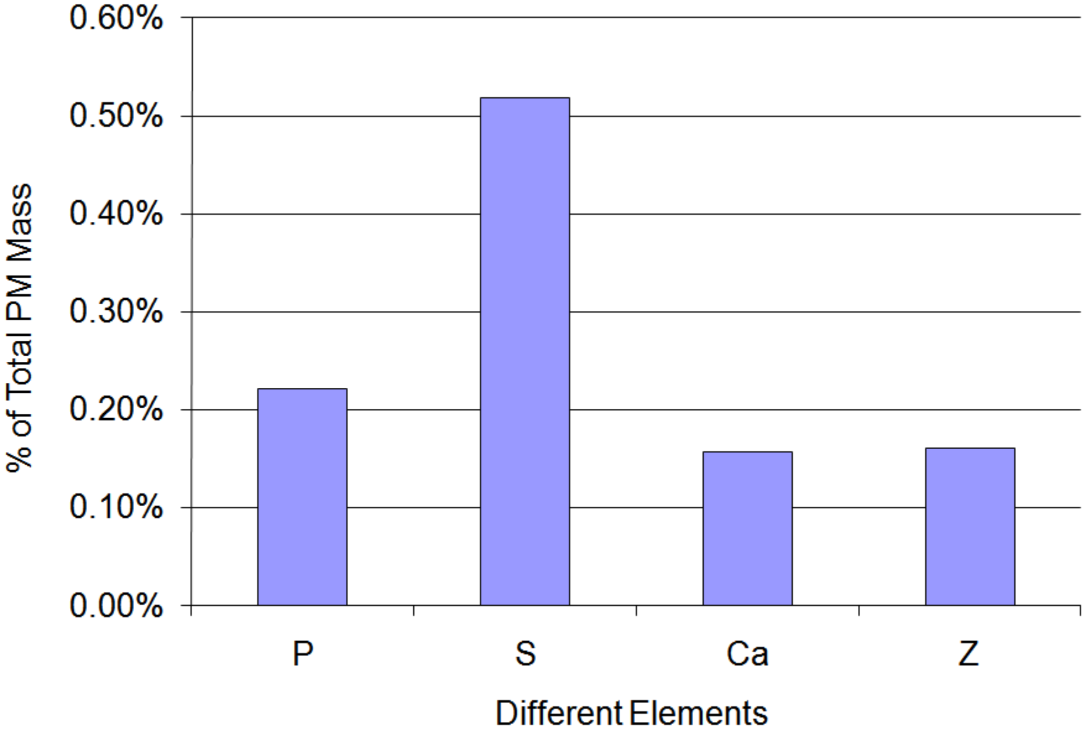

FIGURE 41. ELEMENTAL COMPOSITION AS A PERCENT OF TOTAL PM MASS
(No Statistical Analyses Were Performed On These Data)

7.6 PM Apportionment

We compared the exhaust emission rates for the four alternative tracers of lubricating oil, elements (Ca, P, Zn and Mo), hopanes and steranes, unresolved complex mixture (UCM) of ~C_{20} to C_{35} alkanes, and deuterated hexatriacontane ($C_{36}D_{74}$), with corresponding concentrations of the oil tracers in lubricating oils. Separate estimates of the lubricating oil consumption (LOC) rates were derived from ratios of the mass emission rates of the four oil tracers to their mass fractions in the oils. These LOC rate estimates were then compared to the measured LOC (HE vehicle only) and to the NE and HE vehicle exhaust emissions of PM, TC and OC. We estimated the fuel and oil contributions to the exhaust PM, TC and OC by multiple regressions using high molecular weight PAH as the fuel tracer and each of the alternative oil tracers.

7.6.1 Composition of Lubricating Oils and Fuels

Table 38 summarizes the chemical composition of the fresh and aged lubricating oils and gasolines with zero or 10% ethanol by volume, as tested during the CLOSE Project. Oil samples include the fresh and aged oils as received, and samples taken after the cold (20°F) tests with fresh and aged oils on E0 and then E10 for both the normal and high emitter. For example, the normal emitter was operated over multiple emission tests with fresh oil and a sample was taken from the crankcase drain oil after the cold tests on E0 fuels, and then the normal emitter was operated over multiple emissions tests with fresh oil on E10 fuels and a sample was taken from the crankcase drain oil after the cold tests. Thus five oil samples were taken from the normal-emitter (two fuel types and two oils, plus one repeat test on E0 with fresh oil), and four oil samples were taken from the high emitter. The summary includes the concentrations (µg/g) of oil additive elements (Ca, P, Zn and Mo), sum of hopanes and steranes, identified C_{12}-C_{19} alkanes, identified C_{20}-C_{35} alkanes (i.e., individually resolved peaks above the UCM), UCM of ~C_{20}-C_{35} alkanes, measured and expected $C_{36}D_{74}$, sum of all quantified PAH from naphthalene to coronene, and the three high molecular weight PAH, benzo(ghi)perylene, indeno[123-cd]pyrene and coronene. Elements were measured by both XRF and ICP-MS for oils samples from the normal emitter vehicle only.

The mass fraction of UCM alkanes was about 75 percent for the fresh oil (as received) and about 45 percent for the aged oil (as received). The lower fractions of UCM alkanes in the aged oil can result from combustion of the oil in the engine, entrainment of the more volatile alkanes with the exhaust, and oxidation of the oil. The insoluble oxidation products consist of polar compounds that are not extracted with the UCM alkanes during sample preparation and were not measured in this study. After completing each series of tests in the NE vehicle, the fractions of UCM alkanes were lower for the fresh oil (54 to 66 percent) and, considering the uncertainty of the UCM estimates, were comparable to pre-test concentrations for the aged oils (53 and 55 percent). In contrast, the post-test UCM mass fractions of the oils from the HE vehicle were substantially lower (near 20 percent) for both fresh and aged oils, indicating that the lubricating oils had degraded rapidly in this HE vehicle.

TABLE 38. CONCENTRATIONS OF OIL ADDITIVE ELEMENTS, HOPANES, STERANES, ALKANES AND POLYCYCLIC AROMATIC HYDROCARBONS (µG/G) IN FRESH AND AGED LUBRICATING OILS, AND GASOLINES WITH ZERO OR 10% ETHANOL BY VOLUME

(No Statistical Analyses Were Performed On These Data)

	Lubricating Oil Additive Metals[2]					Sum of Alkanes					Sum of PAH	
Lubricating Oils and Gasolines[1]	Ca	P	Zn	Mo	Hopanes Steranes	Identified C_{12}-C_{19}	Identified C_{20}-C_{35}	UCM C_{20}-C_{35}	Measured $C_{36}D_{74}$	Expected[3] $C_{36}D_{74}$	all[4] PAH	High MW PAH[5]
Oils												
Fresh as received	2240	291	860	58	85	110	4,870	740,000	0	0	100	1.4
Aged as received	2529	491	1070	89	89	171	2,870	450,000	0	0	1,100	10.0
NE-F-E0-72,20	2353 (1941)	318 (722)	1031 (863)	76 (72)	105	75	5,240	540,000	520	9,370	1,490	10.3
NE-F-E10-72,20	2270 (1948)	305 (722)	967 (917)	70 (71)	131	273	8,150	660,000	2,040	9,700	1,880	2.7
NE-A-E0-72,20	2497 (2089)	276 (654)	1025 (877)	84 (79)	104	76	6,290	530,000	700	9,030	1,680	18.6
NE-A-E10-72,20	2412 (2050)	211 (631)	989 (839)	81 (82)	95	116	8,730	550,000	710	9,100	1,950	14.3
HE-F-E0-72,20	2298	161	1106	86	126	89	6,340	210,000	570	9,020	2,700	10.6
HE-F-E10-72,20	2279	0	1050	81	141	99	6,700	220,000	390	9,040	2,300	3.5
HE-A-E0-72,20	2392	0	1064	91	107	95	6,000	220,000	870	9,050	2,380	21.3
HE-A-E10-72,20	2328	0	1058	84	114	94	5,830	210,000	730	8,890	780	3.4
NE-F-E0 repeat	2318	330	962	69	107	101	8,000	630,000	2,450	9,910	1,720	6.1
Gasolines												
Regular (E0)	NA	NA	NA	NA	1.0	149	55	1,525	NA	NA	4,780	0.12
E10	NA	NA	NA	NA	1.5	894	47	1,307	NA	NA	10,990	0.12
Original Cold CO	NA	NA	NA	NA	0.7	74	39	1,342	NA	NA	2,520	0.00
Cold E10	NA	NA	NA	NA	0.9	83	39	1,516	NA	NA	2,610	0.09
New Cold CO (E0)	NA	NA	NA	NA	0.7	145	29	493	NA	NA	1,810	0.00

[1] Code: NE - normal emitter, HE - high emitter, F - fresh oil, A - aged oil, E0 and E10 - gasoline with 0 and 10% ethanol by volume.

[2] All oils were analyzed for elements at DRI by XRF and subset of oil samples analyzed at EAI by ICP-MS is shown in parentheses.

[3] Lubricating oil for the light-duty vehicles were blended with 7.35 g of $C_{36}D_{74}$ per quart of oil.

[4] Sums include PAH from naphthalene to coronene.

[5] High molecular weight PAH include, benzo(ghi)perylene, indeno[123-cd]pyrene and coronene.

Unlike UCM alkanes, the concentrations of hopanes and steranes in both fresh and aged oil increased after testing in both the NE and HE vehicles. The increases in concentrations were generally higher for the HE vehicle. The concentrations of the additive elements in the fresh oil increased after testing in both the NE and HE Vehicles. Vaporization and/or combustion of the lighter alkanes in the oils could account for the generally higher concentrations of hopanes and steranes in the oil samples after testing. This could also account for the higher post-test concentrations of additive element. The lower post-test concentrations of additive elements in the HE vehicle indicate deposition or other loss of these additive metals. Phosphorous concentrations were zero for most oil samples (both fresh and aged oil) from the high emitter vehicle. However, this may have been due to self-absorption of the phosphorus X-rays by elemental carbon present in the oil samples. All oil samples from the high emitter vehicle were much darker than the oils taken from the normal-emitting vehicle. This is especially remarkable given that the HE oils were subjected to far fewer repeat UDC cycles. While concentrations of Ca, Zn and Mo in the oils measured by XRF and ICP-MS were generally within 20%, the XRF values for P were consistently lower (~0.4) than measured by ICP-MS. Values for P were excluded from the LOC estimates and PM apportionments of fuel combustion and lubricating oils.

The lubricating oils used in the CLOSE light-duty vehicle tests were blended with 7.35 g of $C_{36}D_{74}$ per quart of oil, which equates to an expected concentration in the oil of about 9,000 µg of $C_{36}D_{74}$ per gram of oil. The measured concentrations were substantially lower (400 to 2,450 ppm) than expected and highly variable. Especially puzzling was that the repeat samples had $C_{36}D_{74}$ concentrations of 523 and 2,042 ppm. Assuming that no errors were made in the addition of the tracer to the oil samples, these results suggest that $C_{36}D_{74}$ was consumed at varying rates during the tests or not uniformly mixed in the oil samples when drawn for analysis several months following the emission testing sequence. In contrast, the exhaust emissions of $C_{36}D_{74}$, shown in Table 39, were more similar among the various tests for the HE vehicle, indicating that the oils were more uniformly mixed in the crankcase during testing. While the LOC estimates can be affected by variations in uniformity of the oil samples, the multiple regression results are based on emissions data and should not be affected.

TABLE 39. PARTICLE-PHASE EXHAUST EMISSION RATES (TUNNEL BLANK SUBTRACTED) OF OIL ADDITIVE AND ENGINE WEAR ELEMENTS, HOPANES AND STERANES (H&S), IDENTIFIED AND UNRESOLVED COMPLEX MIXTURE (UCM) OF ALKANES AND CYCLOALKANES, DEUTERATED HEXATRIACONTANE, PAH AND SUM OF THREE HIGH-MW PAH COLLECTED ON TEFLON-IMPREGNATED GLASS FIBER (TIGF) FILTERS

(No Statistical Analyses Were Performed On These Data)

	Lubricating Oil Additive Metals (µg/mi) [2]						Alkanes (µg/mi)					PAH (µg/mi)
Vehicle Test[1]	Ca XRF (ICP)	P XRF	Zn XRF (ICP)	Mo XRF (ICP)	Wear Metals[3] ug/mi	H&S µg/mi	Identified C_{12}-C_{19}	Identified C_{20}-C_{35}	UCM C_{20}-C_{35}	$C_{36}D_{74}$	all [4] PAH	High MW PAH [5]
NE-F-E0-72	18 (16)	6	6 (5)	0.5 (0.3)	5	0.0	2	5	6	0.0	0.4	0.0
NE-F-E0-20	89 (80)	33	37 (29)	2.3 (1.5)	24	0.3	12	2115	272	0.2	4.8	0.9
NE-F-E10-72	22 (19)	8	8 (6)	0.6 (0.4)	5	0.1	5	0	0	0.0	1.3	0.0
NE-F-E10-20	126 (110)	48	51 (39)	2.8 (1.8)	26	0.2	9	1036	192	0.0	4.7	0.7
NE-A-E0-72	31 (27)	9	10 (7)	0.9 (0.6)	4	0.1	0	0	0	0.0	1.0	0.0
NE-A-E0-20	77 (69)	25	28 (21)	2.2 (1.4)	16	0.3	42	1546	203	0.0	7.5	1.5
NE-A-E10-72	31 (27)	10	10 (7)	1.1 (0.6)	2	0.1	1	0	0	0.0	2.1	0.1
NE-A-E10-20	89 (79)	30	32 (24)	2.7 (1.5)	17	0.3	220	806	26	0.1	8.1	2.0
HE-F-E0-72	1273 (1368)	226	437 (376)	41 (36)	54	75.5	306	1723	40300	214	146	1.0
HE-F-E0-20	1164 (1418)	202	379 (365)	38 (35)	39	59.0	336	3456	38900	212	152	1.8
HE-F-E10-72	1214 (1513)	171	363 (358)	29 (27)	23	49.5	542	4977	41900	391	104	0.3
HE-F-E10-20	1181 (1392)	177	368 (355)	30 (28)	26	49.0	594	3177	40300	468	94	0.1
HE-A-E0-72	1182 (1427)	261	335 (324)	42 (39)	27	52.6	467	1603	34900	399	86	0.2
HE-A-E0-20	1294 (1468)	305	412 (361)	49 (41)	32	44.8	641	925	41600	563	137	0.6
HE-A-E10-72	1252 (1406)	318	442 (392)	49 (41)	71	35.5	432	822	32200	394	98	0.4
HE-A-E10-20	1126 (1271)	288	385 (352)	43 (37)	38	35.4	437	743	28900	410	74	0.6

[1] Code: NE - normal emitter, HE - high emitter, F - fresh oil, A - aged oil, E0 and E10 - gasoline with 0 and 10% ethanol by volume.
[2] Elements were analyzed at DRI by XRF and ICPMS (shown in parentheses).
[3] Sum of the engine wear metals (Cu, Al, and Fe by ICPMS).
[4] Sums include PAH from naphthalene to coronene.
[5] High molecular weight PAH include, benzo(ghi)perylene, indeno[123-cd]pyrene and coronene

Each of the gasoline samples contained trace amounts of hopanes and steranes that could confound the aforementioned apportionment method. The potential contributions from the fuel to exhaust emissions of hopanes and steranes ranged from 149 to 168 μg/mi, based on fuel consumed multiplied by mass fractions of hopanes and steranes in the fuel. The potential contributions from the oils, estimated from the LOC rates (using elemental tracers) times the mass fractions of hopanes and steranes in oil, are 1.1, 4.4 and 59.1 μg/mi for the NE vehicle at 72°F, NE vehicle at 20°F and HE vehicle at both temperatures, respectively. These estimates are based on an unlikely assumption that hopanes and steranes from both the fuel and oil are entirely conserved without loss in the engine or exhaust system. Most of the hopanes and steranes in the fuel are consumed in the engine along with the fuel. Hopanes and steranes would be emitted with the unburned fuel with greater amounts for fuel-rich high emitters.

Although the actual loss rates of hopanes and steranes from the fuels and oils are unknown, the CLOSE test data provide indications of their relative contributions. Compared to the potential contributions of hopanes and steranes from unburned fuels and oil, the average exhaust emission rates were 0.1, 1.0 and 53 μg/mi for the NE vehicle at 72°F, NE vehicle at 20°F and HE vehicle at both temperatures, respectively. These exhaust emission rates are similar to the potential contributions of hopanes and steranes from the oils and Figure 42 shows that the composition of individual hopanes and steranes in the oils and HE vehicle exhaust are nearly identical. Furthermore, the ratios of the elemental tracers for oil, Ca, Zn and Mo, to hopanes and steranes are the same in the oil and HE exhaust. These observations indicate that lubricating oils are likely the main contributor to exhaust emissions of hopanes and steranes for the HE vehicle. Results for the NE vehicle are less clear due to greater analytical uncertainty and potentially greater relative contribution of unrelated emissions from surface deposits in the engine and exhaust system components. For example, the ratios of the elemental tracer of oil to hopanes and steranes are about 15-20 times greater in the exhaust compared to the corresponding ratios in the lubrication oils. While comparisons of the potential contribution of the fuel (149 to 168 μg/mi) to exhaust emissions of hopanes and steranes for the NE vehicle (0.1 to 1.0 μg/mi) suggest that most hopanes and steranes are burned in the engine with the fuel, the residual amounts in unburned fuel could be significant for NE vehicles with low LOC rates. The greater analytical uncertainties associated with measurements of low emission rates, as illustrated by the greater variability in composition of individual hopanes and steranes in the NE vehicle exhaust (Figure 42), also contribute to greater uncertainty in quantifying the contributions of fuel combustion and lubricating oil to exhaust PM for NE vehicles.

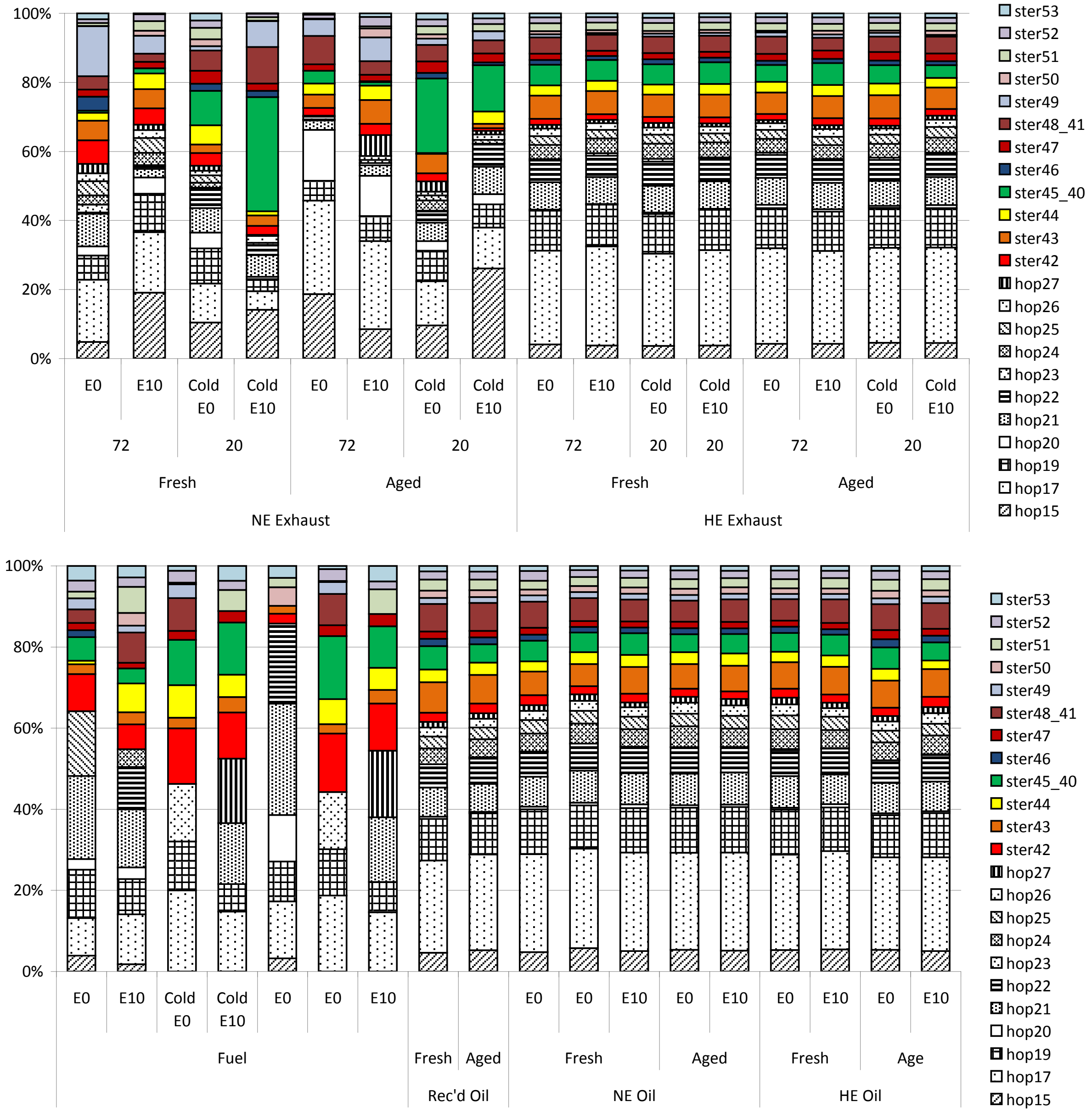

FIGURE 42. COMPOSITION OF INDIVIDUAL HOPANES AND STERANES FROM FUEL AND OIL RELATIVE TO MEASURED EXHAUST EMISSIONS RATES

Table 38 shows that fresh lubricating oils contain relatively low amounts of PAH compared to aged oils. Aged oils accumulate PAH by absorbing unburned fuel and combustion products contained in the blow-by gases. Most of the absorbed PAH from unburned gasoline are low-molecular weight PAH (e.g., naphthalene and methylnaphthalenes). Incomplete combustion of the fuel produces a variety of high molecular weight PAH (e.g., benzo(ghi)perylene, indeno[123-cd]pyrene and coronene) that are potential tracers of PM from fuel combustion. These PAH are valid tracers of fuel combustion if the contributions of the oil to exhaust emissions of the PAH are small. As with the fuel, combustion of the lubricant could also result in formation of high-molecular weight PAH resulting in underestimation of the potential contribution of lubricating oil by this method. We also estimated the potential lubricating oil contributions to the mass emission rates of benzo(ghi)perylene, indeno(1,2,3-cd)pyrene, and coronene in the exhaust PM by multiplying the mass fractions of these PAH in lubricating oils by the estimated LOC rates shown in Table 40. The oil contributions to combustion-derived PAH were small for the normal emitter due primarily to low LOC rates. The oil contributions alone equaled or exceeded the measured exhaust emission rates of high-molecular weight PAH for the high emitter resulting in overestimations of the fuel combustion contributions to PM emissions. Despite this overestimation, most of the PM emissions for the high emitter were apportioned to lubricating oil.

TABLE 40. LUBRICATING OIL CONSUMPTION RATES BASED UPON RATIOS OF THE EMISSION RATES OF ELEMENTAL TRACERS, UCM, SUM OF HOPANES AND STERANES, AND DEUTERATED HEXATRIACONTANE TO THEIR CONCENTRATIONS IN THE CORRESPONDING LUBRICATING OIL

(No Statistical Analyses Were Performed On These Data)

	LOC (mg/mi) based on following tracers						
Vehicle Test[1]	Metals[2]	Ca	Zn	Mo	H&S	$C_{36}D_{74}$	UCM
NE-F-72-E0	7.2	7.6	6.3	6.0	0.8	0.1	2.3
NE-F-72-E10	9.3	9.6	8.4	8.9	0.9	0.0	0.2
NE-F-20-E0	36.9	37.8	35.4	30.6	9.8	0.3	3.2
NE-F-20-E10	54.3	55.5	52.4	40.3	4.6	0.1	0.5
NE-A-72-E0	11.6	12.3	9.8	10.9	0.7	0.0	0.0
NE-A-72-E10	12.1	12.7	10.5	13.4	1.0	0.0	0.2
NE-A-20-E0	29.9	31.0	27.6	26.7	14.1	0.0	0.5
NE-A-20-E10	35.5	36.8	32.7	32.9	8.3	0.1	0.5
HE-F-72-E0	502	554	395	474	620	569	201
HE-F-72-E10	471	533	345	359	367	466	196
HE-F-20-E0	453	507	343	448	488	566	191
HE-F-20-E10	463	518	350	372	366	551	188
HE-A-72-E0	440	494	315	468	512	567	163
HE-A-72-E10	502	538	417	583	333	164	156
HE-A-20-E0	495	541	387	536	438	791	195
HE-A-20-E10	448	484	364	510	329	171	139

[1] Code: NE - normal emitter, HE - high emitter, F - fresh oil, A - aged oil, E0 and E10 - gasoline with 0 and 10% ethanol by volume.

[2] LOC estimates based on sum of Ca, Zn and Mo.

7.6.2 Components of Exhaust PM

Table 39 shows sums of the elemental tracers of lubricating oil and engine wear, and sums of several groups of particle-phase organic compounds (POC) collected on the TIGF filters. Data for the vehicle tests are shown in the order in which they were conducted and are averages of the two replicates for each series of tests. Oil additive elements are shown individually for Ca, P, Zn and Mo measured by XRF and by ICP-MS. The two measurements were in good agreement for the high emitter vehicle with average XRF/ICP-MS ratios and standard deviations of 0.86 ± 0.04, 1.08 ± 0.06 and 1.13 ± 0.04, for Ca, Zn and Mo, respectively. These results indicate that PM deposits on the filter samples were uniform. However, values for XRF were higher than ICP-MS by factors of 1.13±0.02, 1.32±0.04 and 1.58±0.14, for Ca, Zn and Mo, respectively for samples from the normal emitter vehicle. Engine wear metals in Table 39 are sums of Al, Cu, and Fe measured by ICP-MS. The groups of particle-phase organic compounds include: identified C_{12}-C_{19} alkanes, identified C_{20}-C_{35} alkanes (i.e., individual peaks appearing above the UCM "peak"), UCM of C_{20}-C_{35} alkanes, $C_{36}D_{74}$, sum of all quantified PAH from naphthalene to coronene, and the three high molecular weight PAH, benzo(ghi)perylene, indeno[123-cd]pyrene and coronene.

As expected, the amounts of various components of exhaust PM for the NE and HE vehicles are consistent with higher contributions of lubricating oil for the HE. The higher PM emission rates for the HE vehicle are accompanied by organic carbon/total carbon (OC/TC) ratios greater than 90%, and substantially greater emissions of oil additive elements, hopanes and steranes, UCM and $C_{36}D_{74}$ than for the NE vehicle. Based on estimates OC from UCM (by dividing UCM by 1.17 mass ratio of $C_{27}H_{56}/C_{27}$), UCM accounted for about 50% of the measured OC for all tests of the HE vehicle and 36% and 3% for the NE vehicle tested at 20°F and 72°F, respectively. NE UCM emission rates were very low with correspondingly higher uncertainties. Elemental carbon is the dominant component of total particle-phase carbon emissions for the NE, suggesting the relatively greater contribution of fuel combustion to PM emissions from the low-emitting normal emitter. The emission rates of high molecular weight PAHs were comparable for the NE and HE vehicles resulting in similar contributions of fuel combustion PM from the MLR analysis, which is consistent with similar EC emission rates.

The blank-subtracted emission rates of volatile phase of semi-volatile organic compounds collected on the backup XAD-4 cartridges are shown in Table 41 for the NE and HE test vehicles. For a few of the NE tests, subtraction of the tunnel blanks for C_{12}-C_{19} alkanes resulted in negative emission rates. PAH exhibit a wide range of volatility with naphthalene existing almost entirely in the gas phase, while five-ring and higher ring PAH are adsorbed predominantly on particles. The intermediate three- and four-ring PAH (semi-volatile PAH) are distributed between the two phases. The emissions of semi-volatile PAH for the NE vehicle exceeded particle-phase PAH by approximately two orders of magnitude and particle-phase OC by about a factor of two. The organic compound tracers of lubricating oil (hopanes and steranes, UCM and $C_{36}D_{74}$) and fuel combustion tracers (high molecular weight PAH) were all predominantly in the particle phase.

TABLE 41. VOLATILE PHASE OF SEMI-VOLATILE COMPOUNDS EXHAUST EMISSION RATES (TUNNEL BLANK SUBTRACTED) OF IDENTIFIED HOPANES AND STERANES (H&S), IDENTIFIED AND UNRESOLVED COMPLEX MIXTURE (UCM) OF ALKANES AND CYCLOALKANES, DEUTERATED HEXATRIACONTANE, PAH AND SUM OF 3 HIGH-MW PAH[1] COLLECTED ON BACKUP XAD-4 CARTRIDGES

(No Statistical Analyses Were Performed On These Data)

		Alkanes (µg/mi)				PAH (µg/mi)	
Vehicle Test[1]	H&S µg/mi	Identified C_{12}-C_{19}	Identified C_{20}-C_{35}	UCM C_{20}-C_{35}	$C_{36}D_{74}$	all[2] PAH	High MW PAH[3]
NE-F-E0-72	0.0	1	0	1228	0.0	97	0.00
NE-F-E0-20	0.7	14	0	1449	0.0	861	0.00
NE-F-E10-72	0.0	13	0	123	0.0	242	0.00
NE-F-E10-20	0.5	29	194	151	0.0	494	0.00
NE-A-E0-72	0.0	2	0	0	0.0	92	0.00
NE-A-E0-20	1.2	-60	86	70	0.0	903	0.00
NE-A-E10-72	0.0	20	0	126	0.0	283	0.00
NE-A-E10-20	0.5	-84	186	224	0.0	680	0.00
HE-F-E0-72	2.3	139	79	1531	6.6	2116	0.00
HE-F-E0-20	2.3	194	229	856	6.8	2240	0.00
HE-F-E10-72	2.3	498	333	1167	16.2	4009	0.00
HE-F-E10-20	2.7	264	198	961	14.2	2558	0.00
HE-A-E0-72	2.0	575	265	666	11.8	3163	0.00
HE-A-E0-20	1.9	218	259	1017	10.5	2378	0.00
HE-A-E10-72	2.5	451	324	960	7.7	3688	0.00
HE-A-E10-20	2.1	177	429	613	9.1	1546	0.00

[1] Code: NE - normal emitter, HE - high emitter, F - fresh oil, A - aged oil, E0 and E10 - gasoline with 0 and 10% ethanol by volume.

[2] Sums include PAH from naphthalene to coronene.

[3] High molecular weight PAH include, benzo(ghi)perylene, indeno[123-cd]pyrene and coronene.

7.6.3 Estimates of LOC from Chemical Components of Exhaust PM and Lubricating Oil

Lubricating oil consumption rates were estimated from ratios of the exhaust emission rates of oil tracers to their mass fractions in the corresponding lubricating oils assuming the following linear relationship, E_t (µg/mi) = mC_t (µg/g), where E_t is exhaust emission rate of oil tracer t in µg/mile and C_t is the concentration of oil tracer t in µg/g. The slopes, although related to the lubricating oil consumption (LOC) rate, underestimate the true LOC rate due to losses of oil by combustion oxidation of organic compounds; evaporation of volatile components of the oil; deposition on internal surfaces of the combustion chamber, exhaust system, the CVS and sample transfer lines. The use of elemental tracers yields larger LOC estimates than organic tracers because some fraction of the organic components of oil are consumed during combustion, while the elements are largely conserved and are emitted in the exhaust as ash.

The LOC rate estimates shown in Table 40 are based upon ratios of the emission rates of the four alternative oil tracers: elemental tracers, UCM, sum of hopanes and steranes, and deuterated hexatriacontane to their concentrations in the corresponding lubricating oil. The LOC rates estimated for the normal emitter were generally negligible using $C_{36}D_{74}$ (0 to 0.3 mg/mi) or UCM (0 to 3.2 mg/mi) as the oil tracers, which are reflected in the low OC emission rates (0 to 0.5 mg/mi). The range of LOC estimates were higher using hopanes and steranes (1 to 14 mg/mi) and highest using elements (7 to 55 mg/mi) as the tracer. The higher LOC estimates with elements are consistent with greater loss of the organic tracers.

LOC estimates for the HE vehicle ranged from 440 to 502 mg/mi and 329 to 620 mg/mi using metals (sum of Ca, Zn and Mo) and hopanes and steranes, respectively. LOC rate estimates using the individual metals are also shown in Table 40 for comparison. A similar range of LOC rate estimates was obtained using $C_{36}D_{74}$ for the first five of eight series of tests (466 to 569 mg/mi) and more variable for the final three series of tests (164 to 791 mg/mi). UCM as the tracer yielded consistently lower LOC estimates (139 to 201 mg/mi), which may be due to partial combustion of the UCM alkanes. However all LOC rates for the HE vehicle exceed the OC emission rates of 45-79 mg/mi (Table 35). All of the LOC estimates are much lower than the measured LOC for the high emitter of 2,560 mg/mi indicating substantial loss of the oil by deposition on surfaces of combustion chamber, exhaust system, transfer lines, and CVS or combustion in the engine and catalytic converter.

7.6.4 Estimation of Fuel-Combustion and Oil Contributions by Multiple Regression

We estimated the fuel and oil contributions to the exhaust emission rates of PM, TC and OC (mg/mi) by the multiple regressions equation, $TC = m_1x_1 + m_2x_2 + b$ (fitted through zero) using tracers for lubricating oil and gasoline combustion as was recently done by Kleeman.[22] Fuel combustion contribution is m_1x_1 where x_1 is the emission rate (mg/mi) of the sum of high molecular weight PAH, benzo(ghi)perylene, indeno[123-cd]pyrene and coronene. The oil contribution is m_2x_2 where x_2 is the emission rate (mg/mi) of the alternative oil tracer (additive elements, UCM, hopanes + steranes or $C_{36}D_{74}$). The coefficients, m_1 and m_2, are ratios of the mass emissions of PM, TC or OC per mass of fuel and oil tracers, respectively. The regressions were performed using PAH as the fuel tracer and each of the alternative oil tracers.

The summary of the multiple regressions results for TC in Table 42 shows good correlations for all oil tracers with r^2 values ranging from 0.88 to 0.99. Considering the margin of error, all of the TC emissions of the high emitter vehicle were apportioned to lubrication oil using metals, hopanes and steranes, and UCM as the oil tracer. Oil was the main source of TC emission with the $C_{36}D_{74}$ tracer, but with greater variability. Over 80 percent of the TC emissions were apportioned for the normal emitter vehicle to fuel combustion using UCM and $C_{36}D_{74}$ as oil tracers. The range in apportionments to fuel combustion from 20% to about 90% using hopanes and steranes is partially due to the higher uncertainties associated with the very low emission rates of this oil tracer from the normal emitter vehicle. Use of metals as the oil tracers resulted in apportionments of TC to mostly oil (>70%) due to the aforementioned concentration of metal in the oil with use. In addition, deposits in the engine and exhaust system may have contributed additional metals.

7.6.5 Conclusions

While the results of the CLOSE Project do not represent the entire in-use vehicle population, they demonstrate the potential use of lubricant tracer species to apportion the contributions of lubricating oils to PM emissions from light-duty gasoline-powered motor vehicles. Consistent with estimated high LOC rates, multiple linear regression results showed that nearly all of the exhaust PM from the CLOSE LD high emitter was associated with lubrication oil as expected. While the presence of elemental tracers and UCM alkanes indicates some contributions of the oil to exhaust PM for the CLOSE normal emitter, the relative fuel and oil contributions are uncertain due to low emission levels. The emissions of semi-volatile PAH for the NE vehicle exceeded particle-phase PAH by approximately two orders of magnitude and particle-phase OC by about a factor of two indicating that the NE gasoline-powered vehicles may contribute more SOA precursor than direct PM.

Noteworthy is the observation that the UCM fraction of the aged oil was substantially lower for both fresh and aged oils from tests with the HE vehicle (Table 31). These decreases in the weight fractions of UCM alkanes in the oils may be due to differential loss through volatility, conversion from oxidation or some other mechanism. The products of oil oxidization were not determined in this study. This decrease was not taken into account in the MLR analysis since end-of-test or lowest UCM content of the oil was used while the exhaust samples were collected during earlier tests with lubricating oil with varying, but likely higher UCM content. This could potentially bias the regression analysis and overestimate the lubricant allocation. The similarity in MLR results for UCM and hopanes and steranes as alternative oil tracers may very well be an artifact of the fact that only two vehicles representing two extremes are included. Additional work is needed to determine the fate of the missing UCM.

TABLE 42. LUBRICATING OIL AND FUEL COMBUSTION CONTRIBUTIONS TO TOTAL CARBON EMISSIONS BASED UPON MULTIPLE LINEAR REGRESSION USING ELEMENTAL TRACERS, UCM, SUM OF HOPANES AND STERANES, AND DEUTERATED HEXATRIACONTANE AS ALTERNATIVE TRACERS FOR OIL CONTRIBUTIONS AND HIGH-MOLECULAR WEIGHT PAH AS THE FUEL COMBUSTION TRACER

(No Statistical Analyses Were Performed On These Data)

		Fuel Combustion and Lubrication Oil Contributions to Total Carbon (mg/mi) [2]							
		Metals		**UCM C_{20}-C_{35}**		**Hopanes + Steranes**		**$C_{36}D_{74}$**	
		$R^2 = 0.97$		$R^2 = 0.99$		$R^2 = 0.99$		$R^2 = 0.88$	
Vehicle Test[1]	TC mg/mi	Fuel Combustion	Lube Oil	Fuel Combustion	Lube Oil	Fuel Combustion	Lube Oil	Fuel Combustion	Lube Oil
LD-NE-F-E0-72	0.3	0.0 ± 0.0	1.0 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0
LD-NE-F-E10-72	1.2	0.0 ± 0.1	1.3 ± 0.1	0.1 ± 0.0	0.0 ± 0.0	0.0 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	0.0 ± 0.0
LD-NE-F-E0-20	2.7	1.0 ± 2.9	5.3 ± 0.3	2.6 ± 1.3	0.5 ± 0.0	1.2 ± 2.7	0.4 ± 0.0	9.6 ± 4.1	0.0 ± 0.0
LD-NE-F-E10-20	4.2	0.8 ± 2.2	7.5 ± 0.5	2.0 ± 1.0	0.3 ± 0.0	0.9 ± 2.1	0.2 ± 0.0	7.5 ± 3.2	0.0 ± 0.0
LD-NE-A-E0-72	0.7	0.0 ± 0.0	1.7 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.1	0.0 ± 0.0
LD-NE-A-E10-72	1.5	0.1 ± 0.2	1.7 ± 0.1	0.2 ± 0.1	0.0 ± 0.0	0.1 ± 0.2	0.1 ± 0.0	0.6 ± 0.2	0.0 ± 0.0
LD-NE-A-E0-20	3.5	1.6 ± 4.7	4.4 ± 0.3	4.3 ± 2.2	0.4 ± 0.0	1.9 ± 4.5	0.4 ± 0.0	15.8 ± 6.7	0.0 ± 0.0
LD-NE-A-E10-20	3.8	2.2 ± 6.5	5.0 ± 0.3	5.9 ± 3.0	0.0 ± 0.0	2.6 ± 6.1	0.4 ± 0.0	21.7 ± 9.2	0.0 ± 0.0
LD-HE-F-E0-72	81	1.1 ± 3.3	68 ± 4	3.0 ± 1.5	70 ± 2	1.3 ± 3.2	96 ± 6	11.1 ± 4.7	31 ± 3
LD-HE-F-E10-72	64	0.4 ± 1.0	62 ± 4	1.0 ± 0.5	73 ± 2	0.4 ± 1.0	63 ± 4	3.5 ± 1.5	57 ± 6
LD-HE-F-E0-20	74	2.0 ± 5.7	62 ± 4	5.2 ± 2.6	68 ± 2	2.3 ± 5.4	75 ± 4	19.0 ± 8.1	31 ± 3
LD-HE-F-E10-20	76	0.2 ± 0.5	61 ± 4	0.4 ± 0.2	70 ± 2	0.2 ± 0.4	62 ± 4	1.6 ± 0.7	69 ± 7
LD-HE-A-E0-72	57	0.2 ± 0.6	64 ± 4	0.6 ± 0.3	61 ± 2	0.2 ± 0.6	67 ± 4	2.1 ± 0.9	59 ± 6
LD-HE-A-E10-72	53	0.5 ± 1.3	72 ± 4	1.2 ± 0.6	56 ± 2	0.5 ± 1.3	45 ± 3	4.5 ± 1.9	58 ± 6
LD-HE-A-E0-20	81	0.6 ± 1.9	72 ± 4	1.7 ± 0.9	73 ± 2	0.8 ± 1.8	57 ± 3	6.3 ± 2.7	83 ± 8
LD-HE-A-E10-20	47	0.7 ± 2.0	64 ± 4	1.8 ± 0.9	50 ± 1	0.8 ± 1.9	45 ± 3	6.5 ± 2.8	60 ± 6

[1] Code: NE - normal emitter, HE - high emitter, F - fresh oil, A - aged oil, E0 and E10 - gasoline with 0 and 10% ethanol by volume.[2] Contributions were determined by multiple linear regression, TC = $m_1x_1 + m_2x_2 + b$ (fitted through zero). Fuel combustion contribution is m_1x_1 where x_1 is the sum of high molecular weight PAH include, benzo(ghi)perylene, indeno[123-cd]pyrene and coronene. Oil contribution is m_2x_2 where x_2 is the oil tracer identified in the column headings, additive elements, UCM, hopanes + steranes, or deuterated hexatriacontane.

7.7 Light-Duty Gasoline Vehicles Major Technical Findings

Fresh and Aged oil

PM emissions nominally increased with aged oil in three of the four normal PM emitter (NE) test configurations (E10 at 20ºF), but PM nominally decreased from the high PM emitter (HE) with aged oil.

E0 and E10 Fuel

PM emissions nominally increased with E10 from the normal emitter, but no trend was apparent with the high emitter.

Low and High Particulate Matter Emitter

The high PM emitter produced much higher rates of all emissions compared to the low emitter. PM rates were 20-400 times higher from the high emitter.

Normal (72°F) and Low (20°F) Temperature

In the NE vehicle, PM emissions increased at low temperature compared to high temperature tests, as expected. In contrast, in the HE vehicle, PM nominally decreased at low temperature. The lack of PM response to temperature from the HE vehicle is an important finding relevant to modeling fleet emissions. Because high emitters contribute disproportionately, the temperature effects across a full range of moderate to high emitter vehicles should be studied to ensure accurate modeling of the fleet.

Particle Number and Size Distributions

Particle Number (PN)

- The combination of cold-start and cold ambient temperature operation resulted in the highest PN emissions from the NE.
- The NE vehicle with fresh oil emitted higher number of solid and volatile particles, compared to emissions with the aged oil. This was observed at the cold-start and the hot-start portion of the drive cycle.
- E10 resulted in higher particle emissions from the NE compared to E0, particularly at 72°F. At 20°F, there was not a consistent trend between E10 and E0.
- Over 70 percent of the number of particles emitted from the NE were solid in nature.
- The highest PN concentrations observed with the high emitter are a factor of 3000 and 30 higher than the lowest and highest concentration observed with the NE, respectively.
- Contrary to what was observed with the NE, the HE showed much higher particle number emissions with the aged oil, compared to that with the fresh oil. For the HE, there was not a difference in the PN emissions between the cold-start and the hot-start PN emissions using the fresh oil.

- The HE number emissions were dominated by volatile particles. With the fresh oil, more than 65 percent of the particles were volatile in nature. With the aged oil, the number of volatile particles represents more than 85 percent of total particle number. This trend is opposite to what was observed with the NE, where solid particle number and mass dominate total PN and PM composition.

Particle Size Distribution

- The total and solid distributions seem to exhibit a similar bimodal lognormal structure that consists of a nuclei mode <20 nm, and an accumulation mode.
- For the fresh oil, the accumulation mode peaked at about 50 nm to 60 nm and the nuclei mode peaked at 10 nm. The accumulation mode for the aged oil was lower than the fresh oil in concentration, and it was at least 20 nm smaller in diameter than that for the fresh oil. Since the accumulation mode consists mainly of solid particles, the fresh oil seems to contribute to the formation and growth by coagulation of solid particles leading to a higher concentration and a larger particle size, compared with the aged oil. Filter measurements and OC/EC were inconsistent with these findings. Filter measurements showed higher PM with the aged oil, compared to the fresh oil. However, the reader should keep in mind that the size distribution data were taken for a limited number of tests, while the PM data were based on an interval of 16 different tests spanned over 16 days.
- For the light-duty HE vehicle at 72°F, the size distributions are monomodal lognormal distributions. The accumulation mode for total particles peaks between 30 nm and 50 nm and is volatile in nature. This is different from the NE, where the accumulation mode was mainly composed of solid particles. For solid particle emissions from the HE, the distribution has a nuclei mode at 10 nm similar to that observed with the normal emitter.

LD PM Apportionment

- Consistent with estimated high LOC rates, multiple linear regression results showed that nearly all of the exhaust PM from the LD high emitter was associated with lubrication oil.
- While the presence of elemental tracers and UCM alkanes indicates some contributions of the oil to exhaust PM for the normal emitter, the relative fuel and oil contributions are uncertain due to low emission levels.
- The emissions of semi-volatile PAHs for the NE vehicle exceeded particle-phase PAHs by approximately two orders of magnitude, and particulate OC by about a factor of two, indicating that the NE gasoline-powered vehicle may contribute more secondary organic aerosol precursor than direct PM.

8.0 MEDIUM-DUTY VEHICLE TESTS

8.1 Vehicle Selection and Description

Medium-duty vehicle selection was made in collaboration with the CLOSE Project Management Team. SwRI identified potential candidate medium-duty diesel vehicles for testing and made vehicle recommendations to the Project Management Team. We then waited for technical approval prior to procuring the test vehicles.

8.1.1 Medium-Duty Vehicle Selection Criteria

SwRI used the light-duty vehicle selection criteria as guidelines for choosing the medium-duty vehicles. It was expected that the normal-emitting diesel vehicle would be 2002 model year or newer with between 30,000 and 75,000 miles on the odometer. SwRI was to rent the vehicle from a local leasing agent that had been utilized in the past to procure medium-duty diesel pickup trucks. The high-emitting diesel vehicle was to be from a model year 1996 or older and known to emit high levels of PM, have high lubrication oil consumption, and/or have visible smoke related to lubrication oil.

8.1.2 Medium-Duty Normal PM Emitter Vehicle Selection and Description

SwRI made arrangements to lease the medium-duty (MD) normal PM emitting diesel, but upon delivery of vehicle that was originally chosen for the project we found that it was a 2008 model equipped with a diesel particle filter (DPF). It was returned to the rental agency and a new search was begun for another MD diesel normal emitter.

The second medium-duty normal emitter we found, and subsequently tested, was a 2007 ¾-ton pickup truck with 6.0L V8 engine. The engine was turbo-charged, and direct injected, with exhaust gas recirculation (EGR) and an oxidation catalyst for emissions control. It was rear-wheel drive and had a 3053 lb capacity (passengers and cargo). This vehicle was delivered to us with 57,665 miles on the odometer and returned with 59,031 miles.

8.1.3 Medium-Duty High PM Emitter Vehicle Selection and Description

SwRI spent three months searching for the high PM emissions medium-duty vehicle. We searched through Craigslist, Ebay, Autotrader, and newspapers. We spoke with dealers in San Antonio and Austin, wholesale dealers, the Texas Department of Transportation, and SwRI personnel and families.

The vehicle for the medium-duty high PM emitting (HE) was chosen from solicitations sent to SwRI employees and families. It was a one-owner 1989 ¾-ton pickup truck with a 7.3L V8 engine. The engine was naturally aspirated, with indirect fuel injection, and a 5-speed manual transmission. This engine had just less than 500,000 miles of operation and was all factory original under the valve covers. Nothing had been replaced in the long block of the engine. The fuel injector pump was replaced at about the 465,000 mile point. Oil consumption was around 1/2 gallon (difference between full and add mark on the dip stick) per 3,000 miles. Most of this was consumed by the engine. There were some oil leaks, but they were not dripping to the ground when the engine was parked.

Since the medium-duty high emitter had a standard transmission, the speed trace the driver follows for the UDC test cycle had to be augmented with transmission shift points for test repeatability purposes. The medium-duty high particulate emitter (MD-HE) was first driven on the road to find the transmission shift points associated with vehicle speed. We found that first gear is an ultra-low gear for use only during high-load low-speed operation. We decided not to use first gear during the emission test cycle. Transmission shift points were then added to the UDC trace based on acceleration requirements and vehicle speed, plus observation of the upcoming vehicle speeds in the UDC. We practiced the UDC and made notes on appropriate shift points which were then added to the driver's trace. We then repeatedly practiced the trace and made adjustments to the shift points as needed for smooth vehicle operation. We found that the fourth gear synchronizers in the transmission were non-operative. We had to double clutch each shift into 4th gear during the tests.

During practice tests, the left rear brake began to emit smoke. We removed the brake drum for inspection and replaced the brake pads, after which no further problems were experienced. Also, during initial practice operation the HE vehicle was found to be leaking hydraulic fluid from the power steering system, and leaking fuel from the fuel filter. Parts were ordered and repairs made to the power steering system and fuel filter to fix the leaks before emissions testing began.

8.1.4 Gaseous and PM Emissions Check-Out Tests

To assess the vehicle's test repeatability, triplicate check-out tests of the medium-duty normal-emitting vehicle were performed with commercial Texas diesel fuel (TxLED), and as received lubricant. Each test consisted of a cold and hot start UDC performed after two initial preparatory tests and an overnight soak. Table 43 shows a summary of the results of these check-out tests. The vehicle's emissions and fuel economy stability were good with the highest coefficient of variation calculated for particulate at 4.7 percent. Based on these results, the vehicle was approved for testing.

TABLE 43. CHECK-OUT TEST RESULTS FROM THE MEDIUM-DUTY NORMAL PM EMITTING VEHICLE EMISSIONS AND FUEL ECONOMY REPEATABILITY TESTS

	Test 1	Test 2	Test 3	Average	Standard Deviation	Coefficient of Variation
HC, g/mile	0.416	0.418	0.440	0.425	0.013	3.1%
CO, g/mile	1.484	1.535	1.572	1.530	0.044	2.9%
NOx, g/mile	4.075	4.049	4.098	4.074	0.025	0.6%
PM, mg/mile	114.3	104.2	108.4	109.0	5.1	4.7%
Fuel Economy, mpg	13.48	13.27	13.56	13.44	0.15	1.1%

Note: These pre-check tests used different fuel than “for record” tests. These tests are not part of the particle characterization tests. Tests were performed at a nominal 72°F, with commercial fuel and lubricant as received.

Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

Once the vehicle’s repairs were completed and the driver’s trace had been augmented with the shift schedule, emissions repeatability check out tests were performed with the candidate MD-HE diesel vehicle. Results of the emissions repeatability tests are shown in Table 44. These results were sent to the CLOSE participants with the recommendation that we utilize it for the project. SwRI received approval to proceed with testing this MD-HE vehicle from the CLOSE Project technical team.

TABLE 44. CHECK-OUT TEST RESULTS FROM THE MEDIUM-DUTY HIGH PM EMITTING VEHICLE EMISSIONS AND FUEL ECONOMY REPEATABILITY TESTS

	MD-HE-F-D-REP-2	MD-HE-F-D-REP-5	MD-HE-F-D-REP-6	Average	Standard Deviation	Coefficient of Variation
HC, g/mile	0.180	0.164	0.142	0.162	0.019	11.8%
CO, g/mile	1.264	1.281	1.278	1.274	0.009	0.7%
NOx, g/mile	7.429	7.826	7.582	7.612	0.200	2.6%
PM, mg/mile	464.2	574.8	386.9	475.3	94.4	19.9%
Fuel Economy, mpg	15.84	15.72	15.7	15.75	0.08	0.5%

Note: These check-out tests used different fuel than the “for record” tests. These tests are not part of the particle characterization tests. Tests were performed at a nominal 72°F, with commercial fuel and lubricant as received.

Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

8.2 Lubricants

The medium-duty vehicles were tested with both fresh and aged lubricants. A description and the supplier’s analyses of the lubricants are included in Section 5.1 in Tables 3 and 5. The drain and fill and the lubricant’s initial degreening procedure is also described in Section 5.1. Oil samples include the fresh and aged oils as received, and samples taken after the cold (20°F) tests with fresh and aged oils on diesel and B20 for both the normal and high emitter. For example, the normal emitter was operated over multiple emission tests with fresh oil and a sample was taken from the crankcase drain oil after the cold tests on diesel, and then the normal emitter was operated over multiple emissions tests with fresh oil on B20 and a sample was taken from the crankcase drain oil after the cold tests. Thus four oil samples were taken from the normal-emitter (two fuel types and two oils), and four oil samples were taken from the high emitter.

8.3 Fuels

The medium-duty vehicles were operated from test fuel installed in the on-board tanks. Test fuels are described in Section 5.2.2 in Table 11. Fuel systems on all vehicles were flushed with the test fuels prior to the initiation of testing. The fuel flush procedure used for the medium-duty vehicles was the same one used for light-duty vehicles, as described in Section 7.3.

8.4 Emission Test Procedures

This is a pilot study of exhaust emissions effects from the use of different fuels and lubricants with some tests conducted at different temperatures. It is important to note that the scope of work in this study is limited to short-term effects on emissions when a fuel or lubricant was changed. The fuels and lubricants used in this study could have long-term effects on emissions which were not measured.

8.4.1 Driving Cycle

Medium-duty vehicles were also tested over replicate cold-start Unified Driving Cycles (UDC). Thus, only one UDC per day was run. The UDC was conducted as a cold-start, four-phase test, in a manner similar to the light-duty Federal Test Procedure. The UDC consisted of a 300-second cold-start phase (Bag 1) followed by an 1,135-second hot stabilized phase (Bag 2), a 10-minute soak, and a hot-start phase (Bag 3) which is a repeat of the 300-second Bag 1, and a 1,135-second hot stabilized phase (Bag 4) which is a repeat of Bag 2. For all emission tests, the vehicles were soaked for at least 12 hours at test temperature prior to emissions evaluations.

Both medium-duty vehicles were tested in SwRI's Temperature Controlled Emissions Enclosure (TCEE), and exhaust samples were collected and analyzed in the same manner as for the light-duty gasoline vehicles. Sampling utilized an 18-inch diameter by 16-foot long stainless steel dilution tunnel and constant volume sampler. Tunnel cleaning and conditioning was conducted in the same manner as for the light-duty vehicles. A summary of the test matrix, tunnel blank and background sampling schedule, and tunnel cleaning and conditioning events are shown in the test matrix in Table 1.

Based on previous testing of ¾- and 1-ton diesel pickup trucks over both the FTP-75 and the UDC, SwRI expected that a single cold-start test cycle would be needed to collect sufficient sample mass for chemical analyses, and this was found to be correct. Thus, a total of 16 UDCs were conducted with each vehicle (1 UDC per sample × 2 oils × 2 fuels × 2 temperatures × 2 replicate samples).

Based on previous experience measuring vehicle PM exhaust emissions during programs conducted for NREL and CRC, it is possible for initial PM emission rates to be higher than those measured after a number of replicate tests. It was thought that the PM deposition mechanism in the vehicles' exhaust systems may not have a chance to reach equilibrium during a standard vehicle preconditioning procedure. This effect could have a major impact on the results of this study; therefore, to minimize this effect SwRI performed a conditioning sequence of UDC runs with each vehicle prior to sample collection. This conditioning was conducted in conjunction with tunnel and sample system conditioning.

8.4.2 Chassis Dynamometer

For medium-duty vehicles, a Clayton Model ECE-50 passenger car dynamometer with direct-drive variable inertia flywheel systems was used for testing. The inertia system on this dynamometer can simulate vehicle weights from 1,000 (lb-) up to 7,250 lb in 250-lb increments. The chassis dynamometer is located in the SwRI-built TCEE.

8.5 Emission Test Results

8.5.1 Regulated Gaseous and PM Mass Emissions

8.5.1.1 Medium-Duty Normal PM Emissions Vehicle

Composite filters were used during each test to capture PM during all four phases of the cold/hot UDCs. These composite filters were used for subsequent analyses at Desert Research Institute (DRI). During the initial check-out tests of the MD normal emitter, it was found that sufficient PM mass for subsequent analyses was captured on the composite filters during a single cold/hot UDC. Therefore, only two cold/hot UDCs were performed in each fuel, temperature, and oil test configuration to capture PM for later characterization. However, a third test was performed in order to complete three tests for particle number and size distribution.

Following approval of the vehicle for testing, it was then flushed with project test fuel (TxLED diesel), the engine was flushed with fresh lubricant with tracer, and the vehicle was driven for 150 miles on-road in order to perform an initial shear of the oil. The vehicle was then tested at nominal ambient temperatures of 72°F and 20°F. Summaries of the average results of tests of the medium-duty normal emitter are shown in Tables 45 and 46, respectively.

TABLE 45. MEDIUM-DUTY NORMAL PM EMITTING VEHICLE AT 72°F (No Statistical Analyses Were Performed On These Data)

	72°F -- Average of Duplicate Tests											
	TxLED Diesel						B20					
	Fresh Oil			Aged Oil			Fresh Oil			Aged Oil		
	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation
HC, g/mile	0.402	0.018	4.6%	0.398	0.021	5.3%	0.381	0.027	7.1%	0.375	0.007	1.9%
CO, g/mile	1.503	0.038	2.5%	1.567	0.064	4.1%	1.416	0.062	4.4%	1.354	0.050	3.7%
NOx, g/mile	4.267	0.235	5.5%	4.347	0.240	5.5%	4.674	0.131	2.8%	4.400	0.049	1.1%
PM, mg/mile	112.5	13.5	12.0%	110.7	5.2	4.7%	96.4	1.41	1.5%	88.0	0.8	0.9%
Fuel Economy, mpg	13.04	0.50	3.8%	13.56	0.01	0.1%	12.86	0.14	1.1%	13.80	0.50	3.6%

[a] PM as determined from phase-by-phase filter samples collected during each test.
Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

TABLE 46. MEDIUM-DUTY NORMAL PM EMITTING VEHICLE AT 20°F (No Statistical Analyses Were Performed On These Data)

	20°F -- Average of Duplicate Tests											
	TxLED Diesel						B20					
	Fresh Oil			Aged Oil			Fresh Oil			Aged Oil		
	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation
HC, g/mile	0.507	0.030	6.0%	0.484	0.011	2.2%	0.499	0.001	0.3%	0.542	0.027	5.0%
CO, g/mile	2.111	0.015	0.7%	2.103	0.085	4.0%	2.022	0.004	0.2%	2.085	0.099	4.7%
NOx, g/mile	6.780	0.115	1.7%	6.283	0.402	6.4%	6.479	0.582	9.0%	6.091	0.002	0.0%
PM, mg/mile	169.4	15.6	9.2%	123.9	1.0	0.8%	129.8	5.3	4.1%	124.5	12.6	10.2%
Fuel Economy, mpg	11.97	0.00	0.0%	12.89	0.12	0.9%	12.12	0.36	3.0%	12.68	0.24	1.9%

[a] PM as determined from phase-by-phase filter samples collected during each test.
These tests are not part of the particle characterization tests.
Tests were performed at a nominal 72°F, with commercial fuel and lubricant as received.
Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

Composite filters were used during each test to capture PM during all four phases of the cold/hot UDCs and were then used in subsequent analyses at Desert Research Institute (DRI). These composite filters were compared to the phase-by-phase results shown in the summary tables after every test. To illustrate how the composite filters' PM emission rates compare to the phase-by-phase filters' rates, Table 47 shows the PM emission rates measured phase-by-phase and those collected as composites during all phases. All filters used to collect PM in Table 47 are 47mm in diameter. The phase-by-phase and Teflon SwRI filters are of Teflon media with an outer polypropylene support ring. The Teflon DRI filters are Teflon media, and the Glass DRI filters are glass fiber filters. For comparison purposes, the data in Table 47 were graphed and are shown in Figure 43, which shows that the PM emission rates calculated with the various filter media were comparable to each other. The phase-by-phase and SwRI Teflon filters were similar media and measured similar PM rates. The glass DRI and the Teflon DRI filters typically measured nominally higher and lower than the SwRI filters, respectively.

TABLE 47. SUMMARY OF PHASE-BY-PHASE AND COMPOSITE PM EMISSION RATES FROM THE MEDIUM-DUTY NORMAL EMITTING VEHICLE

(No Statistical Analyses Were Performed On These Data)

PM Composite Results, mg/mile				
Test Number	**Phase-By-Phase**	**Teflon SwRI**	**Glass DRI**	**Teflon DRI**
MD-NE-F-D-72-1	282.0 [a]	117.6	108.3 [b]	102.5 [b]
MD-NE-F-D-72-2	99.2	99.3		
MD-NE-F-D-72-3	126.1	117.2	120.9	NA [c]
MD-NE-F-D-72-4	112.3	111.1	114.9	105.7
MD-NE-F-D-20-1	180.4	187.7	195.7	190.0
MD-NE-F-D-20-2	158.3	157.7	165.1	149.6
MD-NE-F-B20-72-1	97.4	93.3	94.1	88.1
MD-NE-F-B20-72-2	95.4	93.4	95.9	85.1
MD-NE-F-B20-20-1	126.0	124.2	128.1	118.7
MD-NE-F-B20-20-2	133.5	133.0	137.4	126.8
MD-NE-A-D-72-1	107.0	104.1	106.1	96.7
MD-NE-A-D-72-2	114.3	110.8	113.8	104.2
MD-NE-A-D-20-2	123.2	123.1	128.0	116.1
MD-NE-A-D-20-3	124.6	123.1	129.5	118.3
MD-NE-A-B20-72-3	87.4	94.4	95.4	101.8
MD-NE-A-B20-72-5	88.5	86.0	88.3	87.4
MD-NE-A-B20-20-2	137.7	140.4	143.8	133.1
MD-NE-A-B20-20-3	123.3	126.9	129.4	119.3

[a] Test MD-NE-F-D-72-1 Phase 1 PM mass was extremely high.
[b] These filters were composited over two cold/hot UDCs. (MD-NE-F-D-72-1 and MD-NE-F-D-72-2).
[c] The filter sampling system failed to start during the cold/hot UDC.

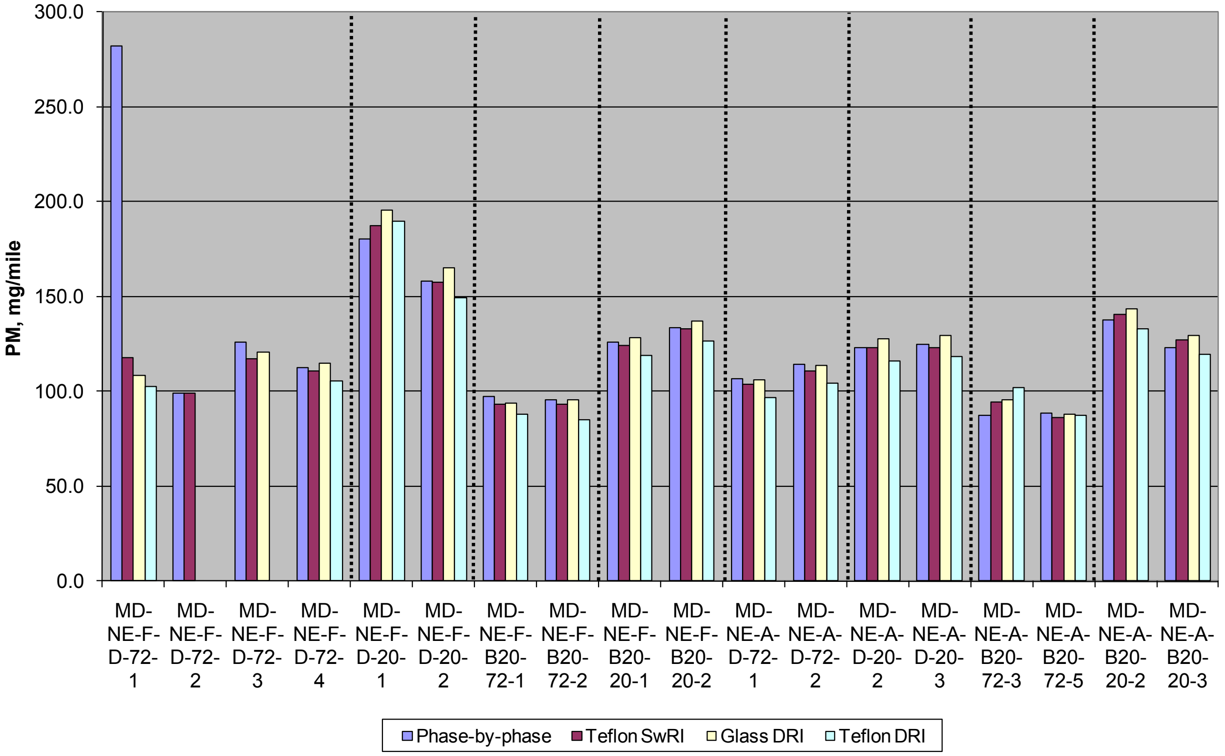

FIGURE 43. MEDIUM-DUTY NORMAL EMITTER PHASE-BY-PHASE COMPOSITE FILTERS COMPARISON
(No Statistical Analyses Were Performed On These Data)

8.5.1.2 Medium-Duty High PM Emissions Vehicle

Regulated gaseous and particle-phase emission rates along with fuel economy data from the medium-duty high PM emitter tests are shown in Tables 48 and 49 at room temperature and 20°F, respectively. Both Tables 48 and 49 include results from the tests using TxLED diesel and B20 diesel with fresh and aged oils.

TABLE 48. MEDIUM-DUTY HIGH PM EMITTING VEHICLE AT 72°F
(No Statistical Analyses Were Performed On These Data)

	72°F -- Average of Duplicate Tests											
	TxLED Diesel						B20					
	Fresh Oil			Aged Oil			Fresh Oil			Aged Oil		
	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation
HC, g/mile	0.195	0.008	4.4%	0.126	0.004	2.8%	0.131	0.004	2.7%	0.159	0.020	12.5%
CO, g/mile	1.253	0.049	3.9%	1.291	0.018	1.4%	1.219	0.003	0.2%	1.323	0.002	0.2%
NOx, g/mile	6.262	0.023	0.4%	7.672	0.134	1.8%	7.560	0.165	2.2%	6.387	0.108	1.7%
PM, mg/mile	408.4	13.2	3.2%	486.5	12.4	2.6%	446.2	10.4	2.3%	500.3	14.1	2.8%
Fuel Economy, mpg	15.83	0.35	2.2%	16.64	0.05	0.3%	16.46	0.40	2.4%	16.77	0.19	1.1%

[a] PM as determined from phase-by-phase filter samples collected during each test.

Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

TABLE 49. MEDIUM-DUTY HIGH PM EMITTING VEHICLE AT 20°F
(No Statistical Analyses Were Performed On These Data)

	20°F -- Average of Duplicate Tests											
	TxLED Diesel						**B20**					
	Fresh Oil			**Aged Oil**			**Fresh Oil**			**Aged Oil**		
	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation
HC, g/mile	0.419	0.040	9.5%	0.305	0.044	14.4%	0.392	0.018	4.5%	0.389	0.018	4.6%
CO, g/mile	1.791	0.189	10.5%	1.904	0.128	6.7%	1.925	0.163	8.4%	2.039	0.149	7.3%
NOx, g/mile	6.105	0.002	0.0%	7.741	0.173	2.2%	7.776	0.042	0.5%	7.509	0.230	3.1%
PM, mg/mile	331.3	7.1	2.2%	351.9	27.0	7.7%	408.2	6.2	1.5%	429.2	31.6	7.4%
Fuel Economy, mpg	15.38	0.10	0.6%	15.57	0.03	0.2%	15.92	0.11	0.7%	15.28	0.49	3.2%

[a] PM as determined from phase-by-phase filter samples collected during each test.

Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

8.5.1.3 Discussion of Regulated Emissions Results

Figure 44 presents the average hydrocarbon emissions from all the medium-duty vehicle tests. The normal PM emitter produced more hydrocarbon emissions than the high PM emitter in all configurations. The high PM emitter probably has more advanced fuel injection timing than the normal emitter which would have promoted more complete combustion of fuel. Hydrocarbon emissions increased in all configurations when either medium-duty vehicle was tested cold (20°F). Average rates of HC emissions were nominally lower with B20 fuel in the normal PM emitter from 72°F temperature tests, but no trend is evident due to the fuel change from cold test results. From the high PM emitter, HC emissions show no trends at any test temperature when comparing diesel to B20 fuel. There are no apparent trends in HC emissions from either vehicle when comparing average HC emissions from fresh and aged oil tests.

Figure 45 presents the average carbon monoxide emissions from all the medium-duty vehicle tests. The normal PM emitter produced more CO emissions than the high PM emitter in most configurations; the exception being aged oil tests on B20 fuel. With both fuels, CO emissions increased nominally in all configurations when either medium-duty vehicle was tested cold. Average rates of CO emissions were nominally lower with B20 fuel in the normal PM emitter from all tests except cold, aged oil tests. CO emissions from the high emitter show no trends at room temperatures when comparing diesel to B20 fuel. There are no apparent trends in CO emissions from the normal emitter when lubricant was changed from fresh to aged oils.

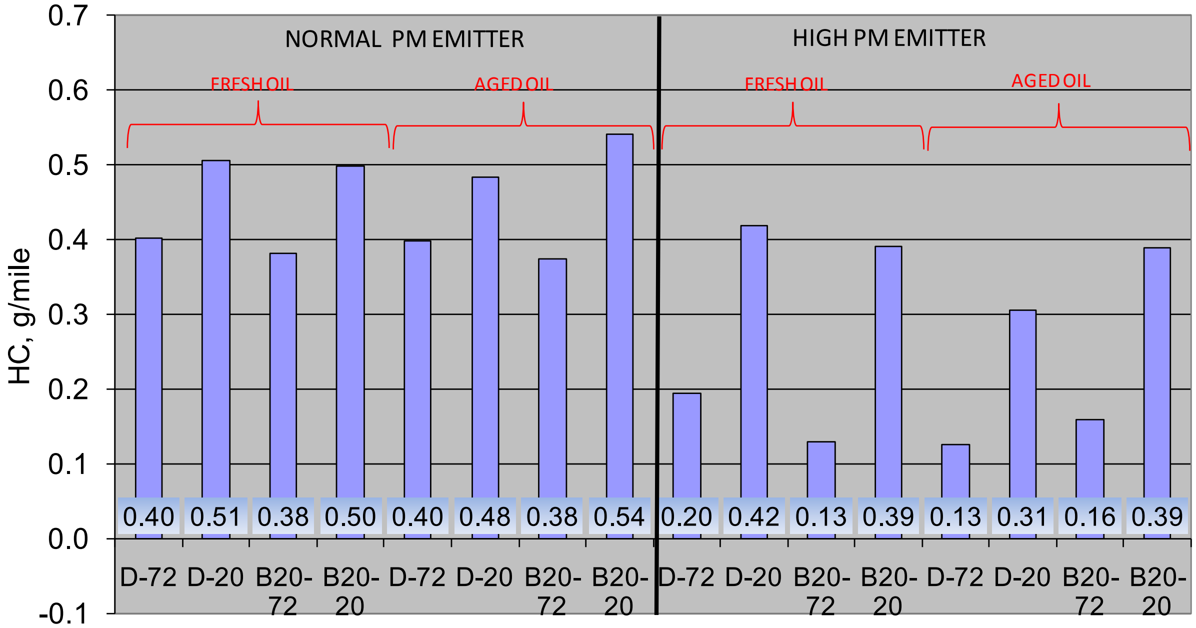

FIGURE 44. MEDIUM-DUTY VEHICLES' AVERAGE HYDROCARBON EMISSION RATES
(No Statistical Analyses Were Performed On These Data)

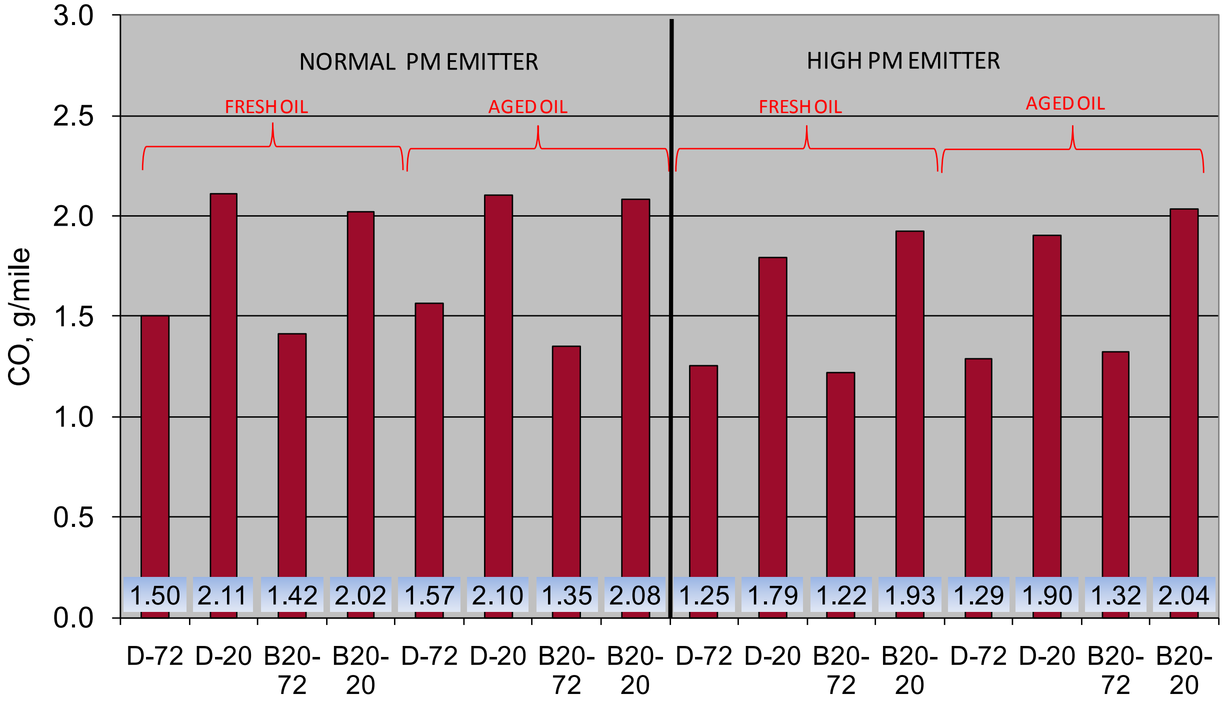

FIGURE 45. MEDIUM-DUTY VEHICLES' AVERAGE CARBON MONOXIDE EMISSION RATES
(No Statistical Analyses Were Performed On These Data)

Figure 46 presents the average oxides of nitrogen emissions from all the medium-duty vehicle tests. The normal PM emitter produced less NO_X emissions than the high PM emitter in all but one configuration (cold tests with fresh oil on diesel fuel). Again, earlier fuel injection timing may have caused higher NO_X emissions from the medium-duty high PM emitter. Overall, NO_X emissions increased nominally in all cold (20°F) tests of the normal PM emitter, but did not generally increase in the high PM emitter. There are no apparent trends in average rates of NO_X emissions when we switched to B20 fuel in the normal PM emitter. From the high PM emitter, NO_X emissions nominally increased with B20 fuel on fresh oil, but nominally decreased with B20 fuels on aged oil. There are no apparent trends in emission rates from the high emitter when comparing average NO_X emissions from fresh and aged oil tests.

Figure 47 presents the average fuel economies measured in all the medium-duty vehicle tests. Fuel economy from the high PM emitter was better in all test configurations. Again, earlier fuel injection timing may have produced better fuel economy with the medium-duty high PM emitter. Fuel economy nominally decreased in all cold temperature tests. There are no consistent trends in fuel economy when fuel was changed from diesel to B20 with either vehicle.

Figure 48 presents the average PM emissions from all medium-duty vehicle tests. The high PM emitter produced higher PM rates in all configurations compared to the normal PM emitter. PM rates nominally increased in all cold (20°F) tests of the normal PM emitter, but decreased in all cold tests of the high PM emitter. We expect the PM from the high emitter to come primarily from the lubricant and, even though the engine comes up to a normal operating temperature, during the 20°F tests the lubricant remains cooler longer than during the 72°F tests. The cooler lubricant’s higher viscosity may reduce its flow into the combustion chamber whether from leaking intake valve guides or the piston’s oil control rings. This would reduce the PM rates during the cold tests. It is also possible that lubricants emitted during the cold tests coat and stay in the vehicle’s cold exhaust system. The nominal reduction of PM emissions during cold emission tests was also noted in the light-duty high emitter tests. With the normal emitter, in all tests but one (the normal emitter on aged oil during cold tests), the switch to B20 fuel nominally reduced the rate of PM emissions. Conversely, with the high PM emitter, the switch from diesel to B20 fuel nominally increased PM emissions.

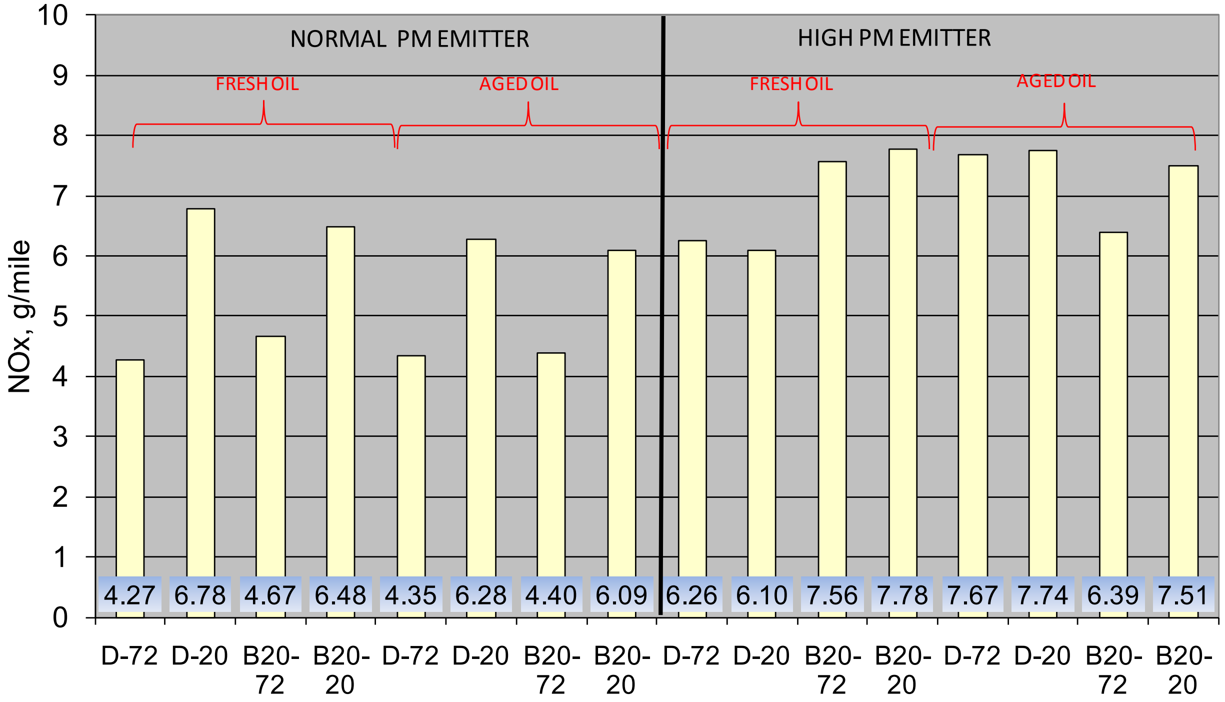

FIGURE 46. MEDIUM-DUTY VEHICLES' AVERAGE OXIDES OF NITROGEN EMISSION RATES
(No Statistical Analyses Were Performed On These Data)

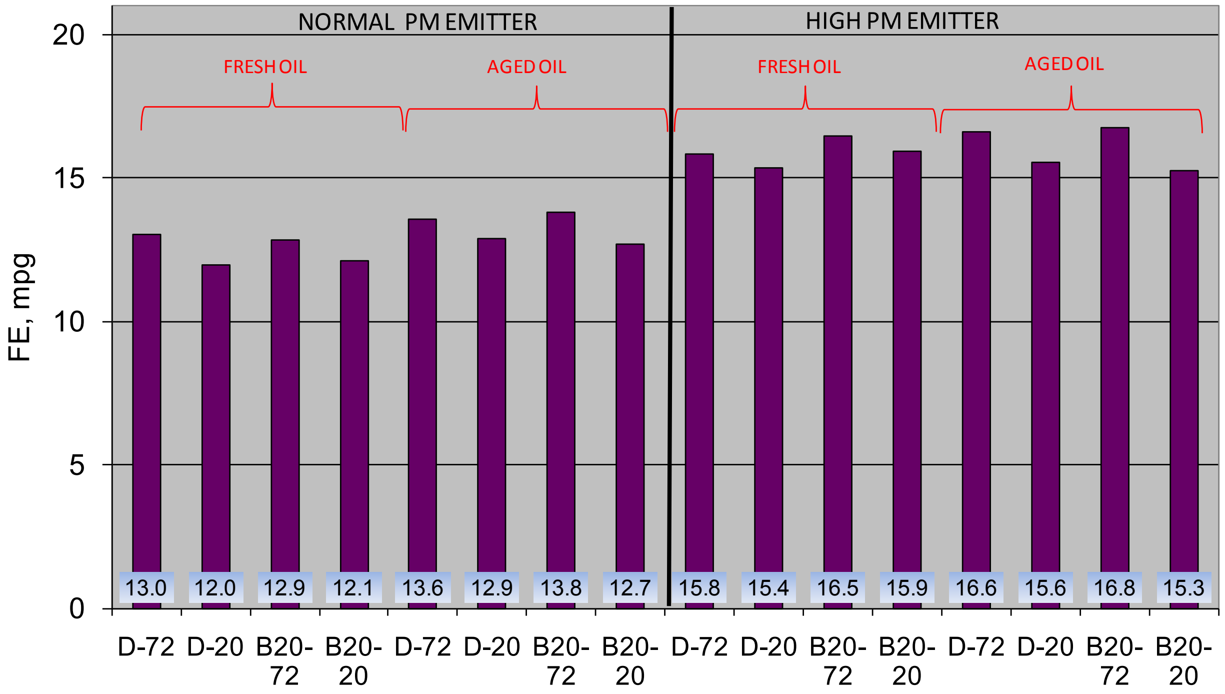

FIGURE 47. MEDIUM-DUTY VEHICLES' AVERAGE FUEL ECONOMY
(No Statistical Analyses Were Performed On These Data)

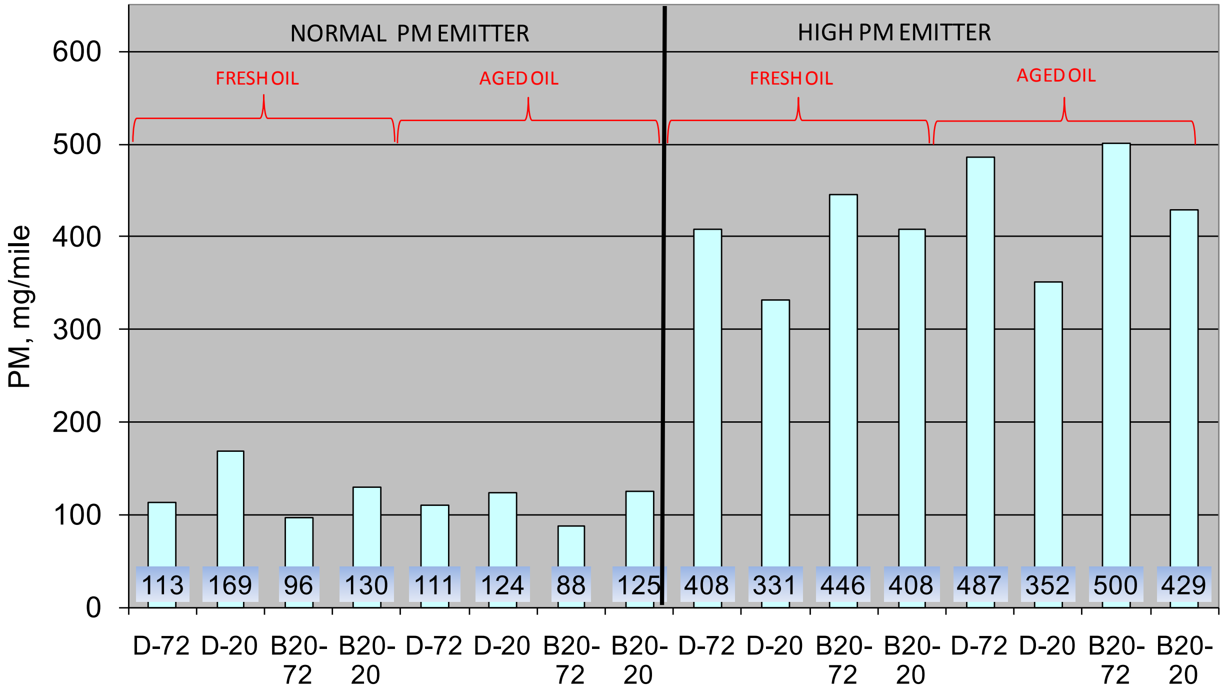

FIGURE 48. MEDIUM-DUTY VEHICLES' AVERAGE PARTICULATE MATTER EMISSION RATES (No Statistical Analyses Were Performed On These Data)

8.5.2 PM and SVOC Analyses

Exhaust particles were characterized by analyzing them for elements, semi-volatile organic compounds (SVOC), elemental and organic compounds (EC/OC), sulfates, and soluble organic fraction (SOF) at DRI. In the following PM characterization subsections, Tables 50 through 62 present the results of these PM characterizations. Data shown in Tables 50 through 62 are the averages of the replicate tests performed in each configuration.

The spreadsheet of light-duty PM analyses results which was devised by Dr. Fujita to investigate the light-duty PM characterization results was used as a template for the medium-duty PM characterization results. The spreadsheet includes the results from the individual tests, and is posted at an ftp site at SwRI for project participants. Dr. Lawrence Smith of SwRI collaborated with Dr. Fujita for the medium-duty vehicle PM apportionment analysis. They used the spreadsheet data to identify elements and compounds of interest in the apportionment study presented in Section 8.6.

8.5.2.1 X-Ray Fluorescence (XRF)

Particles sampled from the medium-duty tests were analyzed by DRI for elements by XRF. Table 50 shows the average results in μg/mile of the replicate tests performed in each configuration. The configurations are identified in the top rows of the table, and elements measured are shown in the left column. Table 51 shows the results of fuels and lubricants analysis for elements by XRF.

8.5.2.2 Inductively Coupled Plasma Mass Spectrometry (ICP-MS) Analysis

PM sampled from the medium-duty tests were analyzed by DRI for eighteen elements by ICP-MS. Table 52 shows the average results in μg/mile of the replicate tests performed in each configuration. The configurations are identified in the top rows of the table, and elements measured are shown in the left column. Table 53 shows the results of fuels and lubricants analysis for elements by ICP-MS.

8.5.2.3 Polycyclic Aromatic Hydrocarbons

Exhaust particles sampled from the medium-duty tests were analyzed by DRI for polycyclic aromatic hydrocarbons (PAH). Table 54 shows the average results in μg/mile of the replicate tests performed in each configuration. Table 28 shows the codes for the PAH species in Tables 54 and 55. Table 55 shows the results of fuels and lubricants analysis for PAHs.

8.5.2.4 Alkanes

PM sampled from the medium-duty tests were analyzed by DRI for alkanes. Table 56 shows the average results in μg/mile of the replicate tests performed in each configuration. Table 30 shows the codes for the alkane species in Tables 56 and 57.

Table 57 shows the results of alkane analyses of the fuels and lubricants from the medium-duty vehicles. The first eight columns identified by a test number are lubricant analyses from samples taken after the test in that configurations were completed. The last two columns show results of the medium-duty fuel analyses for alkanes.

8.5.2.5 Hopanes and Steranes

PM sampled from the medium-duty tests were also analyzed by DRI for hopanes and steranes. Table 58 shows the average results in μg/mile of the replicate tests performed in each configuration. Table 33 shows the codes for the hopanes and steranes species in Tables 58 and 59. Table 59 shows the results of fuels and lubricants analysis for hopanes and steranes. The high hopane levels for the MD-NE-A-B20 lubricant were noted and appear to be anomalous. Nevertheless these data were included in the average of total hopanes and steranes in the lubricants, and their average was used in the apportionment analysis in Section 8.6.5.

TABLE 50. AVERAGE RESULTS OF MEDIUM-DUTY VEHICLE PM ELEMENTAL ANALYSIS BY XRF, μG/MI
(No Statistical Analyses Were Performed On These Data)

Test Number	MD-NE-F-D-72	MD-NE-F-D-20	MD-NE-F-B20-72	MD-NE-F-B20-20	MD-NE-A-D-72	MD-NE-A-D-20	MD-NE-A-B20-72	MD-NE-A-B20-20	MD-HE-F-D-72	MD-HE-F-D-20	MD-HE-F-B20-72	MD-HE-F-B20-20	MD-HE-A-D-72	MD-HE-A-D-20	MD-HE-A-B20-72	MD-HE-A-B20-20
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20
Temp, °F	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Na	40.24	84.03	128.20	40.91	111.24	57.00	59.05	34.43	0.00	101.49	60.92	100.23	0.00	68.61	1.72	279.91
Mg	0.00	1.04	8.22	3.16	14.48	15.95	5.96	9.36	0.00	0.00	0.00	0.00	0.00	0.95	0.00	0.00
Al	9.28	5.73	0.29	1.43	14.15	9.98	2.70	0.00	0.00	0.00	0.00	9.24	0.00	0.00	0.00	6.93
Si	38.54	119.81	14.70	38.91	21.23	37.54	133.87	16.95	1.24	12.45	17.21	12.48	27.18	26.42	9.17	5.71
P	56.05	297.67	42.16	122.13	26.24	87.11	24.74	79.59	351.80	484.36	364.22	477.72	349.90	436.36	360.32	549.83
S	203.19	980.02	86.35	363.76	81.82	277.93	102.48	209.49	325.65	471.44	251.57	422.59	364.32	516.62	4.03	221.17
Cl	17.75	14.72	3.11	5.23	2.43	2.82	12.67	1.64	40.38	35.04	31.60	39.63	32.12	29.43	68.91	79.08
K	8.96	21.89	3.48	10.86	2.12	7.18	19.52	4.21	9.95	9.27	9.86	12.58	10.53	11.24	7.04	12.82
Ca	199.23	909.66	107.67	342.39	76.37	263.44	86.72	225.39	612.38	831.66	606.09	792.17	745.83	885.59	815.68	1181.70
Sc	0.00	0.00	0.00	0.64	0.00	0.00	0.67	0.18	5.76	20.13	11.01	4.85	36.06	46.17	25.64	13.88
Ti	1.62	4.14	0.02	2.21	0.12	0.95	1.67	0.00	1.69	1.26	1.26	1.68	3.35	0.02	4.78	6.90
Va	0.15	0.47	0.00	0.43	0.12	0.30	0.00	0.00	0.18	0.00	0.00	0.61	0.00	0.00	0.00	0.26
Cr	20.76	83.97	5.20	20.62	4.69	16.03	10.51	9.84	6.18	6.16	6.50	9.85	5.75	4.58	12.34	9.89
Mn	15.92	30.44	1.81	10.90	2.27	10.63	36.78	2.55	10.81	8.80	6.45	11.92	3.30	7.33	2.59	21.80
Fe	621.42	2616.38	176.45	803.78	182.33	590.56	307.71	322.69	241.94	532.90	359.00	396.00	193.01	314.58	1305.59	1690.75
Co	0.00	0.00	0.13	0.00	0.24	0.00	0.00	0.00	0.00	0.00	0.81	1.04	0.84	0.78	0.00	0.00
Ni	6.56	20.46	1.30	6.63	1.25	5.43	5.23	2.36	3.63	5.22	1.98	6.56	2.91	4.94	23.48	21.38
Cu	9.11	23.43	4.39	10.38	3.68	10.48	7.41	10.20	6.39	10.56	18.97	29.39	8.06	13.77	38.35	58.87
Zn	125.02	437.39	84.54	192.36	49.16	130.88	56.69	135.97	418.46	630.55	408.72	542.59	442.58	512.92	469.33	824.84
Ga	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.89	0.00	0.00	0.00	0.00	0.00	0.00	0.05
As	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.28	0.00	0.00	0.00	0.00	10.79
Se	0.00	0.00	0.00	0.05	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Br	0.35	0.65	0.34	1.17	0.26	1.00	1.24	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Rb	0.00	1.28	0.22	0.09	0.00	0.00	0.32	0.40	0.66	0.00	0.48	0.03	1.27	0.54	0.00	1.04

TABLE 50 (CONT'D). AVERAGE RESULTS OF MEDIUM-DUTY VEHICLE PM ELEMENTAL ANALYSIS BY XRF, µg/mi
(No Statistical Analyses Were Performed On These Data)

TEST NUMBER	MD-NE-F-D-72	MD-NE-F-D-20	MD-NE-F-B20-72	MD-NE-F-B20-20	MD-NE-A-D-72	MD-NE-A-D-20	MD-NE-A-B20-72	MD-NE-A-B20-20	MD-HE-F-D-72	MD-HE-F-D-20	MD-HE-F-B20-72	MD-HE-F-B20-20	MD-HE-A-D-72	MD-HE-A-D-20	MD-HE-A-B20-72	MD-HE-A-B20-20
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20
Temp, °F	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Sr	0.07	0.00	0.00	0.00	0.03	0.00	0.14	0.27	1.52	2.51	0.99	1.17	1.41	2.14	0.51	1.55
Yt	0.00	0.00	0.24	0.00	0.03	0.00	0.11	0.00	1.35	0.89	0.00	0.00	0.22	0.47	0.00	0.37
Zr	9.79	3.29	0.16	1.68	2.17	0.00	2.24	0.38	0.29	0.78	0.00	0.00	0.56	0.00	0.00	1.88
Nb	0.11	0.13	0.00	0.00	0.29	0.00	0.00	0.00	0.00	1.11	0.00	1.16	0.89	0.08	1.52	0.00
Mo	5.32	22.32	0.88	3.64	0.57	3.35	0.20	1.63	0.38	0.48	0.95	0.50	2.49	0.29	5.35	1.10
Pd	0.28	1.01	2.19	1.03	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	0.00
Ag	0.00	0.68	0.07	1.10	0.00	1.43	0.00	0.21	0.99	0.00	1.95	3.07	0.00	0.00	0.00	0.75
Cd	0.36	0.00	0.00	0.62	0.57	0.43	0.00	0.00	2.64	0.00	0.00	0.00	0.00	0.00	0.00	0.00
In	1.15	0.00	0.60	0.85	0.00	0.00	0.71	0.00	0.00	0.00	0.18	0.54	0.00	0.00	0.00	0.00
Sn	0.93	0.92	1.26	0.87	0.00	1.13	0.00	0.00	0.00	5.34	9.53	4.31	0.13	1.39	0.00	0.00
Sb	0.45	1.00	1.38	0.50	0.00	0.00	0.00	1.16	0.52	1.94	0.00	4.86	0.00	0.00	0.00	2.37
Cs	1.34	0.09	0.81	2.00	0.86	2.12	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	1.54	0.00	2.57	0.00	0.00	0.00	1.20	0.00	2.01	8.40	9.02	11.10	2.54	0.00	7.31	0.98
La	0.00	0.00	2.59	0.00	1.42	3.09	5.79	4.58	22.95	10.36	0.00	0.00	12.76	3.37	0.00	0.00
Ce	0.00	1.66	2.38	0.00	0.00	0.00	3.05	1.76	25.06	0.00	7.40	7.59	10.04	7.94	0.41	13.69
Sm	1.56	0.00	0.79	0.00	4.22	0.00	3.30	1.00	27.33	0.00	3.21	0.00	22.98	0.00	0.00	0.00
Eu	0.82	9.47	0.00	12.39	11.72	12.37	4.32	13.16	9.10	5.38	0.00	20.52	20.32	38.06	11.86	0.00
Tb	6.11	0.00	9.12	0.00	2.16	19.59	17.28	19.18	25.69	0.00	7.75	8.81	33.60	22.34	38.31	10.73
Hf	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.19	8.20	1.54	0.00	6.24	10.02	0.00	0.00
Ta	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.70	20.67	16.74	10.79	19.08	1.55	5.77	10.39
Wo	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75	3.81	0.00	1.45
Ir	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.63	0.00
Au	0.39	0.33	0.79	1.09	0.00	0.41	0.97	0.30	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00
Hg	0.19	0.53	0.33	0.00	0.65	0.00	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tl	0.00	0.00	0.04	0.00	0.17	0.41	0.00	0.10	0.00	0.00	0.62	0.00	0.00	0.00	0.99	0.00
Pb	1.30	2.49	0.72	3.24	0.21	2.16	0.35	0.92	3.77	27.04	121.78	168.74	24.02	40.32	1135.16	1004.56
U	0.00	0.00	0.77	0.00	0.12	0.00	0.13	0.01	2.49	2.77	2.78	2.76	2.29	0.00	2.79	0.00

TABLE 51. MEDIUM-DUTY VEHICLE LUBRICANTS AND FUELS ELEMENTS BY XRF (No Statistical Analyses Were Performed On These Data)

	Lubricant Elements, µg/gram									**Fuel Elements, µg/gram**	
Test Number	**MD-NE-F-D**	**MD-NE-F-B20**	**MD-NE-A-D**	**MD-NE-A-B20**	**MD-HE-F-D**	**MD-HE-F-D REP**	**MD-HE-F-B20**	**MD-HE-A-D**	**MD-HE-A-B20**	**EM-6952-F**	**EM-7002-F**
Emitter	**Normal**	**Normal**	**Normal**	**Normal**	**High**	**High**	**High**	**High**	**High**	**Both**	**Both**
Oil	**Fresh**	**Fresh**	**Aged**	**Aged**	**Fresh**	**Fresh**	**Fresh**	**Aged**	**Aged**	**Both**	**Both**
Fuel	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**
Temp, °F	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**
Na	0	0	0	0	0	0	0	0	0	0	0
Mg	0	0	0	0	0	0	0	0	0	0	0
Al	0	0	0	0	0	0	0	0	0	0	0
Si	0	0	0	0	0	0	0	0	0	0	0
P	168	176	169	143	173	190	205	164	170	0	2
S	2741	2587	2768	2727	2416	2545	2639	2608	2644	0	0
Cl	0	0	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	0	0	0	0
Ca	2242	2254	2337	2714	2129	2296	2161	2220	2236	0	0
Sc	0	0	0	0	0	0	0	0	0	0	0
Ti	0	0	0	0	0	0	0	0	0	0	0
Va	0	0	0	0	0	0	0	0	0	0	0
Cr	1	1	3	4	1	2	1	2	3	0	0
Mn	0	1	1	1	0	1	0	0	0	0	0
Fe	5	4	38	83	11	41	6	33	50	0	0
Co	0	0	0	0	0	0	0	0	0	0	0
Ni	0	0	0	1	0	0	0	0	0	0	0
Cu	0	0	0	5	0	0	0	0	6	0	1
Zn	1433	1434	1515	1551	1444	1511	1461	1496	1559	0	0
Ga	0	0	0	0	0	0	0	0	0	0	0
As	0	0	0	0	0	0	0	0	0	0	0
Se	0	0	0	0	0	0	0	0	0	0	0
Br	0	0	0	0	0	0	0	0	0	0	0
Rb	0	0	0	0	0	0	0	0	0	0	0
Sr	0	0	0	0	0	0	0	0	0	0	0
Yt	0	0	0	0	0	0	0	0	0	0	0
Zr	0	0	0	0	0	0	0	0	0	0	0
Nb	0	0	0	0	0	0	0	0	0	0	0
Mo	0	0	0	6	1	0	0	0	0	0	0

TABLE 51 (CONT'D). MEDIUM-DUTY VEHICLE LUBRICANTS AND FUELS ELEMENTS BY XRF

(No Statistical Analyses Were Performed On These Data)

	Lubricant Elements, µg/gram									Fuel Elements, µg/gram	
Test Number	**MD-NE-F-D**	**MD-NE-F-B20**	**MD-NE-A-D**	**MD-NE-A-B20**	**MD-HE-F-D**	**MD-HE-F-D REP**	**MD-HE-F-B20**	**MD-HE-A-D**	**MD-HE-A-B20**	**EM-6952-F**	**EM-7002-F**
Emitter	**Normal**	**Normal**	**Normal**	**Normal**	**High**	**High**	**High**	**High**	**High**	**Both**	**Both**
Oil	**Fresh**	**Fresh**	**Aged**	**Aged**	**Fresh**	**Fresh**	**Fresh**	**Aged**	**Aged**	**Both**	**Both**
Fuel	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**
Temp, °F	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**
Pd	0	0	0	0	0	0	0	0	0	0	0
Ag	0	0	0	0	0	0	0	0	0	0	0
Cd	0	0	0	0	0	0	0	0	0	0	0
In	0	0	0	0	0	0	0	0	0	0	0
Sn	0	0	0	0	0	0	0	0	0	0	0
Sb	0	0	0	0	0	0	0	0	0	0	0
Cs	0	0	0	0	0	0	0	0	0	0	0
Ba	0	0	0	0	0	0	0	0	0	0	0
La	0	0	0	0	0	0	0	0	0	0	0
Ce	0	0	0	0	0	0	0	0	0	0	0
Sm	0	0	0	0	0	0	0	0	0	0	0
Eu	0	0	0	0	0	0	0	0	0	0	0
Tb	0	0	0	0	0	0	0	0	0	0	0
Hf	0	0	0	0	0	0	0	0	0	0	0
Ta	0	0	0	0	0	0	0	0	0	0	0
Wo	0	0	0	0	0	0	0	0	0	0	0
Ir	0	0	0	0	0	0	0	0	0	0	0
Au	0	0	0	0	0	0	0	0	0	0	0
Hg	0	0	0	0	0	0	0	0	0	0	0
Tl	0	0	0	0	0	0	0	0	0	0	0
Pb	0	0	4	7	0	4	0	4	6	0	0

TABLE 52. AVERAGE RESULTS OF MEDIUM-DUTY VEHICLE PM ELEMENTAL ANALYSIS BY ICP-MS, µg/mi
(No Statistical Analyses Were Performed On These Data)

TEST NUMBER	**MD-NE-F-D-72**	**MD-NE-F-D-20**	**MD-NE-F-B20-72**	**MD-NE-F-B20-20**	**MD-NE-A-D-72-1**	**MD-NE-A-D-20-2**	**MD-NE-A-B-20-72**	**MD-NE-A-B-20-20**	**MD-HE-F-D-72**	**MD-HE-F-D-20**	**MD-HE-F-B20-72**	**MD-HE-F-B20-20**	**MD-HE-A-D-72**	**MD-HE-A-D-20**	**MD-HE-A-B20-72**	**MD-HE-A-B20-20**
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20
Temp, F	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Mg	3.91	14.94	3.69	4.05	1.38	4.03	6.05	2.21	2.60	4.67	3.32	8.52	0.16	6.79	3.41	3.53
Al	20.29	51.01	65.54	22.49	8.95	34.47	43.55	5.77	34.64	38.53	10.99	16.63	9.66	69.39	0.60	30.00
Ca	179.99	869.80	158.23	324.96	92.23	281.79	114.10	239.28	157.12	243.72	163.90	199.11	219.83	245.31	187.45	266.66
Va	0.14	0.38	0.03	0.10	0.07	0.12	1.20	0.09	0.02	0.19	0.02	0.02	0.01	0.01	0.00	0.02
Cr	21.08	38.11	4.45	10.80	6.86	18.43	13.58	7.26	9.61	4.14	6.23	0.25	0.00	0.00	0.00	2.06
Mn	6.88	16.29	3.03	7.51	1.88	7.64	38.16	4.50	4.21	4.17	3.29	3.93	2.55	3.46	3.75	7.64
Fe	381.16	1649.75	141.42	460.63	134.80	418.68	451.96	258.29	154.75	347.38	181.62	236.03	113.21	205.32	499.19	910.80
Ni	9.62	15.09	3.06	5.39	1.39	10.69	8.45	2.10	2.43	3.54	1.66	3.22	1.35	3.51	7.39	14.68
Cu	4.39	16.30	5.64	6.11	1.72	7.61	9.24	8.19	29.79	71.71	43.04	21.70	6.02	8.54	39.11	44.86
Zn	103.69	326.61	72.79	150.58	42.04	106.64	55.37	117.22	344.67	566.45	344.82	458.99	376.07	453.36	401.91	678.76
Mo	2.94	12.12	0.67	3.13	0.50	2.45	0.72	1.35	0.25	0.65	0.09	0.24	0.02	0.15	0.69	0.92
Ag	0.07	0.12	0.00	0.41	0.00	0.11	0.77	0.01	0.05	0.07	0.01	0.00	0.00	0.00	0.13	0.00
Cd	0.21	0.34	0.04	0.04	0.01	0.01	0.19	0.00	0.18	0.50	0.40	0.68	0.12	0.13	1.35	1.84
Sn	0.95	1.77	0.54	0.77	0.19	0.41	0.52	0.36	2.47	6.88	7.50	12.89	2.05	2.21	27.10	36.21
Ba	2.59	3.58	0.70	0.61	0.86	2.11	1.85	0.25	1.65	0.82	5.43	1.68	1.75	1.01	3.72	5.28
Ce	0.76	4.18	0.18	1.07	0.09	1.14	0.59	0.64	0.16	0.08	0.14	0.08	0.07	0.07	0.10	0.09
Hg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pb	0.48	2.39	0.39	0.74	0.21	0.72	0.66	0.75	6.07	24.56	108.97	144.47	22.53	31.68	1039.83	822.61

TABLE 53. MEDIUM-DUTY VEHICLE LUBRICANTS AND FUELS ELEMENTS BY ICP-MS
(No Statistical Analyses Were Performed On These Data)

Test Number	**Lubricants, ng/gram**					**Fuels, ng/gram**		
	MD-NE-F-D REP1	**MD-NE-F-D REP2**	**MD-NE-A-D**	**MD-NE-F-B20**	**MD-NE-A-B20**	**EM-6952-F REP1**	**EM-6952-F REP 2**	**EM-7002-F**
Emitter	Normal	Normal	Normal	Normal	Normal	Both	Both	Both
Oil	Fresh	Fresh	Aged	Fresh	Aged	Both	Both	Both
Fuel	Diesel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20
Temp, F	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20
Mg	7546	7580	6631	6346	8899	<LOD	<LOD	75
Al	1334	1377	3745	1324	2949	84	<LOD	<LOD
Ca	1835432	1871243	2078633	1912186	2344386	<LOD	<LOD	1145
V	46	48	38	51	101	<LOD	<LOD	<LOD
Cr	102	112	991	102	1751	<LOD	<LOD	4
Mn	89	91	276	92	580	<LOD	<LOD	3
Fe	3604	3684	28330	3071	54945	168	196	221
Ni	58	87	350	97	1715	<LOD	<LOD	<LOD
Cu	172	157	4976	136	8843	<LOD	<LOD	5
Zn	1187007	1241977	1389552	1224397	1326866	<LOD	<LOD	29
Mo	623	561	238	162	4661	<LOD	<LOD	<LOD
Ag	<LOD[a]	<LOD	7	<LOD	4	<LOD	<LOD	<LOD
Cd	NM[b]	NM	NM	NM	NM	NM	NM	NM
Sn	NM	NM	NM	NM	NM	NM	NM	NM
Ba	21	24	97	10	383	<LOD	<LOD	<LOD
Ce	NM	NM	NM	NM	NM	NM	NM	NM
Hg	NM	NM	NM	NM	NM	NM	NM	NM
Pb	191	215	3666	150	6075	<LOD	<LOD	1
W	<LOD	<LOD	8	<LOD	3	<LOD	<LOD	<LOD
P	1002286	1018522	1038864	1057434	1061213	<LOD	<LOD	<LOD
S	3029208	3163322	3278174	3123138	3589616	6002	6435	4793
Ti	32	26	60	30	64	<LOD	<LOD	<LOD
Sr	782	837	1044	885	806	<LOD	<LOD	<LOD

a Less than level of detection
b Not measured

TABLE 54. AVERAGE RESULTS OF MEDIUM-DUTY VEHICLE EXHAUST POLYCYCLIC AROMATIC HYDROCARBONS, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	**MD-NE-F-D-72**	**MD-NE-F-D-20**	**MD-NE-F-B20-72**	**MD-NE-F-B20-20**	**MD-NE-A-D-72**	**MD-NE-A-D-20**	**MD-NE-A-B-20-72**	**MD-NE-A-B-20-20**	**MD-HE-F-D-72**	**MD-HE-F-D-20**	**MD-HE-F-B20-72**	**MD-HE-F-B20-20[a]**	**MD-HE-A-D-72**	**MD-HE-A-D-20**	**MD-HE-A-B20-72**	**MD-HE-A-B20-20**
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20
Temp, °F	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
naphth	496.0	882.7	429.8	552.8	528.5	836.4	196.6	333.1	581.3	1233.8	367.7	1288.6	370.0	1229.3	472.5	1025.9
quinoline	14.7	28.0	11.6	5.9	14.8	18.3	6.5	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
mnaph2	376.4	531.8	272.5	285.7	371.8	439.6	116.7	138.0	115.7	290.7	62.3	349.1	65.7	336.4	81.8	240.5
mnaph1	243.6	332.8	173.1	181.7	236.5	278.0	76.2	95.9	86.0	215.9	48.4	246.5	50.9	250.1	59.8	169.8
biphen	80.4	135.2	63.9	72.0	76.8	94.3	25.5	36.3	25.5	65.4	16.4	79.7	15.4	73.9	20.9	56.5
m_2bph	0.0	0.0	75.2	24.2	44.2	96.5	83.2	12.5	197.5	167.1	114.0	211.9	40.8	179.9	0.0	24.9
dmn267	184.5	257.8	132.9	134.5	183.8	199.0	57.9	60.7	28.4	89.5	19.3	143.7	20.6	113.1	26.5	79.5
dm1367	282.2	389.1	252.3	252.4	354.7	381.1	105.3	110.8	51.7	176.5	31.6	283.1	37.8	219.2	50.1	152.8
d14523	124.6	169.7	86.1	84.0	121.1	128.4	37.8	36.1	17.2	58.5	10.9	93.6	13.6	73.9	16.3	48.9
enap12	78.9	108.3	67.9	65.4	89.9	103.6	32.3	36.3	26.0	60.9	17.2	75.9	15.4	68.7	16.9	49.6
acnapy	45.8	101.5	42.0	56.7	43.4	71.2	15.3	30.5	43.2	116.8	29.6	106.3	47.4	103.5	51.7	76.2
dmn12	40.5	57.1	29.3	28.6	40.2	42.5	10.5	11.0	6.6	23.4	4.0	38.6	4.5	29.4	7.5	19.3
dmn18	0.4	1.4	0.6	1.8	0.8	0.7	0.6	0.4	0.0	0.0	0.0	0.6	0.2	0.6	0.1	0.0
acnape	3.5	5.6	2.2	3.1	3.1	4.6	1.1	1.4	7.7	17.8	5.5	20.0	3.3	19.1	4.4	12.1
m_3bph	32.7	88.5	83.3	68.6	105.0	145.4	58.9	27.5	91.3	109.5	58.3	134.3	21.8	130.3	14.0	44.3
m_4bph	7.7	32.7	30.9	24.8	32.0	47.4	15.2	4.3	24.3	40.6	18.3	52.6	7.4	43.5	4.5	18.5
dbzfur	17.8	27.0	14.5	13.7	15.8	17.9	5.3	6.6	7.1	14.7	4.8	15.6	4.3	20.0	6.4	12.7
em_12n	17.0	27.2	15.0	13.8	24.2	23.4	9.0	7.8	19.6	46.4	13.2	56.5	12.0	60.4	18.1	41.1
tmi235n	46.8	80.1	45.3	43.5	60.3	66.5	18.3	23.4	10.3	36.8	8.8	61.0	10.8	48.6	16.5	38.2
btmnap	70.4	93.4	57.3	55.9	75.6	84.2	27.5	29.3	12.1	42.3	10.8	84.3	14.5	62.1	15.6	42.0
atmnap	78.5	111.6	64.2	61.1	76.0	93.9	31.5	32.5	20.5	62.8	18.2	95.2	21.0	81.0	27.6	57.3
ctmnap	77.6	100.9	63.6	62.5	84.2	90.5	32.0	34.1	17.6	48.1	11.7	87.0	16.2	66.8	20.5	48.9
em_21n	6.9	10.1	3.5	2.7	5.5	4.1	1.7	0.4	1.0	2.9	0.9	1.6	0.4	5.0	0.9	3.0
etmnap	45.3	64.9	38.9	39.7	41.6	56.8	18.5	21.2	10.0	31.5	7.0	55.7	10.1	40.3	12.9	33.0
tm245n	9.6	13.2	12.5	4.8	14.2	12.4	4.0	7.1	5.0	10.9	2.7	19.8	3.8	16.7	6.9	12.8

TABLE 54 (CONT'D). AVERAGE RESULTS OF MEDIUM-DUTY VEHICLE EXHAUST POLYCYCLIC AROMATIC HYDROCARBONS, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	MD-NE-F-D-72	MD-NE-F-D-20	MD-NE-F-B20-72	MD-NE-F-B20-20	MD-NE-A-D-72	MD-NE-A-D-20	MD-NE-A-B-20-72	MD-NE-A-B-20-20	MD-HE-F-D-72	MD-HE-F-D-20	MD-HE-F-B20-72	MD-HE-F-B20-20[a]	MD-HE-A-D-72	MD-HE-A-D-20	MD-HE-A-B20-72	MD-HE-A-B20-20
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20
Temp, °F	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ftmnap	35.7	49.6	27.7	29.2	39.7	41.0	14.6	16.5	7.2	22.1	7.0	40.1	7.9	28.1	11.3	24.4
fluore	9.7	18.3	7.6	10.4	9.3	17.7	3.6	9.1	18.8	50.6	14.5	51.3	12.5	51.3	23.1	53.7
tm145n	5.8	10.4	5.0	4.5	7.2	9.6	2.2	2.1	2.7	7.7	1.1	6.4	0.7	10.1	1.3	8.5
jtmnap	24.7	36.7	17.7	19.3	29.2	32.2	8.4	11.4	4.5	16.9	3.6	29.7	5.7	21.1	4.0	13.8
a_mfluo	4.3	14.8	3.7	6.7	4.5	9.5	1.1	1.2	4.0	16.9	2.3	28.4	4.7	23.4	10.4	16.5
b_mfluo	4.7	7.9	3.2	2.5	3.9	6.1	1.8	1.1	0.2	4.6	0.4	3.6	0.9	4.8	2.4	3.9
m_1fluo	10.3	17.6	10.3	7.6	10.1	12.4	2.7	3.1	3.9	12.9	3.5	17.1	6.8	20.6	10.4	16.7
fl9one	2.5	1.8	1.5	0.9	1.9	3.1	0.3	0.5	29.4	24.4	25.6	10.3	28.4	30.1	29.0	29.3
phenan	15.7	55.1	13.3	24.3	19.3	47.4	4.0	13.2	138.8	154.7	136.1	164.3	153.8	160.9	164.4	175.4
anthra	3.3	6.9	3.9	4.0	4.1	7.6	1.8	1.8	18.0	17.6	18.1	19.7	21.0	17.7	21.3	21.9
xanone	2.0	2.7	0.5	1.1	1.0	1.7	0.4	0.7	1.6	8.7	1.8	16.5	3.7	10.2	6.0	9.4
acquone	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
m_2phen	1.4	3.9	1.2	1.9	1.8	2.8	0.7	0.0	26.4	24.5	30.1	28.9	36.3	35.6	41.8	35.5
m_3phen	5.7	8.0	5.2	3.9	5.7	7.3	2.5	2.2	34.6	30.2	38.4	39.0	46.1	41.3	51.6	45.2
pnapone	13.3	12.0	8.7	7.5	14.4	17.1	9.8	13.7	65.0	61.6	59.8	55.4	80.8	69.7	74.4	76.9
m_2anth	0.4	0.8	0.2	0.7	0.6	0.4	0.2	0.2	3.5	3.0	4.3	3.6	4.9	5.2	6.1	4.0
m_45phen	0.0	3.5	0.2	1.6	0.3	3.2	0.0	1.0	8.3	16.2	12.1	21.3	16.3	18.8	20.1	25.6
m_9phen	2.8	4.3	2.7	1.9	3.0	4.4	1.1	0.5	15.9	16.6	16.0	17.6	21.6	20.6	23.0	20.8
mpht_1	0.0	1.4	0.0	0.2	0.1	0.0	0.0	0.0	15.1	15.4	15.9	18.7	20.7	19.8	22.2	20.8
anthron	0.4	1.3	0.6	0.7	0.8	0.5	1.7	0.0	0.3	3.4	0.5	2.8	0.4	1.4	2.5	4.1
m_9ant	0.3	0.4	0.0	0.2	0.1	0.2	0.1	0.1	0.2	1.0	0.5	0.8	0.5	0.7	0.5	0.9
nap2phen	0.0	1.6	0.1	0.7	0.0	1.4	0.1	0.1	9.8	11.2	10.4	14.8	16.4	13.0	16.9	19.6
anrquone	5.2	6.7	4.7	4.6	6.8	7.5	6.1	6.2	18.7	17.5	15.8	21.0	22.7	18.2	18.3	20.8
a_dmph	0.6	1.5	0.4	0.7	1.0	1.2	0.0	0.5	10.7	10.5	11.1	14.4	15.0	15.2	17.5	17.6
b_dmph	0.3	0.6	0.3	0.1	0.5	0.8	0.0	0.2	6.3	6.0	6.7	8.3	9.0	9.3	10.4	10.4

TABLE 54 (CONT'D). AVERAGE RESULTS OF MEDIUM-DUTY VEHICLE EXHAUST POLYCYCLIC AROMATIC HYDROCARBONS, µg/mi

(No Statistical Analyses Were Performed On These Data)

Test Number	MD-NE-F-D-72	MD-NE-F-D-20	MD-NE-F-B20-72	MD-NE-F-B20-20	MD-NE-A-D-72	MD-NE-A-D-20	MD-NE-A-B-20-72	MD-NE-A-B-20-20	MD-HE-F-D-72	MD-HE-F-D-20	MD-HE-F-B20-72	MD-HE-F-B20-20[a]	MD-HE-A-D-72	MD-HE-A-D-20	MD-HE-A-B20-72	MD-HE-A-B20-20
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20
Temp, °F	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
dm17ph	1.6	1.2	1.0	0.9	1.2	1.9	0.1	0.0	48.3	52.7	44.8	66.6	71.7	78.1	84.4	86.8
dm36ph	0.9	1.5	0.5	0.6	0.5	1.7	0.2	0.3	5.9	7.2	6.9	8.7	13.3	11.7	12.5	11.3
d_dmph	1.6	1.8	1.4	1.2	1.7	2.0	1.2	1.4	5.6	6.6	5.0	7.6	7.8	8.3	8.5	8.5
e_dmph	0.9	1.4	1.0	0.5	1.1	1.3	0.4	0.8	4.1	4.1	4.1	4.5	5.7	5.8	6.3	5.5
c_dmph	3.8	4.7	3.2	2.6	3.8	4.6	1.7	2.5	15.3	17.5	14.5	23.1	22.6	23.6	24.5	27.2
fluora	0.0	14.8	0.1	8.0	1.2	15.7	0.0	11.5	68.8	96.8	69.8	116.3	102.4	87.8	104.1	162.7
pyrene	0.9	16.2	0.9	9.7	2.2	16.9	1.4	14.3	97.8	134.0	91.5	142.0	135.2	124.6	147.3	212.5
antal9	0.2	0.6	0.6	0.9	0.2	0.8	0.5	0.3	3.0	4.8	2.7	5.7	4.2	5.9	4.6	7.0
retene	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
bafluo	0.0	0.5	0.1	0.4	0.2	1.1	0.1	0.6	3.1	7.4	2.3	7.9	3.5	6.7	5.3	12.3
bbfluo	0.1	0.2	0.0	0.2	0.1	0.2	0.1	0.5	0.4	1.5	0.5	2.2	0.7	1.6	1.4	4.8
bmpyfl	0.1	0.5	0.2	0.5	0.3	1.3	0.1	0.9	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.1
c1mflpy	0.2	0.6	0.2	0.4	0.3	0.9	0.3	0.5	4.5	7.8	4.0	6.1	5.4	6.6	6.3	10.0
m_13fl	0.1	0.5	0.2	0.5	0.3	0.4	0.0	0.9	4.3	7.2	4.0	5.7	7.0	6.8	7.1	9.3
m_4pyr	0.7	2.1	0.7	1.8	0.8	2.3	0.6	1.3	9.2	14.4	8.1	12.7	9.8	12.9	13.7	22.7
cmpyfl	0.1	0.6	0.1	0.4	0.1	0.4	0.1	0.9	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0
dmpyfl	0.6	0.9	0.5	1.1	1.0	1.2	0.5	1.2	10.7	13.2	10.0	12.7	12.1	14.1	16.9	21.6
m_1pyr	0.2	1.3	0.2	0.7	0.2	1.1	0.2	1.0	4.6	9.9	4.4	8.9	5.5	8.3	7.9	16.7
bntiop	0.1	0.2	0.1	0.1	0.0	0.2	0.2	0.4	0.7	1.1	0.5	0.8	0.5	0.9	0.7	1.2
bzcphen	0.1	0.5	0.1	0.4	0.2	0.6	0.1	1.1	3.4	5.5	2.8	4.2	3.2	3.8	4.1	8.1
bghifl	0.7	11.4	1.2	9.4	2.7	15.2	3.0	21.8	43.0	69.0	37.8	55.1	42.7	41.1	58.4	106.7
phant9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2
cp_cdpyr	0.0	0.7	0.0	0.6	0.0	1.8	0.0	0.9	6.2	8.1	5.7	8.3	7.2	7.1	11.2	15.6
baanth	0.0	1.7	0.0	1.8	0.1	3.0	0.1	3.6	4.3	10.6	3.9	8.7	4.2	5.5	5.4	14.0

TABLE 54 (CONT'D). AVERAGE RESULTS OF MEDIUM-DUTY VEHICLE EXHAUST POLYCYCLIC AROMATIC HYDROCARBONS, µg/mi

(No Statistical Analyses Were Performed On These Data)

Test Number	MD-NE-F-D-72	MD-NE-F-D-20	MD-NE-F-B20-72	MD-NE-F-B20-20	MD-NE-A-D-72	MD-NE-A-D-20	MD-NE-A-B-20-72	MD-NE-A-B-20-20	MD-HE-F-D-72	MD-HE-F-D-20	MD-HE-F-B20-72	MD-HE-F-B20-20[a]	MD-HE-A-D-72	MD-HE-A-D-20	MD-HE-A-B20-72	MD-HE-A-B20-20
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20
Temp, °F	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
chr_tr	0.4	3.7	0.2	2.8	0.5	4.3	0.1	5.5	14.6	32.1	13.6	24.8	14.2	17.3	18.0	41.5
bzanthr	0.8	3.6	0.2	2.4	0.7	3.6	1.1	5.5	8.9	15.6	8.8	13.7	9.2	9.4	10.4	20.3
baa7_12	0.1	0.2	0.0	0.1	0.1	0.2	0.2	1.4	0.8	2.1	0.8	1.4	1.0	1.0	0.5	1.7
m_3chr	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.7	5.9	1.1	1.8	0.6	1.1	1.5	2.5
chry56m	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.1	0.4	0.2	0.3	0.2	0.3	0.3	0.4
m_7baa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.1
dmban712	0.0	0.4	0.2	0.0	0.0	0.0	0.0	0.0	1.5	1.9	1.5	1.7	1.6	1.4	1.3	1.7
bbjkfl	0.0	1.3	0.0	0.9	0.0	1.6	0.1	2.1	3.4	12.4	4.4	14.2	4.9	6.6	5.9	18.1
bafl	0.0	0.2	0.0	0.1	0.0	0.2	0.0	0.2	0.8	2.3	1.0	2.7	1.2	1.5	1.4	3.7
bepyrn	0.2	2.5	0.1	2.2	0.3	3.1	0.1	3.8	2.7	8.0	3.4	8.9	4.1	4.6	4.5	11.5
bapyrn	0.0	2.3	0.1	1.8	0.1	3.4	0.0	4.3	1.6	5.4	1.9	7.1	2.3	3.0	2.6	7.9
peryle	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.2	0.7	1.0	0.7	1.4	0.6	0.8	0.7	1.6
m_7bpy	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.0
bpy910dih	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
incdfl	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3
dbahacr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.3	0.0	0.1	0.1	0.2	0.0
dbajacr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.1	0.6	0.0	0.4	0.1	0.1
in123pyr	0.0	1.6	0.0	0.6	0.0	1.8	0.0	3.3	0.2	0.9	0.2	1.7	0.3	0.6	0.4	1.8
dbahacan	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.2	0.1	0.1	0.0	0.0	0.0	0.2	0.4	0.3
dbajan	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.5	0.2	0.8	0.2	0.5	0.3	0.7
bbchr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.1
pic	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
bghipe	0.0	4.2	0.0	2.4	0.0	3.6	0.1	7.1	0.8	3.5	0.9	6.7	1.4	2.4	2.0	7.2
anthan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.2	0.1	0.2	0.1	0.1

TABLE 54 (CONT'D). AVERAGE RESULTS OF MEDIUM-DUTY VEHICLE EXHAUST POLYCYCLIC AROMATIC HYDROCARBONS, µg/mi

(No Statistical Analyses Were Performed On These Data)

Test Number	**MD-NE-F-D-72**	**MD-NE-F-D-20**	**MD-NE-F-B20-72**	**MD-NE-F-B20-20**	**MD-NE-A-D-72**	**MD-NE-A-D-20**	**MD-NE-A-B-20-72**	**MD-NE-A-B-20-20**	**MD-HE-F-D-72**	**MD-HE-F-D-20**	**MD-HE-F-B20-72**	**MD-HE-F-B20-20[a]**	**MD-HE-A-D-72**	**MD-HE-A-D-20**	**MD-HE-A-B20-72**	**MD-HE-A-B20-20**
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20
Temp, °F	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
dbalpyr	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.2	0.0	0.0
corone	0.0	0.5	0.1	0.1	0.0	0.4	0.0	1.0	0.1	0.4	0.1	0.9	0.3	0.3	0.3	1.2
dbaepyr	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0
dbaipyr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
dbahpyr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
dbbkfl	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.1	0.0	0.0	0.0
dbth	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.0	3.1	3.2	2.8	5.7	2.9	4.7	3.0	4.2
dbcgcar	0.2	0.0	0.0	0.0	0.5	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[a] The PM sample for MD-HE-F-B20-20-2 test was lost. This data is from test number MD-HE-F-B20-20-1

TABLE 55. MEDIUM-DUTY VEHICLE POLYCYCLIC AROMATIC HYDROCARBONS IN LUBRICANTS AND FUEL
(No Statistical Analyses Were Performed On These Data)

	Lubricants, µg/gram								Fuels, µg/gram	
TEST NUMBER	**MD-NE-F-D**	**MD-NE-F-B20**	**MD-NE-A-D**	**MD-NE-A-B20**	**MD-HE-F-D**	**MD-HE-F-B20**	**MD-HE-A-D**	**MD-HE-A-B20**	**EM-6952-F**	**EM-7002-F**
Emitter	**Normal**	**Normal**	**Normal**	**Normal**	**High**	**High**	**High**	**High**	**NE & HE**	**NE & HE**
Oil	**Fresh**	**Fresh**	**Aged**	**Aged**	**Fresh**	**Fresh**	**Aged**	**Aged**	**F&A**	**F&A**
Fuel	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**
Temp	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**
Media	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Fuel	Fuel
naphth	14.6	3.0	10.2	15.3	5.6	6.8	5.1	6.1	239.2	219.5
quinoline	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
mnaph2	14.0	7.0	11.4	15.6	9.4	5.7	4.5	3.9	756.6	587.2
mnaph1	4.1	0.8	4.9	6.2	3.2	2.8	1.6	0.0	402.6	292.5
biphen	0.2	0.3	0.2	0.0	0.3	0.0	0.0	0.2	157.5	124.0
m_2bph	0.0	0.4	0.0	0.0	0.4	0.3	0.0	0.0	192.9	155.7
dmn267	5.5	1.6	4.7	2.7	4.3	0.3	1.2	0.1	1024.5	706.5
dm1367	12.2	7.4	12.5	5.6	11.4	2.9	3.1	2.8	2212.6	1469.9
d14523	1.5	0.5	0.9	1.1	1.4	0.4	0.7	0.3	662.3	445.1
enap12	0.8	0.2	1.1	0.4	1.5	0.0	0.2	0.0	172.4	139.5
acnapy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1
dmn12	0.0	0.0	0.2	0.0	0.0	0.0	0.1	0.0	188.2	135.6
dmn18	0.0	0.0	0.3	0.1	0.2	0.8	0.2	0.0	0.0	0.0
acnape	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.7	13.8
m_3bph	0.5	1.1	1.9	0.0	1.9	0.0	0.0	0.0	330.8	266.8
m_4bph	0.0	0.2	0.7	0.0	0.5	0.0	0.1	0.0	179.2	132.5
dbzfur	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.3	3.4
em_12n	0.0	0.2	0.3	0.4	0.5	0.1	0.3	0.0	71.7	59.7
tmi235n	1.9	0.2	1.1	1.3	3.4	0.4	0.7	1.8	394.4	328.9
btmnap	4.6	1.5	2.6	1.2	4.9	0.3	1.4	2.7	514.8	381.1
atmnap	0.9	1.1	4.9	0.5	2.7	0.2	0.3	0.4	448.2	358.6
ctmnap	4.6	2.5	5.5	3.6	4.5	0.1	0.8	2.7	518.8	415.8
em_21n	0.2	0.0	1.2	0.0	0.2	0.0	0.0	0.1	8.1	6.4
etmnap	2.0	1.3	2.6	0.8	3.8	0.4	0.6	1.8	378.3	289.3
tm245n	0.0	0.2	0.5	0.1	0.2	0.0	0.0	0.0	84.1	61.2
ftmnap	1.9	0.9	2.8	0.7	1.7	0.4	0.6	1.3	233.8	190.2
fluore	0.0	0.2	0.6	1.1	0.6	0.0	0.3	0.5	26.4	29.1
tm145n	0.2	0.5	1.1	0.9	0.8	0.0	0.0	0.0	205.1	50.4
jtmnap	0.7	0.5	1.8	0.4	2.6	0.0	1.3	0.4	206.2	144.0
a_mfluo	0.0	0.3	1.8	0.0	0.6	0.3	1.0	0.6	112.7	96.3
b_mfluo	0.0	0.0	0.5	0.0	0.0	0.0	0.2	0.2	35.0	27.2
m_1fluo	0.0	0.0	0.4	0.0	0.6	0.5	0.6	1.8	95.9	83.8
fl9one	0.0	0.1	0.2	0.2	0.1	0.0	0.3	0.2	5.2	2.0
phenan	0.2	0.2	2.4	0.8	2.5	4.7	6.9	12.5	49.5	39.6
anthra	0.0	0.3	0.1	0.2	0.5	0.3	0.5	0.7	1.8	3.2
xanone	0.0	0.0	5.0	0.0	4.9	0.4	3.0	3.4	428.0	330.3
acquone	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
m_2phen	0.5	0.2	3.1	1.1	3.7	15.3	18.1	22.9	47.3	48.9
m_3phen	0.2	0.8	3.8	1.0	1.1	14.5	18.1	18.2	48.1	45.4

TABLE 55 (CONT'D). MEDIUM-DUTY VEHICLE POLYCYCLIC AROMATIC HYDROCARBONS IN LUBRICANTS AND FUEL

(No Statistical Analyses Were Performed On These Data)

	Lubricants, µg/gram								**Fuels, µg/gram**	
TEST NUMBER	**MD-NE-F-D**	**MD-NE-F-B20**	**MD-NE-A-D**	**MD-NE-A-B20**	**MD-HE-F-D**	**MD-HE-F-B20**	**MD-HE-A-D**	**MD-HE-A-B20**	**EM-6952-F**	**EM-7002-F**
Emitter	**Normal**	**Normal**	**Normal**	**Normal**	**High**	**High**	**High**	**High**	**NE & HE**	**NE & HE**
Oil	**Fresh**	**Fresh**	**Aged**	**Aged**	**Fresh**	**Fresh**	**Aged**	**Aged**	**F&A**	**F&A**
Fuel	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**
Temp	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**
Media	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Fuel	Fuel
pnapone	0.0	0.8	0.9	0.0	0.4	0.7	0.4	1.3	29.2	37.6
m_2anth	0.2	0.2	0.4	0.3	1.7	0.7	1.3	1.1	2.6	1.0
m_45phen	0.6	0.6	0.5	0.5	0.9	1.5	1.0	2.2	0.0	1.5
m_9phen	1.0	1.5	4.5	1.3	2.4	7.4	6.0	11.6	29.4	41.9
mpht_1	0.4	0.9	2.0	1.1	1.1	1.7	0.8	6.4	29.9	21.6
anthron	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
m_9ant	0.9	0.3	0.5	0.2	0.4	1.2	0.4	1.2	3.4	4.3
nap2phen	0.9	1.3	0.7	0.8	0.4	1.2	0.5	0.9	2.2	4.9
anrquone	0.0	1.3	1.1	0.7	1.5	1.8	1.1	0.0	2.8	1.3
a_dmph	2.3	0.5	2.8	2.6	4.8	11.3	14.9	17.0	17.8	14.9
b_dmph	1.1	0.8	3.9	2.2	4.5	5.3	8.0	7.2	12.3	10.4
dm17ph	2.2	1.0	5.6	3.0	3.9	4.3	10.6	11.2	22.3	19.9
dm36ph	0.9	0.3	4.4	3.4	1.5	5.2	3.6	12.8	13.6	11.5
d_dmph	2.1	3.0	2.8	2.0	3.7	6.5	4.5	10.1	18.8	13.9
e_dmph	1.4	0.5	3.8	1.5	5.3	2.4	5.2	8.3	13.5	6.6
c_dmph	4.0	1.7	10.5	4.7	8.5	18.6	28.3	28.7	49.4	37.1
fluora	1.0	1.2	2.2	0.7	0.8	1.6	0.9	0.6	1.7	1.3
pyrene	1.7	0.7	5.5	7.5	6.2	21.1	25.0	29.6	14.3	9.1
antal9	6.8	3.4	6.8	5.9	5.5	7.4	2.7	7.4	0.0	1.9
retene	0.5	0.5	0.7	0.3	0.4	0.3	0.4	0.4	0.3	0.0
bafluo	1.3	0.7	1.0	1.9	0.9	3.9	4.6	4.0	1.8	0.3
bbfluo	2.0	0.8	1.3	1.3	1.4	8.8	2.1	5.9	0.3	0.5
bmpyfl	1.5	1.3	1.9	3.5	2.3	4.9	3.9	2.9	1.3	0.5
c1mflpy	1.3	0.6	1.6	2.0	1.7	0.9	1.1	2.9	0.0	0.8
m_13fl	1.7	1.8	2.0	4.0	2.3	2.9	4.3	4.0	1.3	0.5
m_4pyr	3.3	3.8	6.8	5.5	1.9	8.1	12.0	7.2	11.1	6.8
cmpyfl	3.6	1.5	2.4	3.8	2.6	16.2	10.2	10.9	0.6	0.8
dmpyfl	4.5	1.0	1.6	4.0	1.0	33.2	5.9	10.3	6.8	0.4
m_1pyr	1.0	2.1	3.5	5.6	2.7	2.7	7.0	17.8	3.7	4.4
bntiop	0.0	2.6	2.1	1.8	2.7	5.5	2.5	0.0	0.0	0.2
bzcphen	0.0	0.8	1.8	0.8	1.7	1.1	1.5	0.0	0.2	0.1
bghifl	0.0	0.2	0.7	1.7	1.0	0.9	0.5	1.0	1.0	0.0
phant9	0.0	0.1	0.2	0.4	0.4	0.3	0.1	0.0	0.2	0.0
cp_cdpyr	0.0	0.2	0.2	0.4	0.2	0.3	0.3	0.0	0.1	0.0
baanth	0.0	0.4	0.1	0.6	0.2	1.0	1.2	0.0	0.0	0.1
chr_tr	0.0	1.5	0.8	2.8	2.1	2.9	5.6	5.3	0.0	0.0
bzanthr	0.0	3.6	3.2	3.4	3.5	3.0	1.9	0.0	0.0	0.2
baa7_12	0.0	3.6	0.0	10.5	11.0	10.2	7.3	0.0	0.0	0.0
m_3chr	1.4	1.1	0.8	0.5	1.3	2.7	3.2	0.0	0.0	0.0
chry56m	0.0	0.6	0.0	1.3	0.5	3.3	3.2	0.0	0.4	0.0
m_7baa	0.0	0.8	0.0	0.3	0.6	0.3	0.4	0.0	0.0	0.0

TABLE 55 (CONT'D). MEDIUM-DUTY VEHICLE POLYCYCLIC AROMATIC HYDROCARBONS IN LUBRICANTS AND FUEL
(No Statistical Analyses Were Performed On These Data)

	Lubricants, µg/gram								Fuels, µg/gram	
TEST NUMBER	**MD-NE-F-D**	**MD-NE-F-B20**	**MD-NE-A-D**	**MD-NE-A-B20**	**MD-HE-F-D**	**MD-HE-F-B20**	**MD-HE-A-D**	**MD-HE-A-B20**	**EM-6952-F**	**EM-7002-F**
Emitter	**Normal**	**Normal**	**Normal**	**Normal**	**High**	**High**	**High**	**High**	**NE & HE**	**NE & HE**
Oil	**Fresh**	**Fresh**	**Aged**	**Aged**	**Fresh**	**Fresh**	**Aged**	**Aged**	**F&A**	**F&A**
Fuel	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**
Temp	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**
Media	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Fuel	Fuel
dmban712	0.0	0.1	0.1	0.1	0.3	0.2	0.4	0.0	0.3	0.0
bbjkfl	0.0	0.5	0.5	0.6	0.3	0.7	0.2	0.0	0.1	0.0
bafl	0.0	0.0	0.2	0.2	0.2	0.2	0.1	0.0	0.0	0.0
bepyrn	0.3	0.6	0.2	0.5	0.5	0.2	0.5	0.0	0.0	0.0
bapyrn	0.0	0.4	1.1	0.7	0.5	0.7	0.8	0.0	0.0	0.0
peryle	0.0	1.3	1.0	1.3	0.6	0.6	0.8	0.0	0.0	0.0
m_7bpy	0.0	1.3	0.7	1.1	0.4	0.6	0.8	0.0	0.0	0.0
bpy910dih	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
incdfl	0.0	0.9	1.5	0.0	1.2	0.9	0.6	0.0	0.0	0.0
dbahacr	0.0	0.8	0.0	2.2	0.5	0.9	0.2	0.0	0.0	0.0
dbajacr	0.0	0.8	0.5	3.4	0.7	0.8	0.7	0.0	0.0	0.0
in123pyr	0.0	1.1	1.0	1.5	2.1	1.5	1.7	0.0	0.0	0.0
dbahacan	0.0	1.1	1.3	2.5	3.2	1.5	0.9	0.0	0.0	0.0
dbajan	0.0	1.3	1.4	1.8	0.4	0.5	1.4	0.0	0.0	0.0
bbchr	1.2	1.0	1.2	1.5	1.5	1.0	0.8	0.0	0.0	0.0
pic	0.0	1.2	1.4	0.0	3.1	1.0	1.3	0.0	0.0	0.0
bghipe	1.6	1.3	2.1	2.3	2.3	2.4	2.0	0.0	0.0	0.0
anthan	0.0	0.0	1.0	0.0	1.7	0.0	1.4	0.0	0.0	0.0
dbalpyr	0.0	0.0	3.8	0.0	4.8	0.0	1.7	1.5	0.0	0.0
corone	0.0	0.0	0.9	0.0	0.0	0.0	0.8	0.0	0.0	0.0
dbaepyr	0.0	0.0	1.6	0.0	0.0	0.0	3.6	0.0	0.0	0.0
dbaipyr	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.5	0.0	0.0
dbahpyr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
dbbkfl	0.0	0.0	1.4	0.0	0.0	0.0	3.6	0.0	0.0	0.0
dbth	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	3.6	3.2
dbcgcar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
mchol3	0.0	1.0	0.0	1.3	0.6	0.4	1.3	0.0	0.0	0.0

TABLE 56. MEDIUM-DUTY VEHICLE AVERAGE ALKANES IN EXHAUST, µg/mi
(No Statistical Analyses Were Performed On These Data)

TEST NUMBER	MD-NE-F-D-72-1	MD-NE-F-D-20-1	MD-NE-F-B20-72-1	MD-NE-F-B20-20-1	MD-NE-A-D-72-1	MD-NE-A-D-20-2	MD-NE-A-B-20-72-3	MD-NE-A-B-20-20-2	MD-HE-F-D-72-2RR	MD-HE-F-D-20-1	MD-HE-F-B20-72-3	MD-HE-F-B20-20[a]	MD-HE-A-D-72-1	MD-HE-A-D-20-1	MD-HE-A-B20-72-1	MD-HE-A-B20-20-1
Source	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20
Temp	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
dodec	1050.6	1620.8	875.6	743.6	807.7	1155.5	295.5	385.0	0.2	484.1	0.7	1179.8	1.2	399.8	1.2	348.7
norfarn	533.7	781.2	542.5	446.2	547.9	693.2	242.0	266.1	103.9	637.0	83.1	1058.4	71.1	480.7	78.7	491.1
tridec	1533.0	2503.3	1407.5	1331.9	1356.4	1920.1	564.2	722.8	237.9	1468.4	184.2	2683.2	192.1	1185.0	237.6	1314.7
hpycyhx	74.3	177.5	125.3	104.7	141.4	196.4	58.9	71.7	29.8	187.6	20.5	297.8	21.8	148.1	25.3	133.5
farnes	390.5	640.0	335.5	277.5	333.7	433.9	131.1	181.8	50.8	329.8	59.6	654.0	67.7	287.9	76.7	299.7
tdec	1241.3	2109.5	1413.3	1282.7	1354.2	1946.3	588.9	818.7	126.5	1256.5	97.8	2911.6	122.8	1264.3	161.4	1167.6
ocycyhx	57.5	135.4	96.6	102.3	120.5	127.4	58.1	64.3	14.4	80.2	11.6	186.8	10.2	81.5	9.6	81.7
pentad	1152.4	1963.0	1183.2	1136.9	1095.1	1673.4	493.7	740.7	229.4	1333.1	188.0	2793.6	217.4	1357.5	290.8	1243.1
noycyhx	85.7	151.9	91.2	81.3	100.8	101.0	36.6	56.0	18.9	97.3	11.5	150.5	16.5	95.5	24.0	95.9
hexad	716.8	1419.6	756.7	702.9	638.7	1106.9	229.7	399.4	212.6	984.6	157.6	2079.7	211.6	918.5	279.3	927.0
norprst	347.2	601.1	324.8	253.6	305.1	428.2	78.7	135.7	109.4	446.2	87.2	922.3	80.4	443.7	134.9	446.0
decyhx	31.7	67.4	34.8	25.7	35.6	49.0	13.3	17.0	16.6	60.4	11.2	121.4	15.6	66.4	21.3	62.4
heptad	503.2	1077.9	496.0	448.1	360.2	751.8	116.8	158.6	182.6	1006.6	145.9	2156.0	186.8	1166.5	328.6	1054.3
heptdpris	299.6	523.0	177.3	137.4	162.0	267.6	29.9	22.1	55.6	237.3	45.4	558.3	57.6	331.9	85.1	269.5
dec1yhx	18.2	45.8	20.0	16.9	16.4	32.3	4.1	2.0	23.8	43.6	17.9	70.4	5.9	14.8	9.5	37.4
octad	152.3	501.7	183.4	299.8	98.4	348.5	43.0	117.7	147.9	554.4	124.0	1260.7	159.5	590.7	268.8	649.2
phytan	102.2	249.6	94.2	137.8	90.6	172.7	22.2	56.4	72.0	223.7	53.9	423.1	60.5	218.9	107.0	249.6
dec2yhx	6.4	15.3	12.9	12.9	9.6	11.7	1.7	2.4	11.8	28.4	7.0	56.6	9.4	21.4	5.4	38.8
nonad	97.3	388.3	141.0	333.0	85.8	279.4	90.5	249.8	219.5	509.3	161.1	1009.2	162.7	409.8	201.3	546.1
dec3yhx	7.5	22.5	10.3	16.2	6.4	10.6	4.8	7.5	7.0	7.9	3.7	30.0	7.3	9.1	2.9	9.9
eicosa	101.4	295.7	128.6	298.2	104.9	241.4	128.7	266.6	248.4	518.0	224.6	899.6	236.1	408.3	241.1	560.1
dec4yhx	5.2	12.4	5.4	5.1	2.6	6.0	2.4	3.5	13.8	12.1	8.6	16.5	5.1	7.4	6.8	10.3
heneic	104.1	233.1	56.3	14.4	80.2	154.4	43.5	20.0	166.7	397.4	167.0	51.8	168.1	300.9	157.4	36.9
dec5yhx	3.9	12.5	3.2	14.8	4.7	7.0	3.4	6.8	14.5	26.5	10.5	27.7	12.7	17.3	18.4	20.9
docosa	56.3	123.2	50.0	116.6	48.0	86.4	45.9	105.3	91.5	196.0	101.0	350.8	107.2	181.2	114.8	247.9

TABLE 56 (CONT'D). MEDIUM-DUTY VEHICLE AVERAGE ALKANES IN EXHAUST, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	**MD-NE-F-D-72-1**	**MD-NE-F-D-20-1**	**MD-NE-F-B20-72-1**	**MD-NE-F-B20-20-1**	**MD-NE-A-D-72-1**	**MD-NE-A-D-20-2**	**MD-NE-A-B-20-72-3**	**MD-NE-A-B-20-20-2**	**MD-HE-F-D-72-2RR**	**MD-HE-F-D-20-1**	**MD-HE-F-B20-72-3**	**MD-HE-F-B20-20[a]**	**MD-HE-A-D-72-1**	**MD-HE-A-D-20-1**	**MD-HE-A-B20-72-1**	**MD-HE-A-B20-20-1**
Source	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust	Exhaust
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20
Temp	72	20	72	20	72	20	72	20	72	20	72	20	72	20	72	20
Media	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
dec6yhx	1.5	1.6	0.8	2.8	2.0	1.6	2.9	2.0	6.9	6.8	10.6	13.9	8.6	8.9	9.5	9.9
tricosa	8.7	46.2	8.1	50.9	9.7	36.7	18.6	42.5	103.6	167.7	86.0	155.3	107.8	156.4	106.2	189.5
dec7yhx	2.5	5.2	0.4	3.5	1.2	3.9	0.8	3.7	8.8	9.0	5.5	5.7	6.7	6.6	13.2	10.8
tetcos	0.0	0.0	0.0	9.2	0.0	0.0	0.0	4.1	87.7	116.1	43.3	26.2	96.9	111.5	101.3	135.8
dec8yhx	2.2	0.4	0.1	7.0	0.3	1.5	0.9	1.1	3.9	1.5	3.8	5.4	3.0	5.2	2.4	2.9
pencos	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.9	30.4	18.2	31.0	36.6	59.3	46.2	81.9
hexcos	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.8	35.1	37.7	71.4	21.7	49.8	31.3	57.1
dec9yhx	0.0	0.0	0.0	0.1	0.0	0.0	3.1	0.0	2.2	1.9	3.0	4.6	2.9	2.5	2.5	8.6
hepcos	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.4	15.2	28.3	30.8	12.0	19.1	15.1	12.8
cyhxeic	0.0	1.4	0.7	0.7	0.4	1.3	0.9	0.5	2.0	3.6	1.7	5.9	1.3	4.0	3.5	2.2
octcos	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	14.9	14.4	9.6	17.6	8.3	15.7	11.0	2.6
noncos	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.6	6.3	13.0	17.2	9.3	10.3	9.0	7.7
cyhxhen	0.5	1.4	1.5	1.6	0.6	1.3	0.0	0.5	5.2	9.6	11.8	16.7	4.7	7.1	5.3	7.9
tricont	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	6.8	6.0	5.2	6.5	6.0	2.5	4.2
htricont	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.1	7.2	4.5	7.9	1.9	9.6	2.8	1.3
dtricont	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	6.2	4.6	2.9	5.6	1.9	1.3	0.7
ttricont	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	6.5	2.2	2.7	0.7	0.0	0.0	0.7
tetricont	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	7.4	3.0	2.7	2.6	0.7	0.6	0.4
ptricont	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	2.2	2.0	1.6	1.9	0.2	0.4	2.5
hxtricont	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	2.9	0.6	0.4	1.6	0.5	1.5	1.0
hptricont	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	1.8	0.4	0.5	0.6	0.2	0.7	0.5
otricont	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	3.2	1.6	1.2	2.4	0.4	0.3	0.4
ntricont	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.1	2.8	0.8	1.4	0.2	0.4	0.3
tecont	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.8	0.1	0.2	0.4	0.3
hxtric74	7.3	10.8	3.5	8.3	4.6	12.9	3.3	9.4	58.7	70.1	59.6	61.3	56.2	64.9	54.3	67.5
UCM	16758	32203	23052	25553	17221	23823	17520	12166	333051	1088650	272468	2126333	263915	1087734	342813	1107495

MD-HE-F-B20-20-2 sample was lost. The results from MD-HE-F-B20-20-1 are presented.

TABLE 57. MEDIUM-DUTY VEHICLE ALKANES IN FUELS AND LUBRICANTS (No Statistical Analyses Were Performed On These Data)

	ALKANES CONCENTRATIONS, µg/gram									
SAMPLE ID	**MD-NE-F-D**	**MD-NE-F-B20**	**MD-NE-A-D**	**MD-NE-A-B20**	**MD-HE-F-D-72**	**MD-HE-F-B20**	**MD-HE-A-D**	**MD-HE-A-B20**	**EM-6952-F**	**EM-7002-F**
Source	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Oil	Fuel	Fuel
Emitter	Normal	Normal	Normal	Normal	High	High	High	High	NE & HE	NE & HE
Oil	Fresh	Fresh	Aged	Aged	Fresh	Fresh	Aged	Aged	F&A	F&A
Fuel	Diesel	B20	Diesel	B20	Diesel	B20	Diesel	B20	Diesel	B20
Temp	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20	72 & 20
Tracer	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
dodec	34	27	23	1	20	0	1	0	3681	2909
norfarn	0	52	0	0	51	7	17	0	1642	1235
tridec	75	69	58	2	63	0	1	0	4638	3523
hpycyhx	2	3	4	0	5	0	0	0	352	290
farnes	31	25	21	1	35	0	0	0	4143	3685
tdec	221	183	133	28	213	9	17	12	17626	13699
ocycyhx	17	10	10	2	16	0	1	0	1195	870
pentad	212	186	174	87	245	6	55	48	15372	12226
noycyhx	13	18	15	6	18	0	5	2	903	678
hexad	172	162	171	169	271	35	99	124	12027	9493
norprst	73	39	69	60	153	13	57	37	4503	3644
decyhx	17	17	9	10	14	2	11	7	607	506
heptad	266	207	244	433	415	41	210	228	12689	9161
heptdpris	67	29	56	104	94	13	59	72	3295	7441
dec1yhx	19	7	11	14	20	2	22	14	459	375
octad	266	224	421	388	524	144	285	362	7064	6600
phytan	92	82	151	108	174	52	97	128	2633	2531
dec2yhx	6	21	24	28	42	40	20	17	318	277
nonad	312	254	428	353	503	213	355	411	6334	5305
dec3yhx	15	13	15	32	39	21	8	32	143	109
eicosa	500	357	534	452	605	352	449	487	4594	3861
dec4yhx	64	79	9	37	116	40	46	97	95	70
heneic	689	528	678	508	790	557	567	599	3417	39
dec5yhx	136	88	107	84	56	87	105	106	62	38
docosa	490	441	422	234	515	365	414	392	1437	1106
dec6yhx	59	185	107	85	114	288	147	116	20	19
tricosa	744	667	641	292	860	686	705	607	1124	811
dec7yhx	148	124	136	132	122	113	116	118	9	15
tetcos	430	379	563	371	634	374	545	527	570	461
dec8yhx	144	89	106	39	47	45	100	37	5	4
pencos	365	324	389	378	403	372	459	359	271	223
hexcos	381	380	421	376	302	448	498	189	133	96
dec9yhx	0	10	29	20	21	158	89	33	23	2
hepcos	292	339	377	337	524	159	400	91	55	37
cyhxeic	22	91	17	41	63	57	104	57	3	0
octcos	169	132	133	528	161	176	187	169	22	19
noncos	134	102	168	215	87	242	172	44	7	7
cyhxhen	59	21	29	36	5	48	36	11	8	12
tricont	121	140	90	132	71	82	121	39	2	2
htricont	74	63	65	35	63	6	102	50	1	1
dtricont	31	45	16	31	20	10	1	38	0	0
ttricont	12	6	10	20	22	17	11	5	1	0
tetricont	8	5	5	11	2	15	10	5	0	0
ptricont	3	5	6	12	3	6	1	4	0	0
hxtricont	2	3	4	19	4	3	1	1	0	0
hptricont	5	3	2	5	3	2	2	3	0	0
otricont	3	4	2	3	1	2	3	2	0	0
ntricont	3	12	5	11	3	3	1	4	0	0
tecont	4	4	2	10	2	2	4	1	0	0
hxtric74	231	216	194	5	224	216	200	191	0	0
UCM	240702	257896	230645	215598	270533	239821	229779	214785	307094	318303

TABLE 58. AVERAGE RESULTS OF MEDIUM-DUTY VEHICLE EXHAUST HOPANES AND STERANES, µg/mi
(No Statistical Analyses Were Performed On These Data)

Test Number	MD-NE-F-D-72	MD-NE-F-D-20	MD-NE-F-B20-72	MD-NE-F-B20-20	MD-NE-A-D-72	MD-NE-A-D-20	MD-NE-A-B-20-72	MD-NE-A-B-20-20	MD-HE-F-D-72	MD-HE-F-D-20	MD-HE-F-B20-72	MD-HE-F-B20-20[a]	MD-HE-A-D-72	MD-HE-A-D-20	MD-HE-A-B20-72	MD-HE-A-B20-20
Emitter	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	High	High	High	High	High	High	High	High
Oil	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged	Fresh	Fresh	Fresh	Fresh	Aged	Aged	Aged	Aged
Fuel	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20	Diesel	Diesel	B20	B20
Temp	72.000	20.000	72.000	20.000	72.000	20.000	72.000	20.000	72.000	20.000	72.000	20.000	72.000	20.000	72.000	20.000
Media	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD	F+XAD
TB Correction	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
hop15	0.403	0.619	0.394	0.747	0.506	0.850	0.470	0.873	1.463	1.331	1.557	1.060	1.805	2.065	2.067	2.340
hop17	0.541	1.062	0.716	0.991	0.526	1.028	0.598	1.225	4.336	4.144	4.454	3.421	4.732	5.675	5.104	5.394
hop19	0.466	0.992	0.594	0.917	0.176	0.645	0.148	0.946	4.440	4.758	5.106	3.888	3.964	4.877	5.016	5.118
hop20	0.163	0.305	0.206	0.206	0.159	0.375	0.129	0.329	0.141	0.214	0.215	0.081	0.037	0.210	0.251	0.165
hop21	0.523	0.964	0.716	0.937	0.393	0.620	0.426	1.040	2.185	2.246	2.294	1.974	1.864	2.291	2.084	2.283
hop22	0.440	0.779	0.554	0.673	0.259	0.423	0.269	0.603	1.929	1.846	1.821	1.576	1.486	1.695	1.958	1.713
hop23	0.112	0.112	0.112	0.193	0.108	0.000	0.000	0.000	0.022	0.032	0.000	0.000	0.138	0.000	0.013	0.089
hop24	0.145	0.294	0.115	0.119	0.000	0.000	0.000	0.129	1.143	1.160	1.289	1.070	0.922	1.080	1.172	1.368
hop25	0.413	0.599	0.595	0.505	0.218	0.240	0.214	0.423	0.983	1.012	1.172	1.104	0.979	1.098	3.782	2.154
hop26	0.426	0.563	0.425	0.427	0.071	0.256	0.076	0.359	0.734	0.732	0.718	0.606	0.545	0.653	0.989	1.127
hop27	0.008	0.035	0.003	0.000	0.000	0.000	0.000	0.000	0.521	0.607	0.518	0.406	0.340	0.393	0.452	0.503
ster42	0.322	0.510	0.354	0.425	0.329	0.568	0.440	0.635	0.898	0.778	0.864	0.665	1.006	1.018	0.825	0.912
ster43	0.388	0.934	0.386	0.806	0.204	0.779	0.359	1.015	2.275	2.231	2.268	2.093	2.373	2.425	2.308	2.572
ster44	0.471	0.817	0.495	0.794	0.517	0.834	0.600	1.061	1.284	1.160	1.317	1.216	1.243	1.320	0.967	1.194
ster45_40	0.555	0.255	0.445	0.722	0.450	0.594	0.593	1.193	3.373	3.283	3.102	3.064	3.814	2.799	3.157	3.239
ster46	0.250	0.383	0.379	0.450	0.243	0.358	0.260	0.488	0.664	0.696	0.615	0.548	0.664	0.800	0.705	0.716
ster47	0.232	0.406	0.314	0.493	0.245	0.467	0.242	0.480	1.064	1.049	1.013	1.136	1.194	0.967	0.807	0.951
ster48_41	0.162	0.295	0.146	0.205	0.120	0.129	0.117	0.265	1.543	1.445	1.482	1.227	1.201	0.858	1.334	1.371
ster49	0.054	0.151	0.166	0.202	0.084	0.135	0.039	0.113	0.665	0.619	0.584	0.665	0.716	0.902	0.650	0.851
ster50	0.415	0.639	0.422	0.563	0.241	0.661	0.443	0.597	0.273	0.197	0.236	0.160	0.250	0.258	0.205	0.257
ster51	0.421	0.865	0.532	0.650	0.238	0.490	0.321	0.653	1.233	1.252	1.447	1.043	1.060	1.234	1.129	1.101
ster52	0.409	0.717	0.485	0.658	0.271	0.458	0.295	0.717	0.638	0.652	0.657	0.567	0.662	0.814	0.671	0.707
ster53	0.281	0.579	0.352	0.437	0.194	0.376	0.213	0.576	0.734	0.797	0.671	0.711	0.666	0.658	0.604	0.675

[a] The PM sample for MD-HE-F-B20-20-2 test was lost. This data is from test number MD-HE-F-B20-20-1

TABLE 59. MEDIUM-DUTY VEHICLE LUBRICANTS AND FUELS HOPANES AND STERANES

(No Statistical Analyses Were Performed On These Data)

	Lubricants, µg/gram								**Fuels, µg/gram**	
TEST NUMBER	**MD-NE-F-D**	**MD-NE-F-B20**	**MD-NE-A-D**	**MD-NE-A-B20**	**MD-HE-F-D**	**MD-HE-F-B20**	**MD-HE-A-D**	**MD-HE-A-B20**	**EM-6952-F**	**EM-7002-F**
Emitter	**Normal**	**Normal**	**Normal**	**Normal**	**High**	**High**	**High**	**High**	**NE & HE**	**NE & HE**
Oil	**Fresh**	**Fresh**	**Aged**	**Aged**	**Fresh**	**Fresh**	**Aged**	**Aged**	**F&A**	**F&A**
Fuel	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**	**Diesel**	**B20**
Temp	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**	**72 & 20**
Media	**Oil**	**Oil**	**Oil**	**Oil**	**Oil**	**Oil**	**Oil**	**Oil**	**Fuel**	**Fuel**
hop15	13.71	42.38	13.21	34.43	37.79	43.66	32.13	38.14	0.14	0.19
hop17	40.20	44.26	35.79	280.19	40.46	30.50	29.86	45.73	0.40	0.47
hop19	40.73	31.64	26.61	148.09	33.26	23.58	26.53	32.98	0.18	0.23
hop20	0.00	0.00	0.00	23.63	0.00	0.00	0.00	0.98	0.00	0.00
hop21	26.09	22.90	15.66	114.14	16.21	16.73	15.54	21.47	0.08	0.13
hop22	21.65	19.64	12.30	93.35	10.61	10.47	11.23	20.28	0.05	0.10
hop23	7.08	6.00	3.94	33.49	2.66	2.57	3.36	6.98	0.00	0.00
hop24	15.13	11.40	8.00	60.35	9.02	7.99	5.77	9.11	0.00	0.10
hop25	20.88	6.50	8.91	44.09	5.73	6.07	5.07	10.01	0.00	0.10
hop26	11.34	8.70	4.74	39.22	5.83	4.10	3.86	8.78	0.00	0.00
hop27	5.91	4.67	3.67	27.39	2.73	2.83	2.35	3.11	0.00	0.00
ster42	8.03	8.87	6.49	13.25	17.53	6.37	8.53	11.05	0.09	0.08
ster43	30.58	26.65	19.65	21.46	26.62	21.17	20.33	23.98	0.22	0.24
ster44	22.36	16.64	13.34	16.59	19.31	12.77	14.05	16.47	0.18	0.16
ster45_40	40.09	25.93	23.74	26.04	30.18	23.21	21.39	23.19	0.23	0.41
ster46	9.98	7.32	6.70	9.11	8.67	5.66	6.70	8.63	0.17	0.20
ster47	11.74	9.91	9.85	11.19	11.00	8.19	9.64	11.20	0.03	0.05
ster48_41	10.79	9.98	8.11	24.76	7.96	7.76	7.53	8.96	0.09	0.02
ster49	14.33	5.78	8.04	5.55	5.65	4.69	4.14	5.04	0.05	0.10
ster50	4.49	2.45	2.71	4.26	3.77	2.96	2.33	4.13	0.02	0.02
ster51	15.36	14.49	10.83	18.53	16.23	11.10	10.66	13.00	0.06	0.11
ster52	10.38	11.36	8.19	12.21	9.92	8.89	8.38	10.25	0.04	0.06
ster53	8.25	11.06	8.60	16.86	6.59	7.98	6.97	8.71	0.02	0.23

8.5.2.6 Particle-Phase Elemental and Organic Carbon

PM sampled from the medium-duty vehicles were also analyzed by DRI for elemental carbon and organic carbon (EC/OC). Table 60 shows the average results in µg/mile of the replicate tests performed in each configuration. The configurations are identified in the five left columns of the table, and EC/OC results are shown in the three right columns. In Table 60, EC is elemental carbon, OC is organic carbon, and TC is total carbon.

TABLE 60. MEDIUM-DUTY VEHICLE PARTICULATE ELEMENTAL CARBON AND ORGANIC CARBON
(No Statistical Analyses Were Performed On These Data)

					CARBON EMISSION RATE, mg/mile		
ID	**Emitter**	**Oil**	**Fuel**	**Temp**	**EC**	**OC**	**TC**
MD-NE-F-D-72	Normal	Fresh	Diesel	72	71.8	21.6	93.4
MD-NE-F-D-20	Normal	Fresh	Diesel	20	90.6	41.7	132.3
MD-NE-F-B20-72	Normal	Fresh	B20	72	65.4	27.9	93.3
MD-NE-F-B20-20	Normal	Fresh	B20	20	67.4	48.6	115.9
MD-NE-A-D-72	Normal	Aged	Diesel	72	76.1	24.8	100.9
MD-NE-A-D-20	Normal	Aged	Diesel	20	75.9	39.3	115.2
MD-NE-A-B-20-72	Normal	Aged	B20	72	53.6	27.9	81.4
MD-NE-A-B-20-20	Normal	Aged	B20	20	68.8	47.3	116.0
MD-HE-F-D-72	High	Fresh	Diesel	72	316.0	59.1	375.1
MD-HE-F-D-20	High	Fresh	Diesel	20	180.5	68.6	249.1
MD-HE-F-B20-72	High	Fresh	B20	72	269.7	63.0	332.7
MD-HE-F-B20-20	High	Fresh	B20	20	175.9	86.7	262.7
MD-HE-A-D-72	High	Aged	Diesel	72	332.5	61.2	393.6
MD-HE-A-D-20	High	Aged	Diesel	20	192.6	64.3	256.9
MD-HE-A-B20-72	High	Aged	B20	72	282.3	53.8	336.1
MD-HE-A-B20-20	High	Aged	B20	20	257.6	102.7	360.3

8.5.2.7 Particle-Phase Sulfates

Particles sampled from the medium-duty tests were also analyzed by DRI for sulfates. Table 61 shows the average results in µg/mile of the replicate tests performed in each configuration.

TABLE 61. AVERAGE SULFATE EMISSIONS FROM MEDIUM-DUTY VEHICLES (No Statistical Analyses Were Performed On These Data)

TEST NUMBER	EMITTER	OIL	FUEL	TEMP	AVERAGE SULFATE (µg/mile)
MD-NE-F-D-72	Normal	Fresh	Diesel	72	402
MD-NE-F-D-20	Normal	Fresh	Diesel	20	1561
MD-NE-F-B20-72	Normal	Fresh	B20	72	124
MD-NE-F-B20-20	Normal	Fresh	B20	20	562
MD-NE-A-D-72	Normal	Aged	Diesel	72	126
MD-NE-A-D-20	Normal	Aged	Diesel	20	458
MD-NE-A-B-20-72	Normal	Aged	B20	72	67
MD-NE-A-B-20-20	Normal	Aged	B20	20	344
MD-HE-F-D-72	High	Fresh	Diesel	72	130
MD-HE-F-D-20	High	Fresh	Diesel	20	486
MD-HE-F-B20-72	High	Fresh	B20	72	195
MD-HE-F-B20-20	High	Fresh	B20	20	420
MD-HE-A-D-72	High	Aged	Diesel	72	228
MD-HE-A-D-20	High	Aged	Diesel	20	614
MD-HE-A-B20-72	High	Aged	B20	72	319
MD-HE-A-B20-20	High	Aged	B20	20	927

8.5.2.8 Particle-Phase Soluble Organic Fraction

PM sampled from the medium-duty tests were also analyzed by DRI for soluble organic fraction (SOF). Table 62 shows the average results for the normal emitter and high emitter, in percent SOF, of the duplicate tests performed in each configuration.

In all cases, operation at 20°F nominally increased SOF percentage compared to operation at 72°F. No trends are evident in SOF percentages when comparing the normal emitter to the high emitter. In all cases, operation with B20 nominally increased SOF compared to operation on straight diesel. With the normal emitter, operation with aged oil nominally increased SOF compared to fresh oil operation, but no SOF trend is evident between fresh and aged oil test of the high emitter.

TABLE 62. MEDIUM-DUTY VEHICLES AVERAGE PARTICLE-PHASE SOLUBLE ORGANIC FRACTION
(No Statistical Analyses Were Performed On These Data)

TEST NUMBER	LUBRICANT	VEHICLE	FUEL	AMBIENT TEMPERATURE, °F	AVERAGE SOF, %
MD-NE-F-D-72	Fresh	Normal Emitter	Diesel	72	19%
MD-NE-F-D-20[a]	Fresh	Normal Emitter	Diesel	20	30%
MD-NE-F-B20-72	Fresh	Normal Emitter	B20	72	24%
MD-NE-F-B20-20	Fresh	Normal Emitter	B20	20	46%
MD-NE-A-D-72	Aged	Normal Emitter	Diesel	72	21%
MD-NE-A-D-20	Aged	Normal Emitter	Diesel	20	32%
MD-NE-A-B20-72	Aged	Normal Emitter	B20	72	27%
MD-NE-A-B20-20	Aged	Normal Emitter	B20	20	40%
MD-HE-F-D-72	Fresh	High Emitter	Diesel	72	16%
MD-HE-F-D-20	Fresh	High Emitter	Diesel	72	30%
MD-HE-F-B20-72	Fresh	High Emitter	B20	20	29%
MD-HE-F-B20-20	Fresh	High Emitter	B20	72	40%
MD-HE-A-D-72	Aged	High Emitter	Diesel	20	16%
MD-HE-A-D-20	Aged	High Emitter	Diesel	72	26%
MD-HE-A-B20-72	Aged	High Emitter	B20	20	22%
MD-HE-A-B20-20	Aged	High Emitter	B20	72	50%

[a] MD-NE-F-D-20-2 measured more SOF mass than PM mass. Data point was deleted, and SOF from only MD-NE-F-D-20-1 is reported.

8.5.2.9 Particle Number and Size Distribution

Figures 49 and 50 show the exhaust PN concentration for the medium-duty (MD) normal emitter (NE). The data are shown for the fresh and aged oil using B0 (TxLED) and B20 at 72°F and 20°F. The data are plotted as an average concentration for the cold-start (Bags 1 and 2) and the hot-start (Bags 3 and 4) portion of the UDC. The exhaust PN concentration ranged from about $10x10^6$ part./cm³ to $20x10^6$ part./cm³. No major differences in PN emissions were observed between 72°F and 20°F or between the cold-start and the hot-start portions of the cycle. The B20 resulted in lower solid and volatile PN emission, compared to B0. The PN reduction was on the fuel order of 15 to 20 percent. The MD NE vehicle with fresh oil emitted higher numbers of solid and volatile particles, compared to PN emissions with the aged oil. This trend was observed during both the cold-start and the hot-start portions of the drive cycle. This trend was also consistent with what was observed with the light-duty NE. Figures 51 and 52 show the percent ratio of solid and volatile PN concentration to total PN concentration. Fifty to 83 percent of the number of particles emitted from the MD NE were solid in nature.

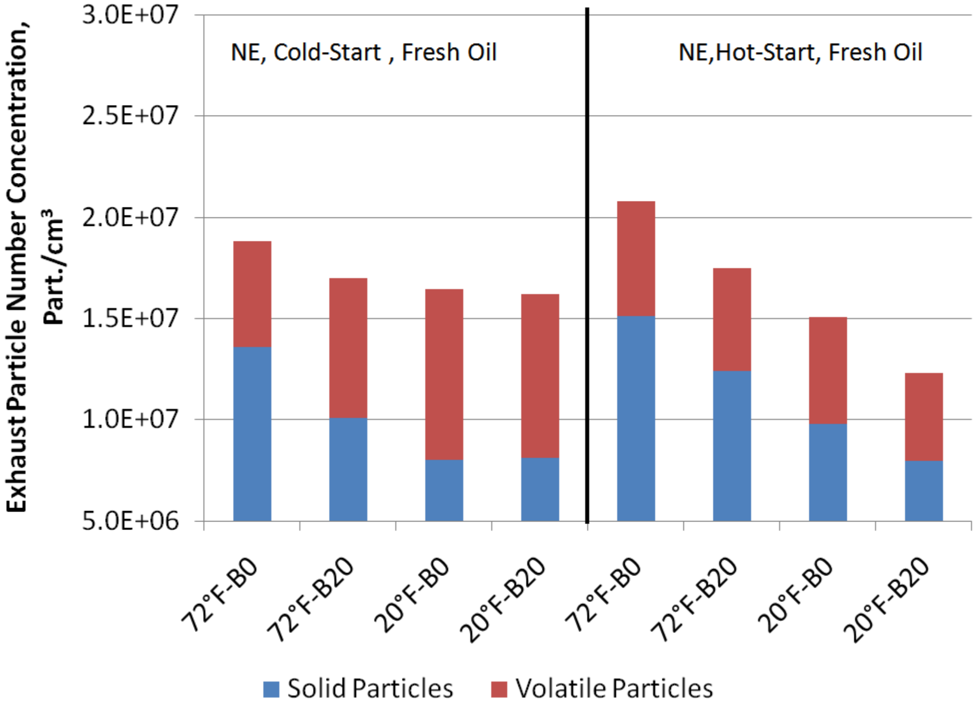

FIGURE 49. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (MEDIUM-DUTY, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

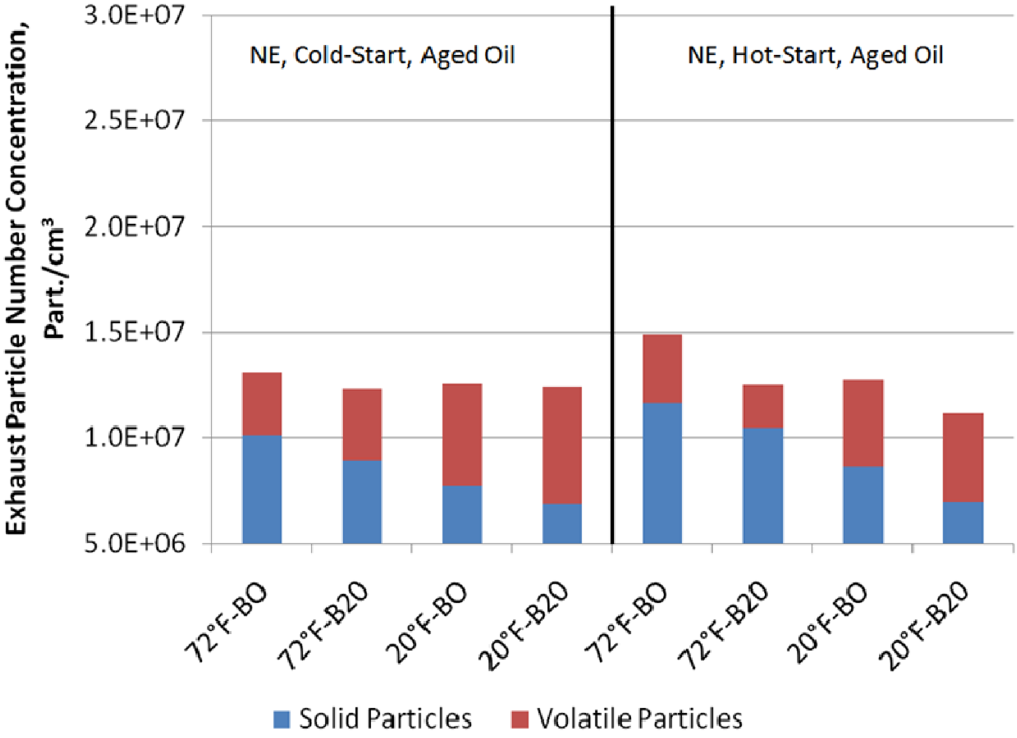

FIGURE 50. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (MEDIUM-DUTY, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

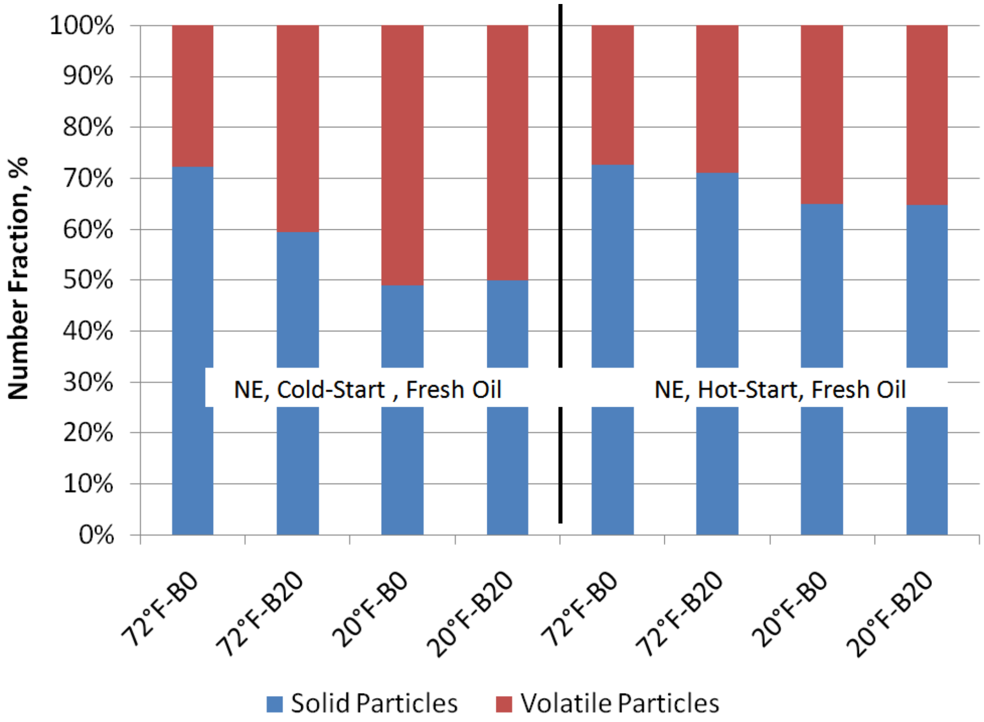

FIGURE 51. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (MEDIUM-DUTY, NORMAL EMITTER, FRESH OIL) (No Statistical Analyses Were Performed On These Data)

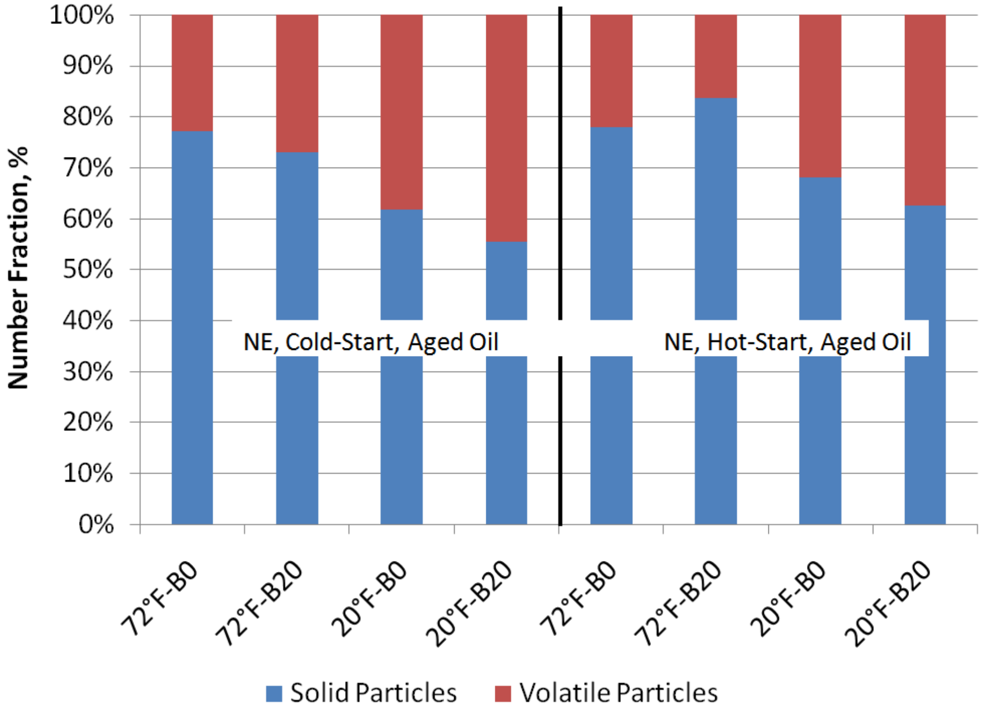

FIGURE 52. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (MEDIUM-DUTY, NORMAL EMITTER, AGED OIL) (No Statistical Analyses Were Performed On These Data)

Figures 53 and 54 show the exhaust PN concentration for the MD high emitter (HE). The exhaust PN concentration ranged from 12x10^6 part./cm³ to 23x10^6 part./cm³. This was very similar in range to the MD NE, but no consistent trend was observed in PN emissions between B0 and B20. No major differences in PN were observed between cold and normal temperature and cold-start and the hot-start portions of the cycle. PN emissions, particularly solid PN, were higher with the aged oil compared to fresh oil. This is consistent with the observation made with the light duty HE between aged oil and fresh oil, although the trend with the MD HE was not as pronounced. As shown in Figures 55 and 56, solid PN ranged from 26 to 65 percent of total PN. This range was lower than observed with the MD NE, suggesting more volatile PN with the MD HE, compared to the MD NE.

Figure 57 through Figure 72 show the size distributions for the MD NE and HE using the fresh and aged oil for the B0 and B20 at 72°F and 20°F ambient temperature. The data are plotted as an average for the cold-start and hot-start portions of the transient cycle. For the NE and HE, the solid particle distributions exhibited a similar monomodal lognormal size distribution structure that consists of an accumulation mode with peaks between 50 nm and 70 nm. The total particle size distribution exhibited a bimodal lognormal distribution structure with a volatile nuclei mode peak between 10 nm and 20 nm. A more pronounced volatile nuclei mode was observed at 20°F compared to 72°F, and with the HE versus the NE. For example, the NE had a small nuclei mode, particularly at 72°F, compared to the accumulation mode, where with the HE, the nuclei mode reached a peak level that is comparable with the peak of the accumulation mode at 72°F, and a higher peak level at 20°F. The increase in volatile nuclei mode particles can be indicative of increased oil consumption using similar technology vehicles with similar fuel and oil usage.

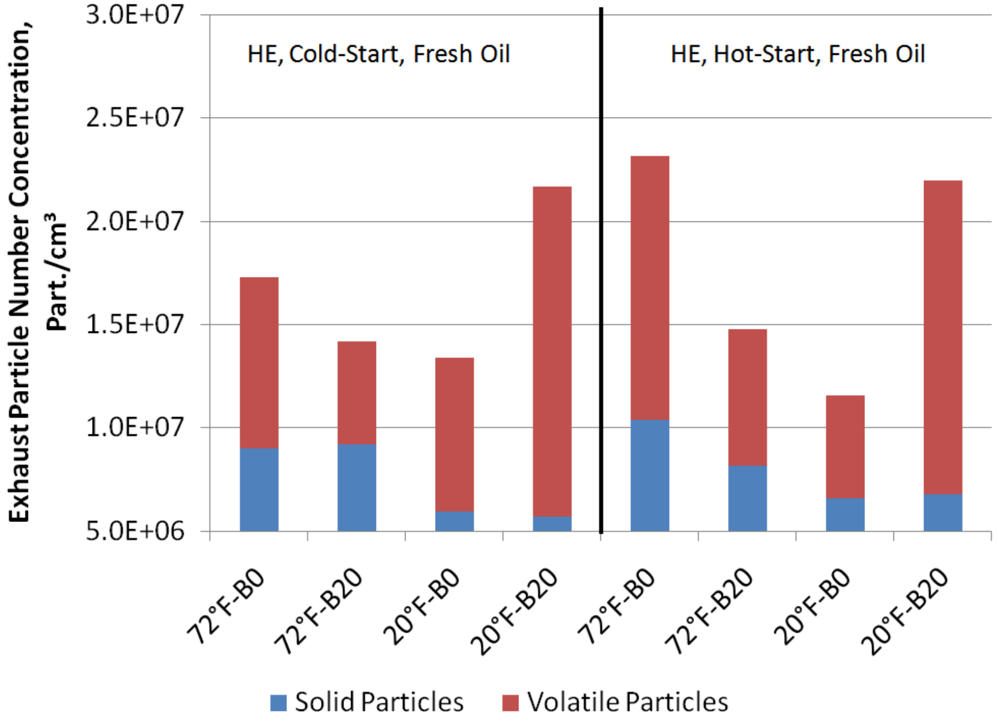

FIGURE 53. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (MEDIUM-DUTY, HIGH EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

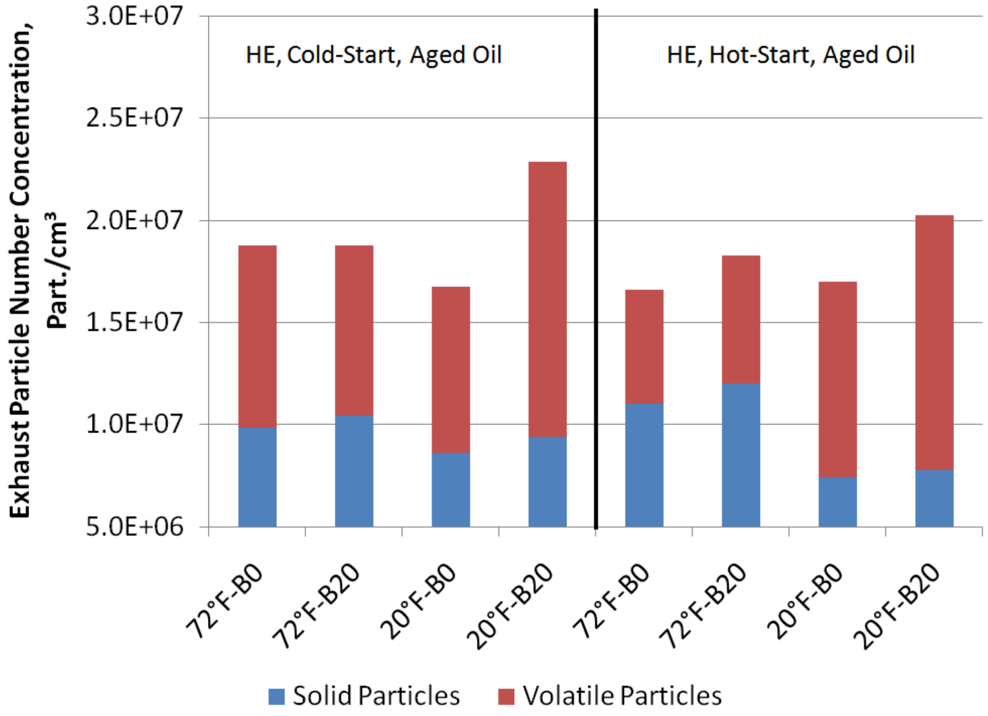

FIGURE 54. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (MEDIUM-DUTY, HIGH EMITTER, AGED OIL) (No Statistical Analyses Were Performed On These Data)

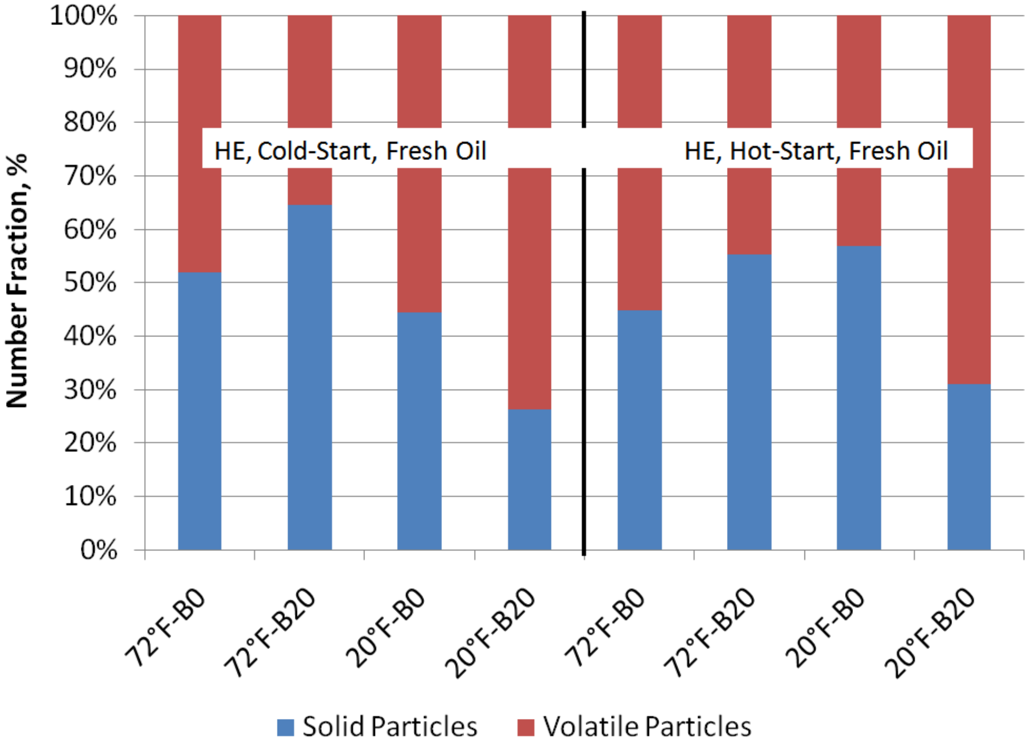

FIGURE 55. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (MEDIUM-DUTY, HIGH EMITTER, FRESH OIL) (No Statistical Analyses Were Performed On These Data)

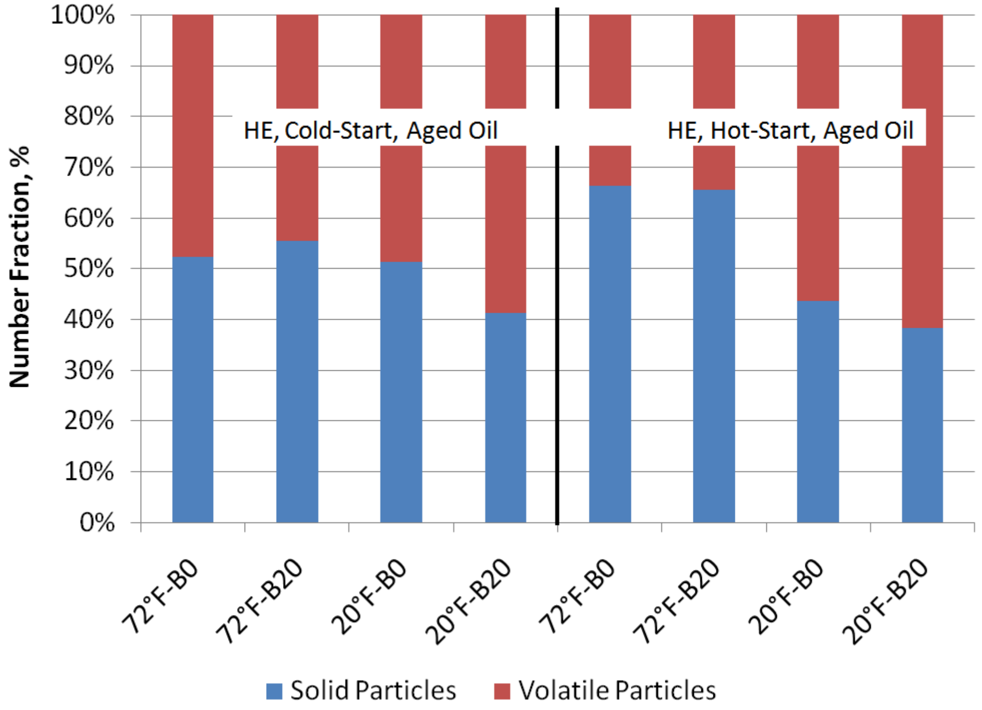

FIGURE 56. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (MEDIUM-DUTY, HIGH EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

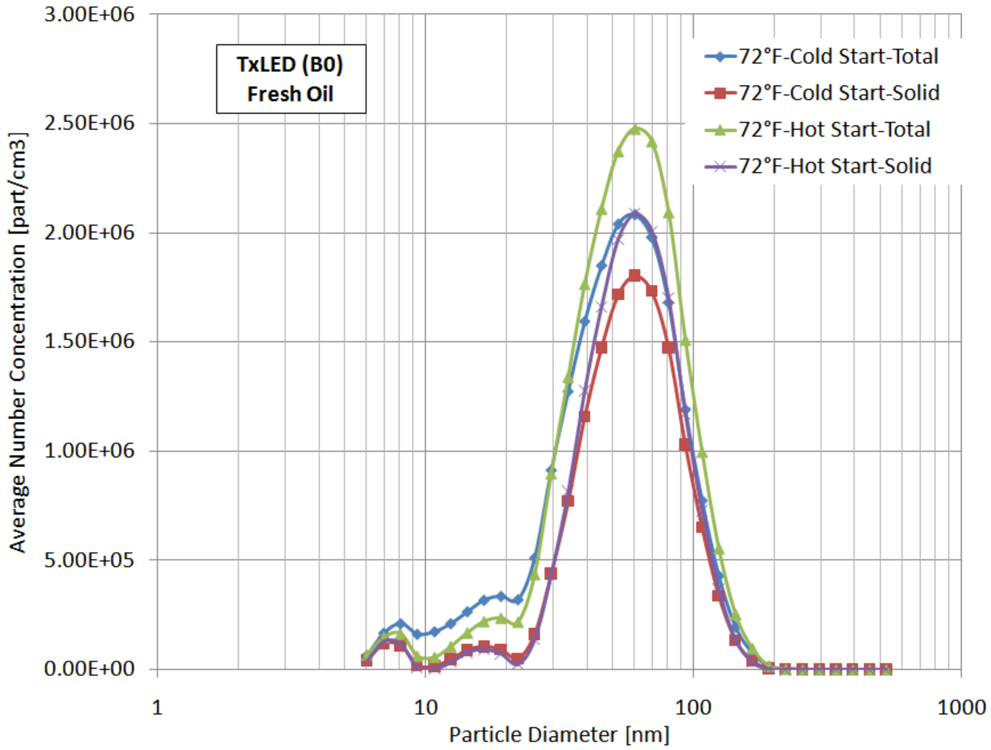

FIGURE 57. NUMBER-WEIGHTED SIZE DISTRIBUTION (B0, 72°F, MEDIUM-DUTY, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

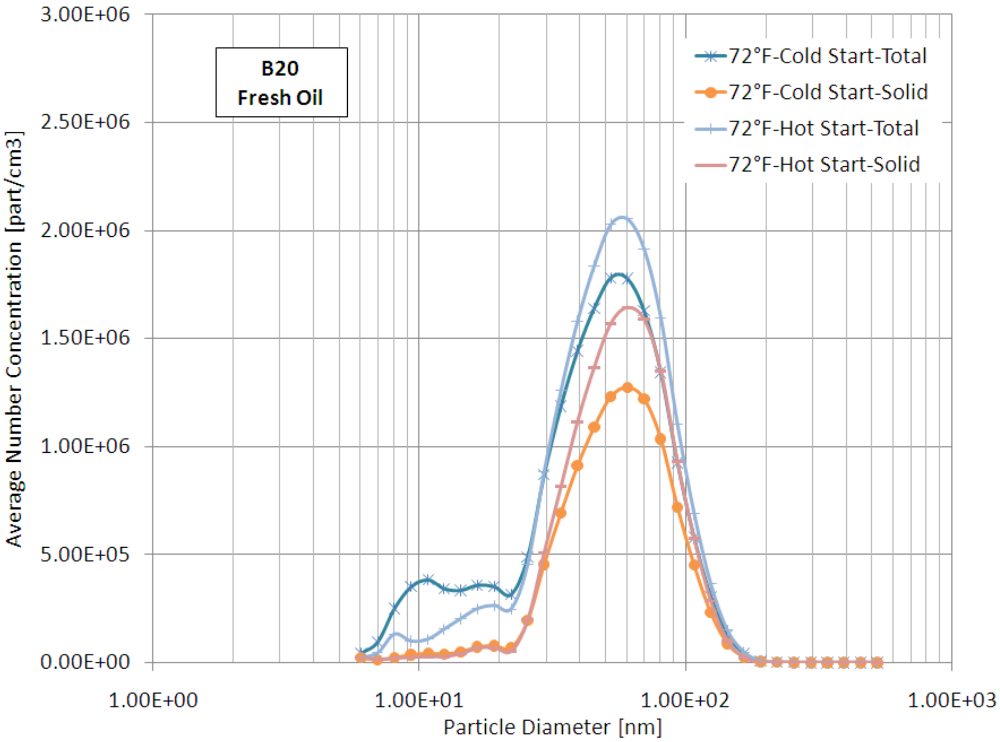

FIGURE 58. NUMBER-WEIGHTED SIZE DISTRIBUTION (B20, 72°F, MEDIUM-DUTY, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

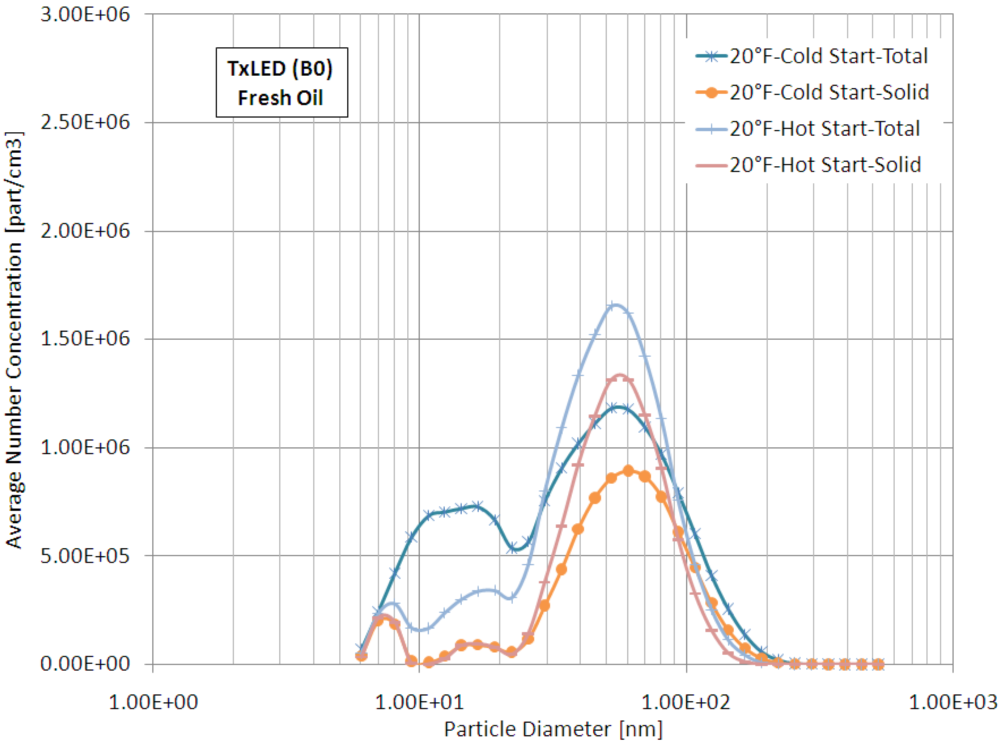

FIGURE 59. NUMBER-WEIGHTED SIZE DISTRIBUTION (B0, 20°F, MEDIUM-DUTY, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

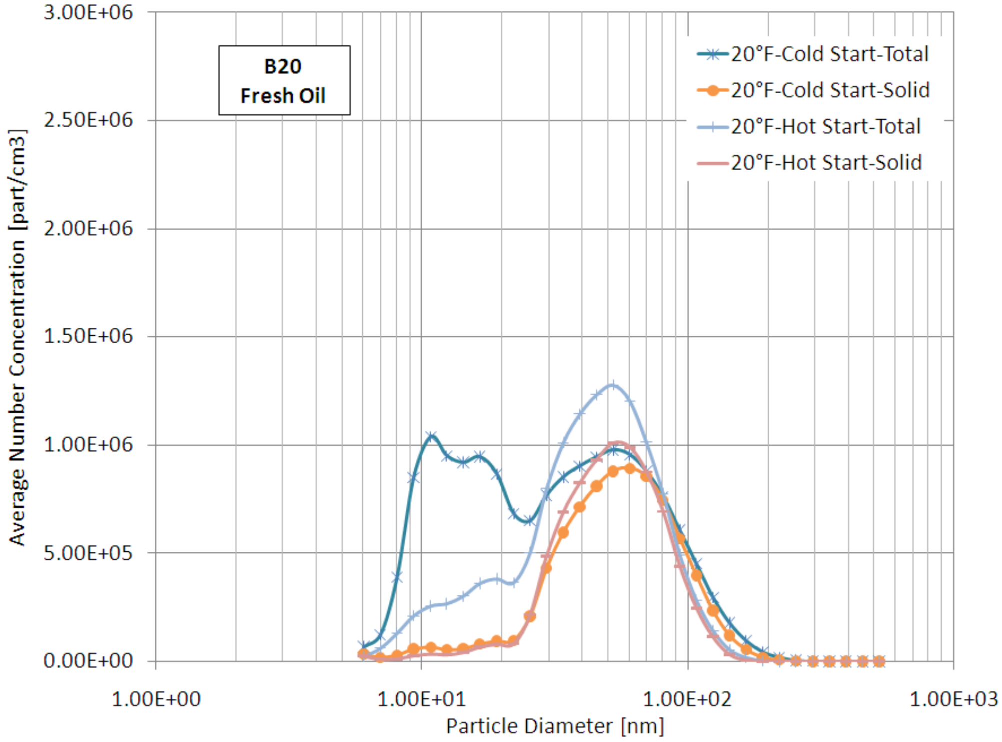

FIGURE 60. NUMBER-WEIGHTED SIZE DISTRIBUTION (B20, 20°F, MEDIUM-DUTY, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

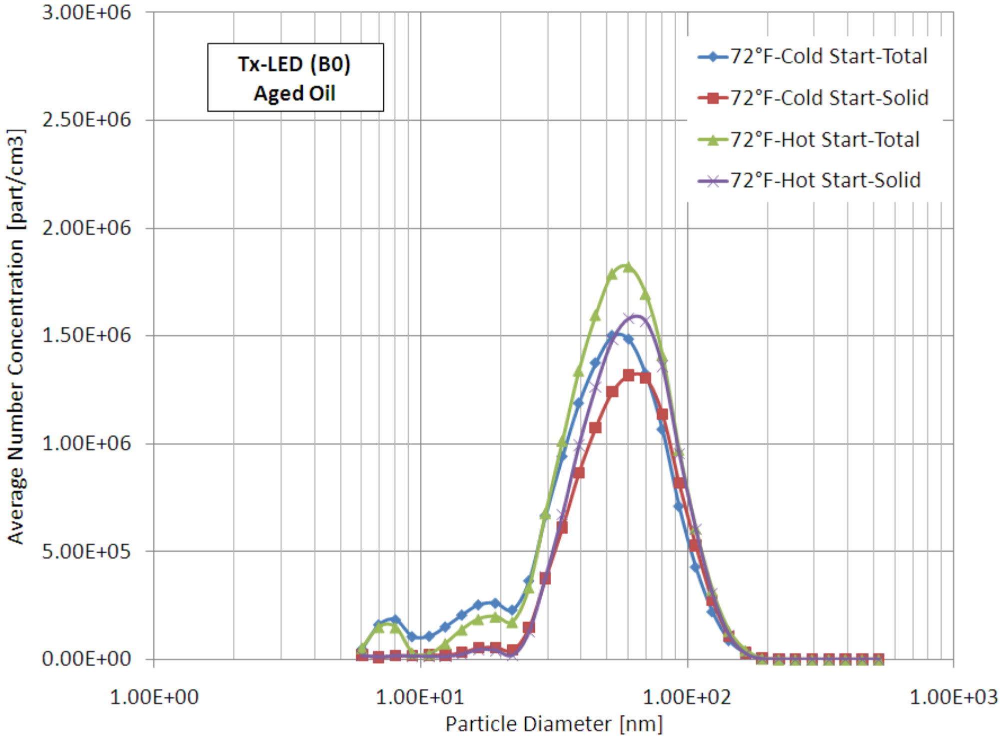

FIGURE 61. NUMBER-WEIGHTED SIZE DISTRIBUTION (B0, 72°F, MEDIUM-DUTY, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

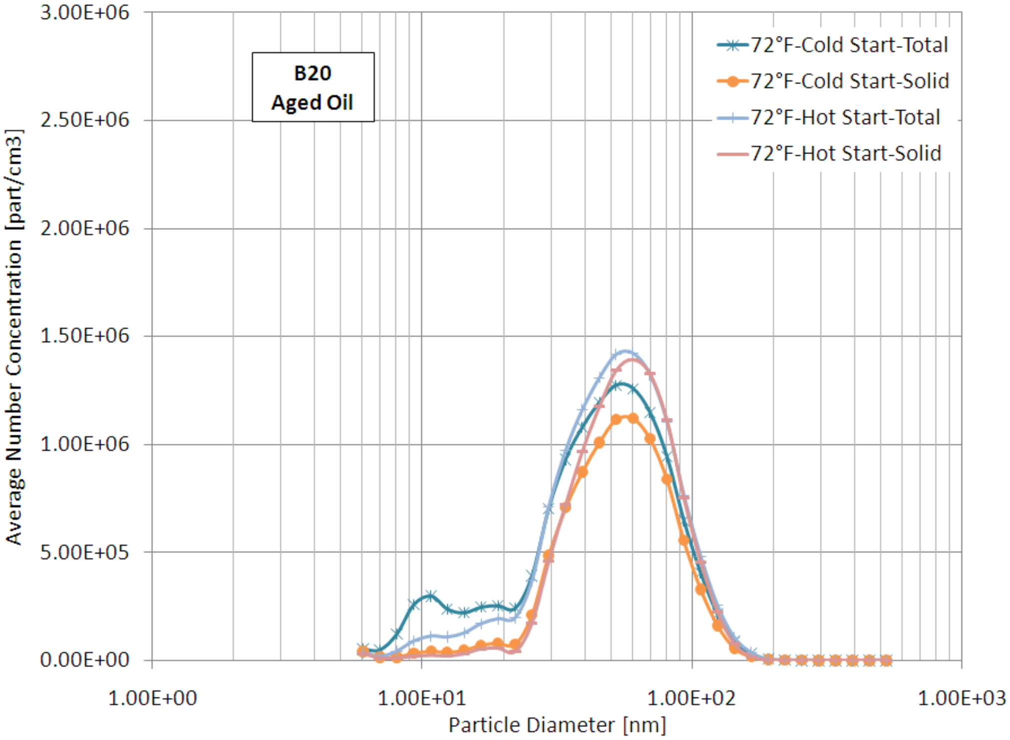

FIGURE 62. NUMBER-WEIGHTED SIZE DISTRIBUTION (B20, 72°F, MEDIUM-DUTY, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

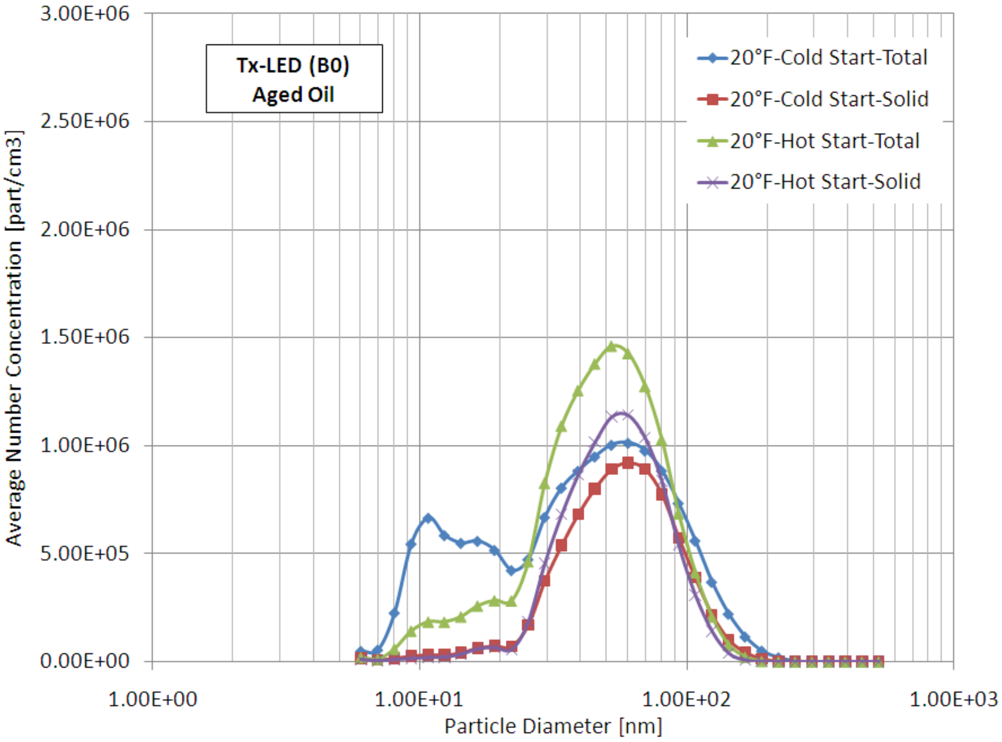

FIGURE 63. NUMBER-WEIGHTED SIZE DISTRIBUTION (B0, 20°F, MEDIUM-DUTY, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

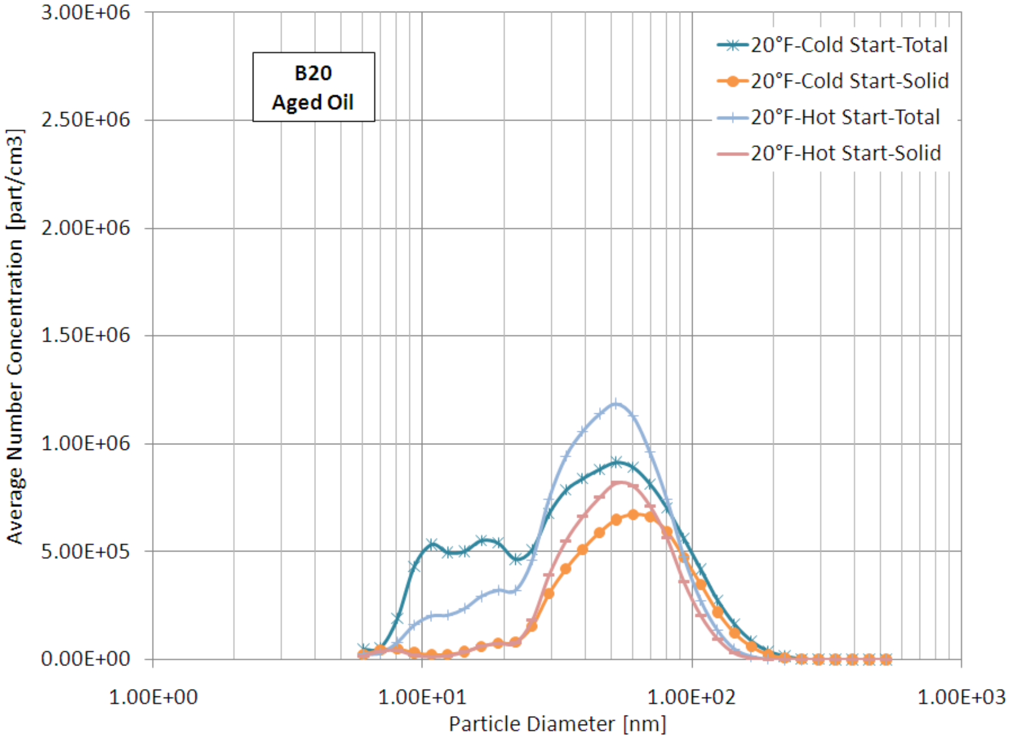

FIGURE 64. NUMBER-WEIGHTED SIZE DISTRIBUTION (B20, 20°F, MEDIUM-DUTY, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

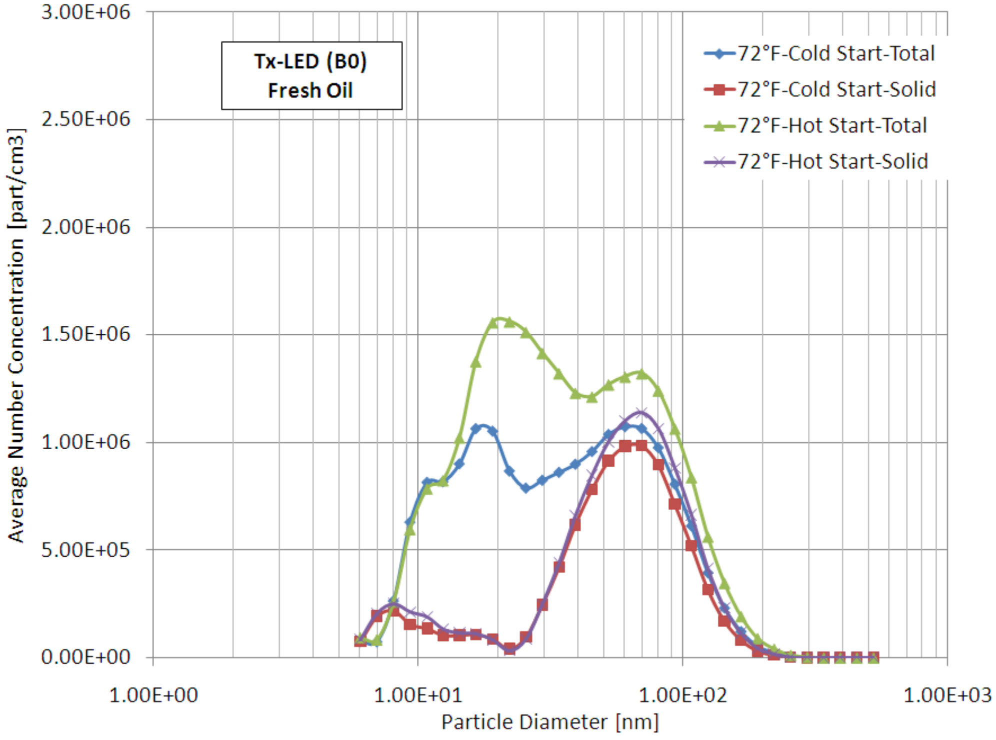

FIGURE 65. NUMBER-WEIGHTED SIZE DISTRIBUTION (B0, 72°F, MEDIUM-DUTY, HIGH EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

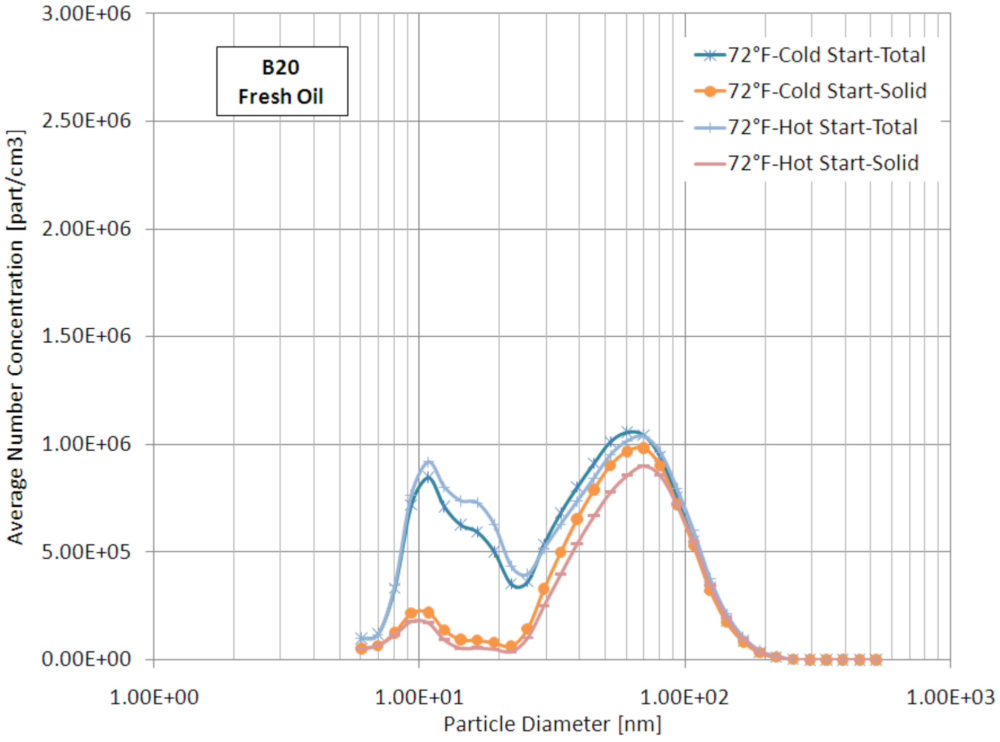

FIGURE 66. NUMBER-WEIGHTED SIZE DISTRIBUTION (B20, 72°F, MEDIUM-DUTY, HIGH EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

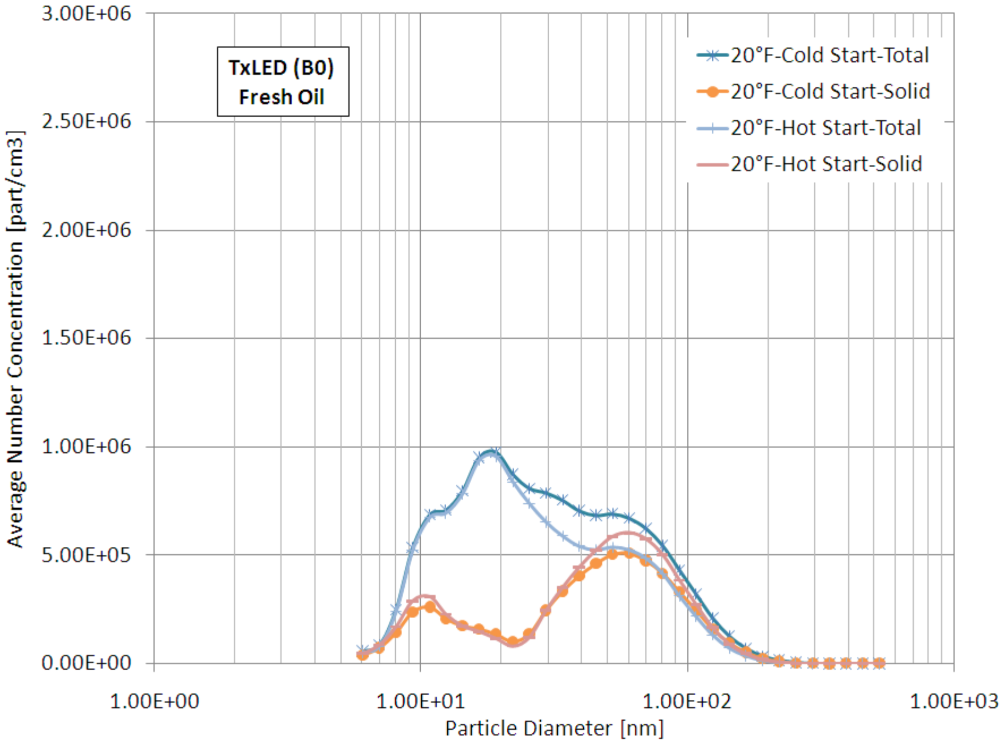

FIGURE 67. NUMBER-WEIGHTED SIZE DISTRIBUTION (B0, 20°F, MEDIUM-DUTY, HIGH EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

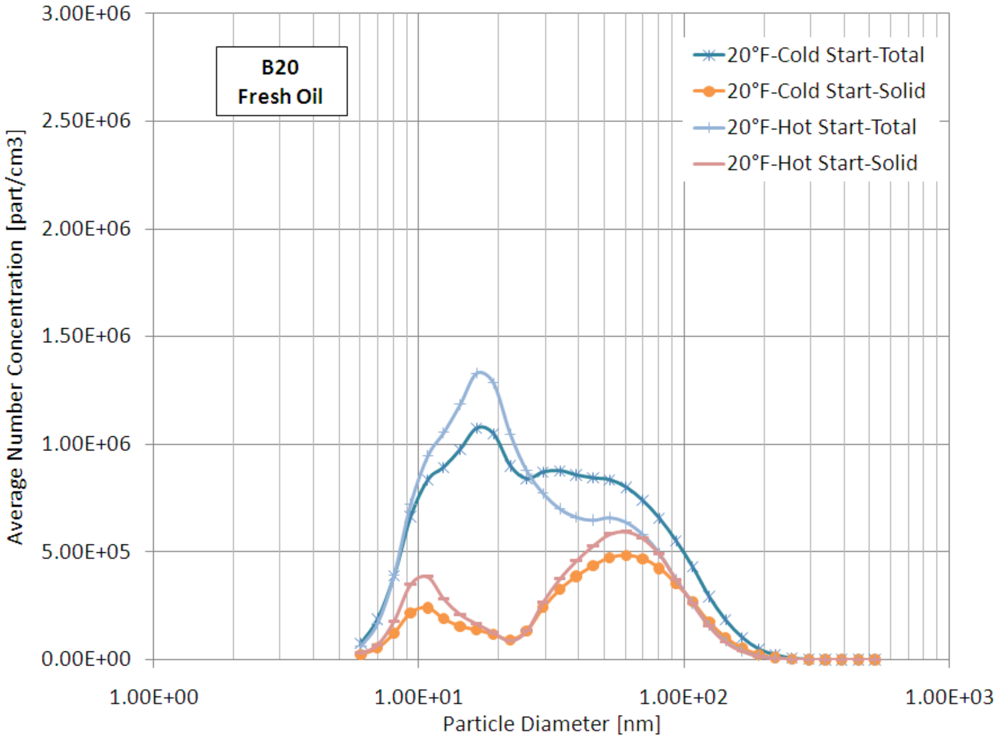

FIGURE 68. NUMBER-WEIGHTED SIZE DISTRIBUTION (B20, 20°F, MEDIUM-DUTY, HIGH EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

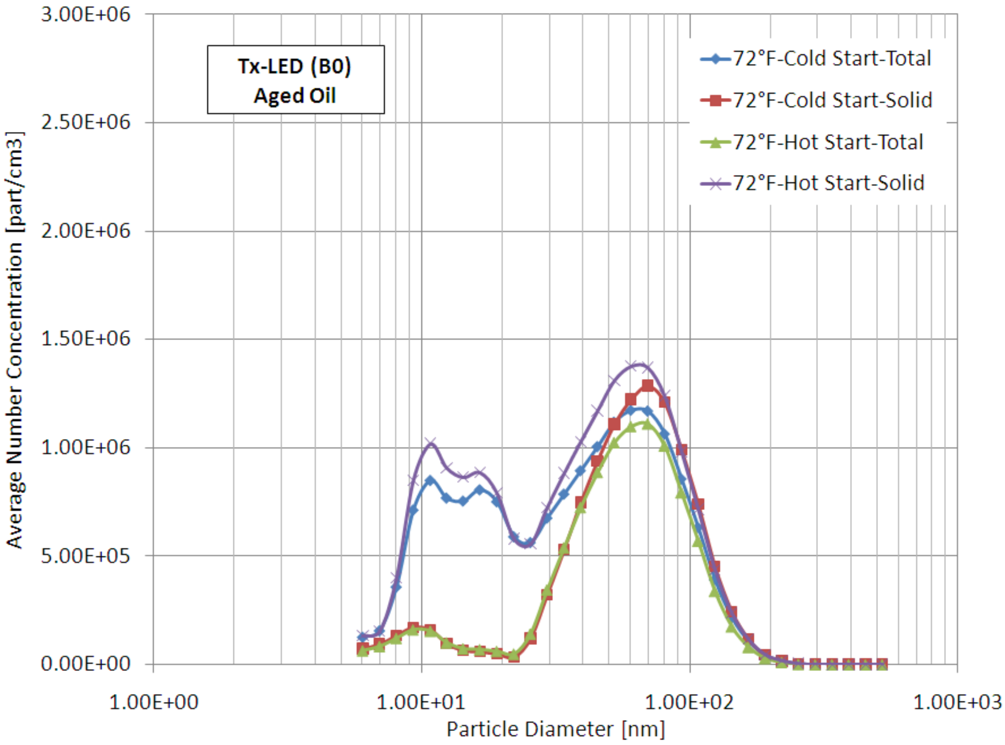

FIGURE 69. NUMBER-WEIGHTED SIZE DISTRIBUTION (B0, 72°F, MEDIUM-DUTY, HIGH EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

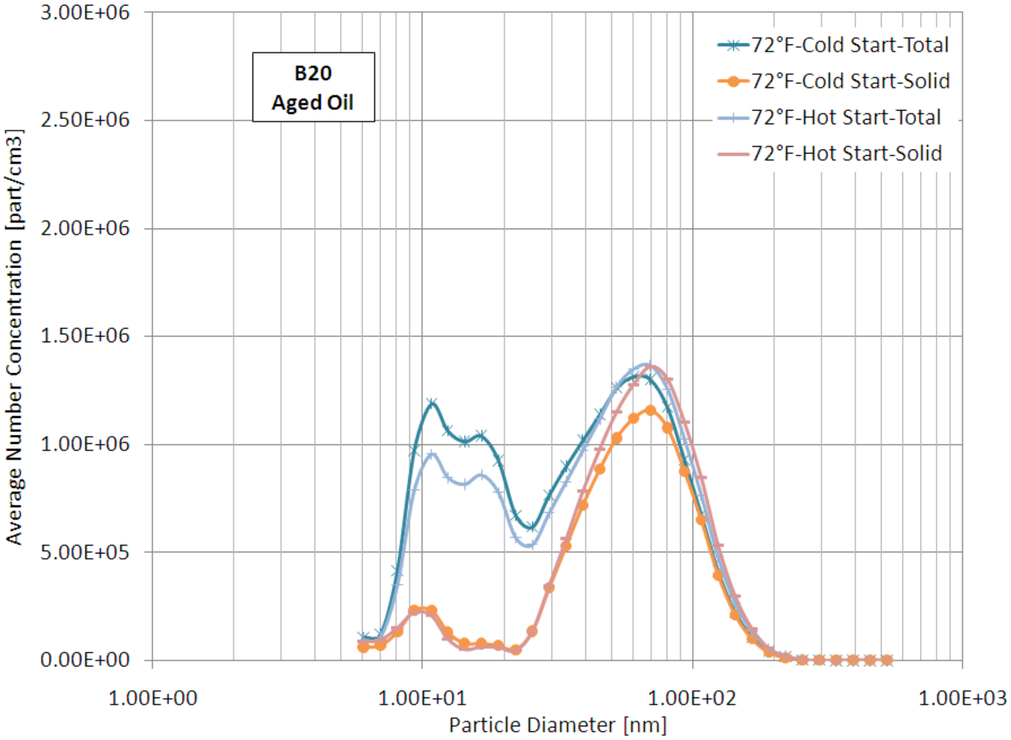

FIGURE 70. NUMBER-WEIGHTED SIZE DISTRIBUTION (B20, 72°F, MEDIUM-DUTY, HIGH EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

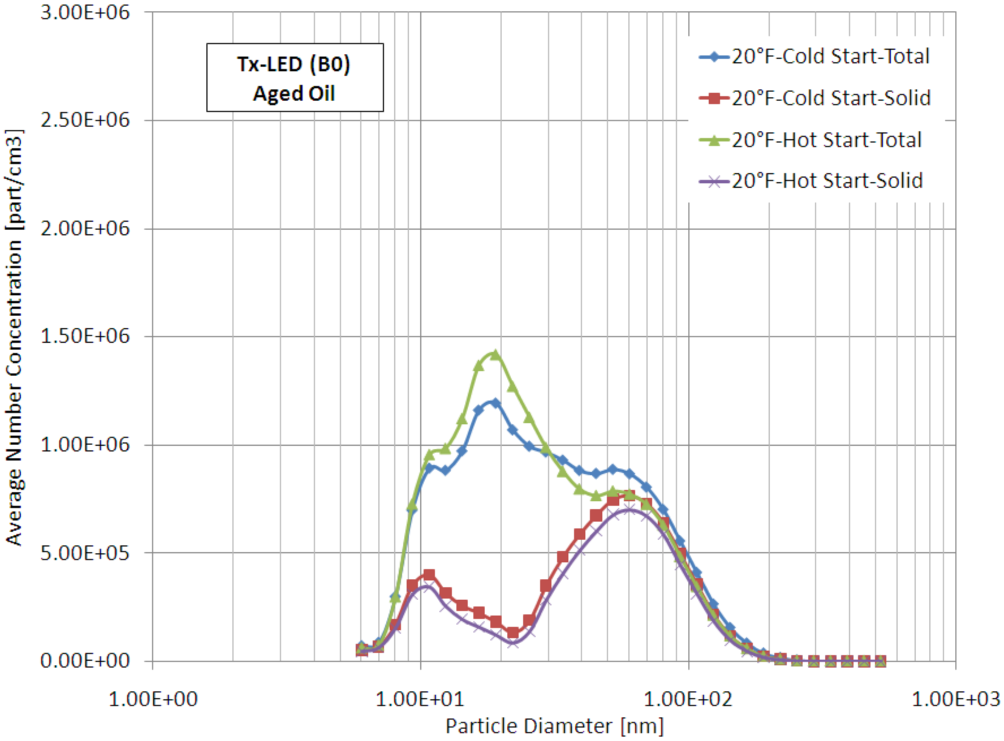

FIGURE 71. NUMBER-WEIGHTED SIZE DISTRIBUTION (B0, 20°F, MEDIUM-DUTY, HIGH EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

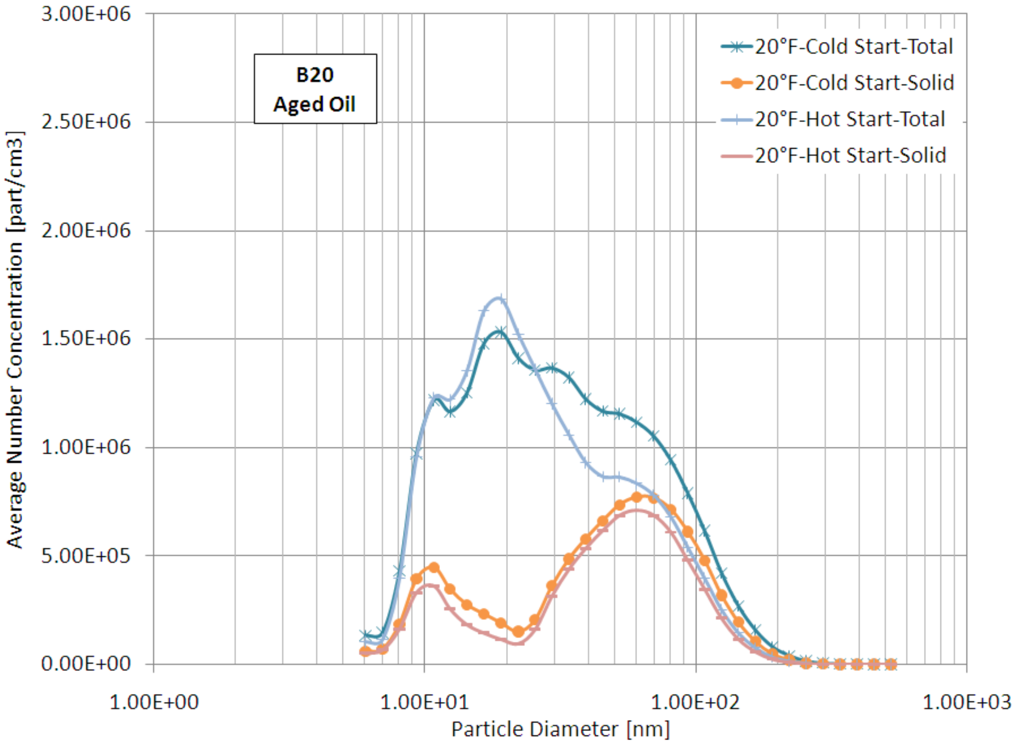

FIGURE 72. NUMBER-WEIGHTED SIZE DISTRIBUTION (B20, 20°F, MEDIUM-DUTY, HIGH EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

8.6 PM Apportionment

For the medium-duty vehicle evaluations, two diesel fueled vehicles were tested in duplicate using the Unified Driving Cycle at two test temperatures (72º and 20ºF) with two test fuels (a diesel fuel and that same diesel fuel blended with 20 percent biodiesel) and with two crankcase oils (a “fresh” or previously unused oil and a similar oil that had been “aged” in another test program). A total of 16 tests were conducted on each of the two vehicles. One of the two vehicles was designated as a normal emitter (NE) and was equipped with an oxidation catalyst, while the second vehicle was designated as a high emitter (HE) and had no exhaust aftertreatment. A more complete description of the vehicles, test cycle, fuels, and lubricants is presented in an earlier section of this report.

In addition to analyses conducted to determine the regulated gaseous exhaust emissions and total PM emissions, a number of analyses were conducted to further characterize the PM. These analyses included XRF and ICP-MS analyses for element content (51 different elements), TOR analyses to determine “elemental” (EC) and “organic” (OC) carbon content, and GC-MS analyses to determine alkanes and cycloakanes (50 compounds), hopanes and steranes (23 compounds) and polycyclic aromatics or PAHs (55 compounds). The GC-MS analyses were also conducted on gas phase emissions to provide a distribution of these semi-volatile organic compounds (SVOCs), between the particle and gas phase of the exhaust. The GC-MS and ICP-MS analyses were also conducted on the test fuels and test oils to provide potential sources and concentrations of compounds found in the exhaust. More specific details on these analyses are presented in Section 8.5 of this report. Hexatriacontane-d74 (n-$C_{36}D_{74)}$ was added to both oils utilized in this study to help in determining the impact of the crankcase oils on the PM emissions. Analyses for this deuterated alkane were conducted as part of the GC-MS analysis for alkanes and cycloalkanes. Exhaust, oil, and fuel samples were all evaluated.

The following approach was followed to determine possible origins (either fuel or lubricant) of exhaust PM for the two medium-duty vehicles:

- Review regulated emissions for trends
- Review chemical analyses of PM, fuel, and oil samples
- Utilize averages and sums when appropriate to minimize variability in data
- Utilize analytical results for elements to estimate an oil consumption rate for each vehicle
- Review carbon analyses for "elemental" (EC) and "organic" carbon (OC) and compare to PM results
- Review hexane and cyclohexane results; utilize hexatriacontane-d74 results to estimate unburned oil contribution to PM
- Review hopane and sterane results: utilize to make a second estimate of unburned oil in PM
- Compare unburned oil estimates to OC
- Investigate impact of PAH emissions rates on PM
- Summarize observations

8.6.1 Regulated Emissions and Fuel Economy

Regulated emissions and fuel economy data from all sixteen tests conducted on each of the two test vehicles were averaged and are presented in Table 63 (Normal Emitter) and Table 64 (High Emitter). To illustrate the impact of each of the test parameters on the average, a percent difference from the average is presented for each set of variables (temperature, fuel, and oil). For example, the eight tests conducted on the high emitter at 72ºF had HC emissions that were 45 percent lower than the overall average value, 0.277 g/mi, while the eight tests conducted at 20ºF were 45 percent higher than the average. When the tests were regrouped by fuel, the eight tests conducted with TxLED diesel fuel (B0 or "D" as shown in the following tables) had HC emissions six percent lower than the 0.277 g/mi average and the biodiesel blend (B20) had HC emissions six percent higher than the average.

TABLE 63. REGULATED EMISSIONS AND FUEL ECONOMY, NORMAL EMITTER (No Statistical Analyses Were Performed On These Data)

Measurement	Average*	Percent Difference From Average					
		72ºF	20ºF	D	B20	Fresh Oil	Aged Oil
HC, g/mi	0.448	-14	+14	<1	<1	<1	<1
CO, g/mi	1.770	-18	+18	+3	-3	<1	<1
NO_x, g/mi	5.417	-18	+18	<1	<1	+3	-3
PM, g/mi	0.120	-15	+15	+8	-8	+6	-6
FE, mpg	12.88	+3.5	-3.5	+0.1	-0.1	-2.7	+2.7

***Averages include all tests from the two test temperature x two test fuel x two test lubricant x duplicate test matrix.**

TABLE 64. REGULATED EMISSIONS AND FUEL ECONOMY, HIGH EMITTER
(No Statistical Analyses Were Performed On These Data)

		Percent Difference From Average					
Measurement	**Average***	**72ºF**	**20ºF**	**D**	**B20**	**Fresh Oil**	**Aged Oil**
HC, g/mi	0.277	-45	+45	-6	+6	+12	-12
CO, g/mi	1.593	-20	+20	-2	-2	-3	+3
NO_x, g/mi	7.127	-2	+2	-3	+3	-3	+3
PM, g/mi	0.420	+27	-27	-6	+6	-5	+5
FE, mpg	15.98	+2.8	-2.8	-0.8	+0.8	-0.5	+0.5

***Averages include all tests from the two test temperature x two test fuel x two test lubricant x duplicate test matrix.**

The high emitter (HE) had higher average PM and NO_x emissions than the normal emitter (NE), but lower average HC and CO emissions and better fuel economy. These results indicate that the HE had been optimized more for power and fuel economy, while the NE had been optimized to meet more stringent NO_x and PM standards.

As can be seen in Tables 63 and 64, test temperature had a much larger impact on exhaust emissions and fuel economy than did fuel type or lubricant age for both medium duty vehicles. Of special note is the observation that PM emissions were 27 percent lower than the average for the HE at 20ºF. This decrease in PM emissions with lower temperature was not observed for the NE. Nominal trends in emissions and fuel economy related to fuel type and lubricant age were generally much smaller than those observed for test temperature and were not nominally consistent for the two test vehicles.

8.6.2 Estimates for Vehicle Oil Consumption Rates

The first step in evaluating the impact of lubricating oil on PM emissions is to determine the amount of lubricating oil entering the exhaust stream. Carbon compounds in lubricating oil can be burned in the engine or aftertreatment system to produce gas phase components, while other elements in the oil such as calcium or zinc are expected to be collected as PM, even if burned. Therefore the elements detected in the ICP-MS and XRF analyses of exhaust were averaged and compared to elements found in the oils. Using both the concentration of selected elements in the exhaust (µg/mi) and in the lubricating oil (µg/g), an oil consumption rate (g/mi) can be calculated. Four elements (phosphorus, zinc, calcium, and sulfur) were found at relatively high concentrations in both the exhaust PM samples and in the oil samples. The emission rates for three of these four elements (sulfur was omitted because it is present in both the fuel and the oil and can be burned to give a gas phase component, sulfur dioxide) were averaged for both the NE and the HE and the results are presented in Table 65. Also in the table are the ratios of the three elements in the exhaust and in the oil. The ratios were calculated by dividing the concentration of each element by the phosphorus concentration. These ratios show that the HE emission rates for phosphorus, zinc, and calcium are very similar to their proportions in the oil, and all three elements could be used to represent the oil consumption process equally. The element ratios for the NE exhaust samples are similar to those in the oil, but illustrate the loss of phosphorus, and to a smaller extent zinc, in the exhaust system (possibly in the oxidation catalyst) as compared to calcium.

TABLE 65. ELEMENTS FROM OIL IN PM
(No Statistical Analyses Were Performed On These Data)

Element	Normal Emitter Average, µg/Mi	Ratio In Exhaust	Ratio In Oil
P	92	1.0	1.00
Zn	152	1.6	1.25
Ca	276	3.0	2.00
Element	**High Emitter Average, µg/Mi**	**Ratio In Exhaust**	**Ratio In Oil**
P	419	1.0	1.00
Zn	531	1.3	1.25
Ca	809	1.9	2.00

An average oil consumption rate for each of the two test vehicles was calculated by dividing the average concentration of an element in the exhaust (µg/mi) by the corresponding average concentration in the oil (µg/g). When these calculations were carried out, 0.16 quarts per 1000 miles or 133 mg/mi (determined from the calcium concentrations only, due to the potential loss of phosphorus and zinc in the exhaust system) was obtained for the NE and 0.49 quarts per 1000 miles or 408 mg/mi (based on average results from phosphorus, zinc, and calcium concentrations) was determined for the HE. While no actual measured oil consumption rate was available for the NE, an average measured rate equivalent to the calculated rate (0.49 quarts per 1000 miles) had been obtained for the HE over 2,311 in-use road miles preceding testing in this program.

8.6.3 Wear Elements

In addition to the exhaust PM elements originating from the oil, groups of elements associated with engine wear were also observed in the exhaust PM samples. Five elements (aluminum, chromium, manganese, molybdenum, and iron) were present at higher levels in the NE exhaust than in the HE exhaust, while 4 elements (copper, tin, nickel, and lead) were found at higher levels in the HE exhaust. Average emission rates for these nine wear elements are presented in Table 66. The first five elements possibly originate from engine wear of aluminum and steel alloy components and indicate more engine wear in the NE vehicle compared to the HE. The remaining five elements could all originate from bearing wear, indicating a high wear rate in the HE. Table 67 presents the impact of the test variables on the emission rates of iron (both vehicles) and lead (HE only). As can be seen in the table, no single variable dominates the iron results for either vehicle, and the fuel type and oil age trends go in opposite directions for the two vehicles. However, the HE lead emissions indicate that the B20 fuel has a relatively large impact on bearing wear in the HE. The aged oil was also found to have a large impact and the combination of these two variables resulted in lead emission rates on the order of 1 mg/mi.

TABLE 66. ELEMENTS FROM WEAR, µg/mi (AVERAGES FOR EACH VEHICLE)
(No Statistical Analyses Were Performed On These Data)

Element	Normal Emitter	High Emitter
Al	32	26
Cr	21	8
Mn	14	9
Mo	5	1
Fe	705	609
Cu	10	23
Sn	1	12
Ni	6	9
Pb	1	316

TABLE 67. TEST VARIABLE IMPACT ON SELECTED WEAR ELEMENTS
(No Statistical Analyses Were Performed On These Data)

Element (Vehicle)	Averages	Percent Difference From Average					
		72ºF	20ºF	D	B20	Fresh Oil	Aged Oil
Fe (NE)	705	-54	+54	-42	-42	+50	-50
Fe (HE)	609	-21	+21	-40	+40	-43	+43
Pb (HE)	316	+2	-2	-92	+92	-75	+75

8.6.4 Carbon Analyses for "Elemental" and "Organic" Content of PM

Exhaust PM samples were analyzed by TOR for "elemental" carbon (EC) or soot content, "organic" carbon (OC), and total carbon (TC) content. The average results for these analyses, and the impact of each of the test variables on these averages is presented in Table 68. The PM results for each vehicle are also shown for comparison. Recall the unusual observation of HE PM levels decreasing with the lower test temperature (Table 64). This observation appears to be the direct result of a decrease in the EC emission rate, as the OC emissions increase as expected with decreasing temperature. All three test variables give opposing nominal total carbon emission results for the two test vehicles. On average, the OC was 33 percent of the total carbon for the NE and 22 percent for the HE.

TABLE 68. TOTAL, "ELEMENTAL," AND "ORGANIC" CARBON EMISSIONS
(No Statistical Analyses Were Performed On These Data)

	Averages* mg/mi	Percent Difference From Average					
		72ºF	20ºF	D	B20	Fresh Oil	Aged Oil
Normal Emitter							
EC	71.2	-6	+6	+10	-10	+4	-4
OC	34.9	-27	+27	-9	+9	<1	<1
TC	106.1	-13	+13	+4	-4	+3	-3
PM	120	-15	+15	+8	-8	+6	-6
High Emitter							
EC	250.9	+20	-20	+2	-2	-6	+6
OC	69.9	-15	+15	-9	+9	<1	<1
TC	320.8	+12	-12	-1	+1	-5	+5
PM	420	+27	-27	-6	+6	-5	+5
***Averages include all tests from the two test temperature x two test fuel x two test lubricant x duplicate test matrix.**							

An attempt was made to account for the total PM mass by combining the measured total carbon mass with a sum of oil and wear derived element mass (Table 69). Sulfur and phosphorus were assumed to be present as sulfate and phosphate and the organic carbon mass was assumed to have 1.5 hydrogen atoms per carbon atom. When these various masses were combined, the totals were found to represent 94 percent of the measured PM for the NE and 80 percent of the measured PM for the HE.

TABLE 69. CARBON AND OTHER ELEMENT TOTALS COMPARED TO TOTAL PM, AVERAGES, mg/mi (No Statistical Analyses Were Performed On These Data)

	Normal Emitter	High Emitter
Total Carbon	106.1	320.8
Elements[a]	2.4	4.7
Hydrogen Mass for OC[b]	4.4	8.7
Total	112.9	334.2
Measured PM	120	420

[a] Mass for S and P assumed to be SO_4 and PO_4
[b] Mass for 1.5 H per C assumed

8.6.5 Estimation of Unburned Oil Content in PM

The elements phosphorus, zinc, and calcium were utilized to determine an overall oil consumption rate for the two test vehicles, 133 mg/mi for the NE and 408 mg/mi for the HE. However, some or most of the organic content of the oil could be burned in the engine or, in the case of the NE, in the oxidation catalyst. One approach to determining how much of the organic material from the oil remains in the PM is to compare SVOCs in the PM to those unique to the oil, as was done for determining the overall oil consumption rate. This approach assumes that the oil either survives the combustion process intact (including all tracers) or is completely consumed. GC-MS analyses of the SVOC alkanes and cycloalkanes, and of the hopanes and steranes provided data to make these estimates.

The oil utilized in this study contained a hexatriacontane-d74 ($C_{36}D_{74}$) tracer that was determined to be at a 210 µg/g level in the oil (average of 7 of the oil samples utilized in this study). The average PM emission rate (all sixteen tests) for hexatriacontane-d74 was 7.5 µg/mi for the NE and 62 µg/mi for the HE. If the emission rates in µg/mi are divided by the oil concentration in µg/g, the result gives an estimated "unburned" oil emission rate. The calculated average emission rate for unburned oil for the normal emitter was 36 mg/mi, while the projected unburned oil emission rate for the HE was 290 mg/mi.

This approach was repeated using the sum of 11 hopanes and 12 steranes that were analyzed in this study. Hopanes and steranes are found in the oil and have been utilized as markers for the presence of lubricating oil. The total average concentration of these 23 hopanes and steranes in the test oils was 310 µg/g. The total average PM exhaust emission rate for the NE was 9.8 µg/mi and the corresponding average for the HE was 33 µg/mi. Dividing the exhaust emission rates by the oil concentration result in estimated unburned oil emission rates of 33 mg/mi for the NE and 107 mg/mi for the HE. It should be noted that these hopanes and steranes were also found in the fuels utilized in this part of the study (average of 2.5 µg/g).

While the oils contained approximately 125 times more hopanes and steranes than the fuels, the test vehicles consumed on average 1900 (NE) and 500 (HE) times more fuel than oil. If the survival rate of the fuel hopanes and steranes is not negligible, their presence will confound the unburned oil estimates. Table 70 presents a comparison of the calculated unburned oil estimates to the organic carbon (OC) component of PM as determined by TOR.

TABLE 70. COMPARISON OF UNBURNED OIL ESTIMATES TO OC

Approach	Average Emission Rate, mg/mi	
	Normal Emitter	High Emitter
Hexatriacontane-d74	36	290
Hopanes and Steranes	32	107
OC	35	70

There appears to be good agreement of the unburned oil estimates with the total OC for the NE, indicating that the OC component of the PM is primarily unburned oil and that either the hexatriacontane-d74 or the hopane/sterane totals can be utilized to make this prediction. There were high, and possibly anomalous, hopanes levels measured in the lubricants from the tests for MD-NE-A-B20. These data were used in the estimates shown in Table 70 for the normal emitter. If these data were not included in the averaged hopanes and steranes then the estimated unburned oil emission rates would be slightly higher and more in agreement with the OC results. These results also indicate that 74 percent of the oil entering the exhaust stream is burned in the engine or in the oxidation catalyst (calculated oil consumption rate of 133 mg/mi minus average unburned oil consumption rate of 34 mg/mi equals 99 mg/mi of burned oil or 74 percent of the total oil consumed). The NE hopane/sterane totals also vary with the test temperature (26 percent lower than average at 72º and 26 percent higher than average at 20ºF) in the same manner and magnitude as does the OC (Table 70). The variation with test temperature for the hexatriacontane-d74 exhaust PM results is slightly larger (±37 percent), but still reasonable in magnitude and direction of the trend.

The unburned oil estimates using exhaust hexatriacontane-d74 and hopane/sterane measurements, however, do not show good agreement with the TOR OC component for the HE; the hexatriacontane-d74 overestimating the OC by more than three-fold, and the hopanes and steranes by about 50 percent. These overestimates may indicate there is possibly not enough EC in the exhaust to capture all of the lighter components of oil as PM. The heavier oil components, such as the hexatriacontane-d74 tracer are either displacing lighter components from the PM or are preferentially condensing into the PM, or both.

The displacement of lighter oil components from the PM to the gas phase can be illustrated by the emission results for eicosane ($C_{20}H_{42}$) representing a lighter oil component, and hexacosane ($C_{26}H_{54}$), representing a heavier oil component (Table 71). Also, recall that the EC levels for the HE actually decreased with a decrease in temperature (20 percent from the average), while the OC levels increased (15 percent from the average). The NE PM is projected to contain the full range of oil components based on the good agreement between the estimated unburned oil fraction and the measured OC fraction. This projection was found to be true for the lighter component eicosane, which was detected on average as 97 percent PM and only 3 percent gas phase. This percentage drops to 94 percent for the HE at 72ºF and to 79 percent at 20ºF (which has the lower EC levels). The heavier hexacosane was also found in HE PM at 94 percent at 72ºF, but its PM fraction only drops to 91 percent at 20ºF, indicating that this heavier hydrocarbon is displaced from the PM to a lesser extent than the lighter eicosane. This observation will be discussed further in the following discussion of PAH emissions.

TABLE 71. DISPLACEMENT OF LIGHTER ALKANES FROM HE PM AT LOWER TEST TEMPERATURE

Alkane (Vehicle)	**Percentage of Alkane in PM**	
	72°F	**20°F**
$C_{20}H_{42}$ (NE)	95	98
$C_{20}H_{42}$ (HE)	94	79
$C_{26}H_{54}$ (HE)	94	91

8.6.6 PAH PM Emissions

PAH compounds are present in diesel fuel and many are also formed during the combustion process. A total of 55 PAH compounds were evaluated both in the gas phase and in PM of exhaust. The average total PAH PM emission rate was low for the NE, <0.1mg/mi (less than 0.3 percent of the OC). The HE has higher average total PAH PM emissions, ~1 mg/mi (~1 percent of the OC) indicating a slightly higher OC contribution by the heavier components of the fuel and/or of fuel combustion.

A comparison of the magnitude of two of the PAH compounds for the two test vehicles at the two test temperatures is presented in Table 72. This table illustrates the effectiveness of the NE's oxidation catalyst in removing these PAH compounds from the exhaust. A slightly longer light-off time for the oxidation catalyst during the 20ºF tests is also suggested by the increase in emissions. The increase in the two PAH emissions for the HE (no exhaust aftertreatment) at 20ºF may be related to the shift in combustion dynamics as was illustrated by the drop in EC emissions.

TABLE 72. TEMPERATURE AND OXIDATION CATALYST EFFECT ON SELECTED EMISSIONS RATES

PAH (Vehicle)	**PM Emission Rate, µg/mi**	
	72ºF	**20ºF**
Pyrene (NE)	1.3	10.1
Chrysene (NE)	0.3	4.1
Pyrene (HE)	101	149
Chrysene (HE)	15	29

The distribution of the PAH phenanthrene ($C_{14}H_{10}$) between the particle and gas phases is another example of the shifting dynamics of lighter hydrocarbons in the HE exhaust. For the 72°F tests on the HE, 94 percent of the phenanthrene was collected as PM (139 µg/mi in PM vs 9 µg/mi in vapor), but the particle-phase ratio drops to 40 percent at 20°F (66 µg/mi in PM vs 98 µg/mi in vapor). On the other hand, the heavier and less volatile PAH pyrene ($C_{16}H_{10}$) is collected as 99+ percent PM at 72°F (101 µg/mi in PM vs <1 µg/mi in vapor) and 97 percent at 20°F (149 µg/mi in PM vs 4 µg/mi in vapor). While the distribution of SVOCs in the NE exhaust is relatively consistent across the testing conditions, there is a possible shift of SVOCs between the particle and gas phases for the HE, especially in the case of varying test temperature (Table 73). It is reasonable to assume that while a variety of sampling conditions would be expected to give consistent exhaust samples for the NE, variations in collection protocols could produce different results with variations in sampling media, sample flow rate, etc. for the HE. For example, a slightly higher sampling flow rate at higher sample temperature could shift the distribution of SVOCs from PM to vapor phase much more easily in the case of the HE. This possibility would help explain some of the inconsistencies of the HE data, but makes a characterization of the PM more difficult.

TABLE 73. DISPLACEMENT OF LIGHTER PAHS FROM HE PM AT LOWER TEST TEMPERATURE

PAH (Vehicle)	Selected PAHs as Percent of Total PAH in PM	
	72°F	20°F
Phenanthrene (HE)	94	40
Pyrene (HE)	99+	97

8.6.7 PM Apportionment Summary

A number of data analyses were conducted in order to evaluate the make-up and origin of PM from the two medium-duty test vehicles. Several approaches were successful and provided useful information, while others illustrated the complexity of the exhaust environment. The following are some of the observations made in these analyses.

- Elements in oil were used to estimate an oil consumption rate.
- An estimated oil consumption rate for the normal emitter was determined to be a nominal 0.16 quarts per 1000 miles; however, no measured values were available for comparison.
- An estimated oil consumption rate for the high emitter matched a measured oil consumption rate of 0.49 quarts per 1000 miles.
- Total carbon emission rates, along with corrections for measured elements and organic hydrogen, were similar to the measured PM rates for the normal emitter, but not as similar for the high emitter.
- A hexatriacontane-d74 tracer and hopane/sterane totals were utilized to estimate unburned oil emission rates that were similar to the OC measurements for the normal emitter. Corresponding estimations for unburned oil emission rates for the high emitter resulted in values higher than the OC emission rates.
- The carbon fraction of the NE average unburned oil emission rate (34 mg/mi) was determined to be 29 mg/mi (after removing the mass of associated hydrogen atoms). This remaining carbon from the unburned oil represents 83 percent of the measured OC. The much higher levels of expected unburned oil in HE PM and the displacement of lighter SVOCs with heavier SVOCs in the HE PM would indicate that this percentage would even be higher for the HE.
- Alkane and PAH analyses illustrate the complex dynamics of the SVOCs between gas and particle phases in the HE exhaust.

- The potential of varying results for PM composition using different sampling protocols is also illustrated in the case of the HE.

8.7 Medium-Duty Diesel Vehicles Major Technical Findings

Fresh and Aged oil

PM emissions nominally decreased with aged oil in the normal emitter, but nominally increased from the high emitter.

TxLED Diesel (B0) and Twenty Percent Biodiesel (B20) Fuel

PM emissions from the normal emitter were not consistently affected by B20, but nominally increased from the high emitter.

Normal (72°F) and Low (20°F) Temperature

During cold tests, PM emissions nominally increased in all cases with the NE, but nominally decreased in all cases with the HE.

Particle Number and Size Distributions

Particle Number

- For the normal emitter, the exhaust PN concentration ranged from about 10×10^6 part./cm³ to 20×10^6 part./cm³.
- For the normal emitter, no major differences in PN emissions were observed between 72ºF and 20ºF, or between the cold-start and the hot-start portions of the cycle.
- The use of B20 in the NE resulted in lower solid and volatile PN emission, compared to B0. The PN reduction was on the order of 15 to 20 percent.
- The MD NE vehicle with fresh oil emitted more solid and volatile particles, compared to PN emissions with the aged oil. This trend was observed during both the cold-start and the hot-start portions of the drive cycle. This trend was also consistent with what was observed with the light-duty NE.
- Fifty to eighty-three percent of the number of particles emitted from the MD NE was solid in nature.
- For the MD high emitter (HE), the exhaust PN concentration ranged from 12×10^6 part./cm³ to 23×10^6 part./cm³.
- No consistent trend was observed in PN emissions between B0 and B20.
- For the HE, no major differences in PN were observed between 20ºF and 75ºF, or between cold-start and the hot-start portions of the cycle.
- PN emissions from the MD HE, particularly solid PN, were higher with the aged oil compared to fresh oil. This is consistent with the observation made with the light duty HE between aged oil and fresh oil, although the trend with the MD HE was not as pronounced.
- For the high emitter, solid PN ranged from 26 to 65 percent of total PN. This range was lower than observed with the MD NE, suggesting more volatile PN with the MD HE, compared to the MD NE.

Particle Size Distribution

- For the NE and HE, the solid particle distributions exhibited a similar monomodal lognormal size distribution structure that consists of an accumulation mode with peaks between 50 nm and 70 nm. The total particle size distribution exhibited a bimodal lognormal distribution structure with a volatile nuclei mode peak between 10 nm and 20 nm.
- A more pronounced volatile nuclei mode was observed at 20°F compared to 72°F, and with the HE versus the NE. For example, the NE had a small nuclei mode, particularly at 72°F, compared to the accumulation mode, where with the HE, the nuclei mode reached a peak level that is comparable with the peak of the accumulation mode at 72°F, and a higher peak level at 20°F. The increase in volatile nuclei mode particles can be indicative of increased oil consumption using similar technology vehicles with similar fuel and oil usage.

MD PM Apportionment

- An estimated oil consumption rate for the normal emitter was determined to be a nominal 0.16 quarts per 1000 miles; however, no measured values were available for comparison.
- A calculated oil consumption rate for the high emitter matched a measured oil consumption rate of 0.49 quarts per 1000 miles.
- Total carbon emission rates, along with corrections for measured elements and organic hydrogen, were similar to the measured PM rates for the normal emitter, but did not correlate as well for the high emitter.
- A hexatriacontane-d74 tracer and hopane/sterane totals were utilized to estimate unburned oil emission rates that were similar to the OC measurements for the normal emitter. Corresponding estimations for unburned oil emission rates for the high emitter resulted in values higher than the OC emission rates.
- The carbon fraction of the NE average unburned oil emission rate was determined to be 29 mg/mi (after removing the mass of associated hydrogen atoms). This remaining carbon from the unburned oil represents 83 percent of the measured OC.
- Alkane and PAH analyses illustrate the complex dynamics of the SVOCs between gas and particle phases in the HE exhaust.
- The potential of varying results for PM composition using different sampling protocols is clearly illustrated with the HE.

9.0 HEAVY-DUTY NATURAL GAS VEHICLE TESTS

9.1 Vehicle Selection and Description

Vehicle selection was made in collaboration with the CLOSE Project Management Team. SwRI identified potential candidate vehicles for testing and made vehicle recommendations to the CLOSE Project Management Team. We then waited for technical approval prior to procuring the test vehicles. One vehicle from each of the following categories was recruited:

9.1.1 Heavy-Duty Natural Gas Vehicle Selection Criteria

- Normal-emitting natural gas vehicle: This was to be a modern compressed CNG- or LNG-fueled transit bus or school bus of model year 2002 or newer with fewer than 270,000 miles on the odometer. The natural gas engine of this vehicle was to have an advertised displacement of at least 7.6 liters and a minimum rated torque of 660 ft-lbs. This vehicle was expected to be solicited from a Texas transit agency.

- High-emitting natural gas vehicle: This was to be a high-mileage CNG- or LNG-fueled transit bus or school bus, preferably one that was known to emit measurable levels of PM, have high lubrication oil consumption, and/or have visible smoke related to lubrication oil. The natural gas engine of this vehicle was to have an advertised displacement of at least 7.6 liters and a minimum rated torque of 660 ft-lbs. This vehicle was expected to be solicited from a Texas transit agency, and expected to be near the end of its useful life.

9.1.2 Heavy-Duty Natural Gas Vehicle Selection and Description

SwRI spent months searching for the heavy-duty natural gas vehicles for the study. SwRI contacted fleets in Texas and New Mexico regarding testing of heavy-duty natural gas vehicles. Contacted fleets and notes on their responses are listed below:

- City of Houston-‘Metro’ had no CNG vehicles in its fleet.
- City of Fort Worth-‘The-T’ had CNG buses but none were available.
- City of Austin-‘Capital Metro’ had only diesel buses in their fleet.
- City of San Antonio-‘VIA’ the local transit authority did not have any CNG buses.
- City of Dallas-‘DART’ had two fleets of LNG buses. Fleet 1 is 1998 Nova buses powered by Cummins L10G engines. Fleet 2 is 2002 Nova buses powered by Detroit Diesel Corporation (DDC) S50G engines. The 1998 buses were re-powered in 2004-2005. The eleven 2002 buses were repowered in 2008 and 34 remain to be repowered. They said that the 2002 buses would be the best candidates. They searched for a recently rebuilt engine, and an end-of-life high oil consuming engine or an end-of-life low/normal oil consuming engine. They made no commitments and no vehicles were available.
- City of El Paso-‘Sun Metro’ has CNG vehicles in their fleet. We spoke with their Assistant Director for Maintenance and he was not interested is helping us. He stated there was ‘nothing in it for him.’

- City of Albuquerque 'NM-Transit Department' had, from what we have found on the internet, CNG buses in their fleet. None were available.
- We sent an e-mail to the Natural Gas Transit Users Group requesting contact information for transit agencies that have CNG buses in their fleet. We did not receive any additional helpful information.
- We corresponded with the coordinator of the Clean Cities Alamo Area Council of Government (AACOG). He gave us contact names and numbers for the City of San Antonio Fleet Maintenance and Operations but no NG vehicles were in their fleet.

The problems we had locating suitable heavy-duty natural gas vehicles were shared with the CLOSE Project sponsors. Mike Bogdanoff, of South Coast Air Quality Management District (SCAQMD) made inquiries in California and located two CNG-fueled buses from Foothill Transit in Los Angeles, CA. SwRI and Foothill Transit signed a lease agreement (at no cost) to borrow each of the buses for one month. Mr. Bogdanoff made arrangements, through SCAQMD, to fund the shipping of both vehicles to and from San Antonio. Table 74 describes the two heavy-duty natural gas fueled buses that Mr. Bogdanoff procured for the project. A "high emitter" was not identified from the fleet of available natural-gas vehicles, and a high mileage bus was substituted in its place.

TABLE 74. DESCRIPTION OF HEAVY-DUTY NATURAL GAS BUSES

	Normal Emitter	**High Mileage**
Coach Number	1502	1317
Make	North American Bus Industries (NABI)	Orion Bus Industries (Orion)
Model	40.31	Orion V
Year	2006	2003
GVWR, lb	42,540	40,780
VIN	1N90403166A140162	1VHBH3C2236502059
Mileage	162,366	335,064
Engine Make	Cummins	Detroit Diesel S-50G
Fuel Strategy	Lean-burn	Lean-burn
Aftertreatment	Catalytic Muffler	Catalytic Muffler
Engine oil spec.	15W-40	15W-40

Because the HD natural gas and HD diesel vehicles did not exhibit higher PM emissions, they are designated as "high mileage" (HM).

9.1.3 Gaseous and PM Emissions Check-out Tests

Before any tests were performed, the North American Bus Industries (NABI) bus normal emitter was operated at 50 mph for one hour on the dynamometer to condition the dilution tunnel. A series of hot-start UDDS test cycles were then run to assess the repeatability of the bus's emissions. Table 75 shows the results of the repeatability tests conducted. Repeatability of gaseous emissions and fuel economy was quite good with the largest covariance exhibited by NO_X emissions at 13.8 percent. The repeatability of PM emissions was not as good as gaseous emissions, with a covariance of 20.3 percent. The NABI bus was approved for testing by the CLOSE project participants.

TABLE 75. SUMMARY OF REPEATABILITY CHECK TEST RESULTS FROM THE HEAVY-DUTY NORMAL PM EMITTING NATURAL GAS VEHICLE

(No Statistical Analyses Were Performed On These Data)

Test Number	HD-NE-F-NG-REP1	HD-NE-F-NG-REP2	HD-NE-F-NG-REP3	HD-NE-F-NG-REP4	HD-NE-F-NG-REP5	Average	Standard Deviation	Covariance
HC, g/mile	13.94	14.83	13.92	14.55	15.79	14.61	0.77	5.3%
CO, g/mile	1.16	1.29	1.09	1.12	1.13	1.16	0.08	6.9%
NO_X, g/mile	7.55	8.02	7.26	6.87	5.47	7.03	0.97	13.8%
PM, g/mile	0.013	0.019	0.021	0.024	0.022	0.020	0.004	20.3%
Fuel Economy, lb/mile	1.44	1.48	1.37	1.43	1.45	1.43	0.04	2.7%
NMHC, g/mile	1.09	1.19	1.20	1.35	1.43	1.25	0.14	11.0%
CH_4, g/mile	12.85	13.64	12.72	13.20	14.36	13.35	0.66	5.0%

Note: These tests are not part of the particulate characterization tests.
Tests were performed at a nominal 72°F, with commercial fuel and lubricant as received.
Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

Prior to the testing for record of the natural gas fueled heavy-duty normal PM emitter, the engine was flushed and filled with fresh oil that had hexatriacontane tracer blended into it, after which it was operated for 150 miles on the road. Subsequently, buses accumulated 150 miles of operation on the dynamometer after each oil change, and conditioned the exhaust dilution tunnel at the same time.

The second natural gas bus (Orion) with higher mileage, which was expected to have higher PM emissions, was also emission tested for repeatability before running any tests for record. Prior to repeatability tests, the bus was operated at 50 mph for one hour on the dynamometer to condition the tunnel. A series of hot-start UDDS test cycles were then run to assess the repeatability of the bus's emissions. Table 76 shows the emission test results of the repeatability tests conducted. Repeatability of gaseous emissions and fuel economy was quite good with the largest covariance exhibited by NO_X emissions at 14 percent. The repeatability of PM emissions was not as good as with gaseous emissions, with a covariance of 28 percent. Although the ORION bus's PM emissions were similar to the low PM emissions NABI bus, it was approved for testing by the CLOSE Project sponsors as a high-mileage vehicle.

TABLE 76. SUMMARY OF REPEATABILITY CHECK TEST RESULTS FROM THE HEAVY-DUTY HIGH MILEAGE NATURAL GAS VEHICLE

(No Statistical Analyses Were Performed On These Data)

Test Number	HD-HM-F-NG-REP1	HD-HM-F-NG-REP2	HD-HM-F-NG-REP3	HD-HM-F-NG-REP4	HD-HM-F-NG-REP5	Average	Standard Deviation	Covariance
HC, g/mile	13.60	15.78	14.26	14.46	14.98	14.62	0.82	6%
CO, g/mile	6.44	6.80	5.69	6.15	6.56	6.33	0.43	7%
NO_X, g/mile	7.78	5.59	5.87	5.98	6.40	6.32	0.86	14%
PM, g/mile	0.022	0.031	0.017	0.019	0.016	0.021	0.006	28%
Fuel Economy, lb/mile	1.45	1.29	1.28	1.28	1.28	1.31	0.08	6%
NMHC, g/mile	0.88	0.97	0.89	0.93	0.93	0.92	0.03	4%
CH_4, g/mile	12.72	14.82	13.37	13.52	14.05	13.70	0.79	6%

These tests are not part of the PM characterization tests.
Tests were performed at a nominal 72°F, with commercial fuel and lubricant as received.
Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

9.2 Lubricants

The heavy-duty vehicles were tested with both fresh and aged lubricants. Their description and the supplier's analyses are included in Section 5.1 in Tables 3 and 6. The drain and fill procedure is described in Section 5.1. Degreening of the lubricants was accomplished by operating the heavy-duty vehicles for 150 miles on the road or on the chassis dynamometer. Oil samples include the fresh and aged oils as received, and one oil sample each taken after completion of all tests on fresh and then aged oils from the normal- and high-mileage emitter. For example, the normal emitter was operated over multiple emission tests with fresh oil and a sample was taken from the crankcase drain oil, and then the normal emitter was operated over multiple emissions tests with aged oil and a sample was taken from the crankcase drain oil. Thus two oil samples were taken from the normal-emitter (fresh and aged oil), and two oil samples were taken from the high-mileage emitter.

9.3 Fuels

Fuel systems on all vehicles were flushed with the test fuels prior to the initiation of testing. SwRI utilized on-site blending facilities to custom-blend batches of natural gas. Natural gas composition was analyzed to ensure accurate accounting of fuel speciation and molecular weight. Additionally, utility line gas that was delivered with the vehicles was used for dynamometer setup and degreening of the first test lubricant. For the natural gas vehicles, the gas contained in the fuel tanks of each vehicle was isolated from the fuel intake system using the fuel shut-off valves available on each vehicle. A pressurized container of natural gas was positioned outside of the test cell and a hose directed fuel into the test vehicle's fuel intake system. The heavy-duty diesel vehicles were fueled directly from an underground tank dedicated to the project. Analyses results for the natural gas blends used for heavy-duty tests are included in Section 5.2.4.

9.4 Emission Test Procedures

This is a pilot study of exhaust emissions effects from the use of different fuels and lubricants with some tests conducted at different temperatures. It is important to note that the scope of work in this study is limited to short-term effects on emissions when a fuel or lubricant was changed. The fuels and lubricants used in this study could have long-term effects on emissions which were not measured.

9.4.1 Driving Cycle

Heavy-duty vehicles were evaluated over the EPA Urban Dynamometer Driving Schedule (UDDS) for Heavy-Duty Vehicles. The heavy-duty UDDS is also known as the heavy-duty chassis cycle (HDCC). The HDDC cycle is shown in Figure 73. The duration of the HDCC is 1,060 seconds, and the cycle covers a distance of 5.55 miles. The official use of this cycle is for conditioning heavy-duty gasoline-fueled vehicles before an evaporative emissions test. However, the HDCC is commonly used for exhaust emissions testing of heavy-duty vehicles for research purposes, and was based on the engine speed and load conditions used to compile the EPA heavy-duty diesel engine transient test cycle used for emissions certification. Vehicles were operated over a series of cold- and hot-start tests conducted on the same day. For all emission tests, the vehicles were soaked for at least 12 hours at test temperature prior to emissions evaluations.

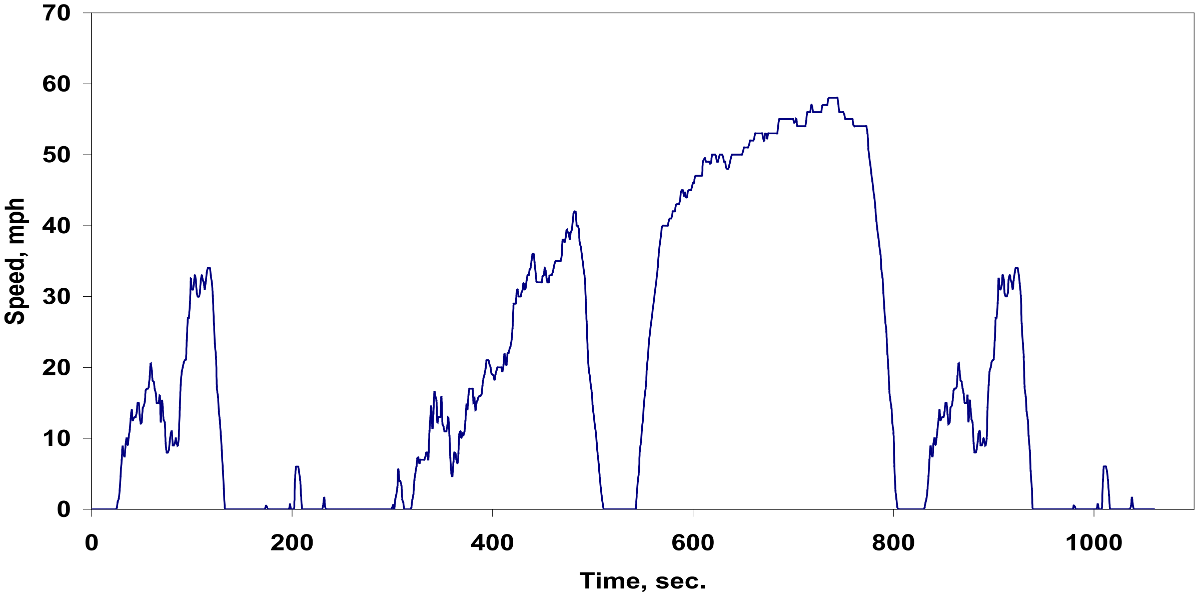

FIGURE 73. HEAVY-DUTY UDDS (HDDC) CYCLE

Engine preparation was accomplished by operating the vehicle over two HDCC cycles followed by a least a 12 hour soak. Tunnel conditioning was conducted in conjunction with the accumulation of 150 miles operation after each oil change and engine preparations.

- Normal-Emitting Natural Gas Vehicle: Based on results from replicate tests performed before beginning PM testing for analysis, six HDDCs (one cold and five hot-starts) were performed for each sample. Thus 24 HDDCs were performed in order to collect all 4 samples (2 oils × 2 replicate samples × 6 HDDCs per sample).

- High-Mileage Natural Gas Vehicle: In order to parallel the testing of the normal-emitting CNG vehicle, SwRI tested this vehicle over the same number of replicate cold- and hot-start HDDCs.

9.4.2 Chassis Dynamometer

Testing of heavy-duty vehicles utilized SwRI's heavy-duty tandem-axle chassis dynamometer manufactured by Reliance Electric Engineered Systems and Burke-Porter. The chassis dynamometer is equipped with two sets of 48-inch rolls designed to accommodate one or two drive axles. Each set of 48-inch rolls is coupled to a 300 horsepower dynamometer. The chassis dynamometer system is capable of simulating 4,500 lbs of equivalent vehicle weight mechanically and 60,000 lbs of equivalent vehicle weight electrically.

9.5 Heavy-Duty Natural Gas Vehicles Emission Test Results

9.5.1 Regulated Gaseous and PM Emissions

Note that longer range precision was not rigorously explored in the test design. Thus statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified. Average results from both heavy-duty natural gas vehicles are shown in Table 77. Regulated gaseous emissions, PM emissions, and fuel consumption rates while operating the vehicles with fresh and aged oil are included. All heavy-duty emission tests were conducted at a nominal 72ºF ambient temperature. Repeatability of the emissions from the replicate tests was good. PM emission rates measured from the high mileage (HM) bus on aged oil showed the greatest variability between the two replicate tests with a covariance of 15 percent. NO_X emissions from the normal emitter (NE) also exhibited higher variability with covariance of 11 and 12 percent on fresh and aged oil, respectively. In addition, non-methane hydrocarbon emissions from the normal emitter on fresh oil showed a covariance of 14 percent, but all other emission rates exhibited low variability with covariances below 10 percent.

TABLE 77. AVERAGE REGULATED EMISSIONS FROM HEAVY-DUTY NATURAL GAS VEHICLES
(No Statistical Analyses Were Performed On These Data)

	72º F - Average of Replicate Tests[a]											
	Normal Emitter						High Mileage					
	Fresh Oil			Aged Oil			Fresh Oil			Aged Oil		
	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation
HC, g/mile	13.4	0.33	2%	14.4	0.78	5%	14.4	0.68	5%	14.6	0.78	5%
CO, g/mile	1.28	0.04	3%	1.47	0.07	5%	6.50	0.33	5%	7.37	0.70	9%
NO_x, g/mile	10.9	1.19	11%	12.6	1.53	12%	7.3	0.03	0%	9.5	0.26	3%
PM, mg/mile[b]	18.2	0.27	1%	14.2	0.77	5%	17.9	0.39	2%	22.2	3.26	15%
Fuel Usage, lb/mile	1.46	0.01	1%	1.41	0.02	1%	1.33	0.01	1%	1.33	0.02	1%
NMHC, g/mile	2.35	0.33	14%	2.82	0.03	1%	2.52	0.08	3%	2.83	0.15	5%
CH_4, g/mile	11.0	0.04	0.4%	11.6	0.81	7%	11.9	0.75	6%	11.8	0.63	5%

[a] Each replicate test consisted of one cold HDDC cycle plus five hot HDDC cycles.

[b] PM as determined from phase-by-phase filter samples collected during each test.

Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

We note that NO_X emissions measured from the heavy-duty natural gas bus with normal PM emissions during repeatability tests differed from those measured during the tests for record. The average hot-start NO_X rate during the repeatability tests was 7.0 g/mile, and the average hot-start NO_X rate during all of the NE tests for record was 10.8 g/mile. The only difference in operation of the vehicle was the fuel used for the tests, and we suspect that the fuel change caused the change in NO_X emissions. During the repeatability tests, we ran on the fuel stored on the bus as it was received from California. During all the tests for record, we ran on a SwRI blend of gases that meets both Federal and California certification fuel concentration protocols. Table 78 compares the analyses of the two fuels.

The methane number of each fuel blend is a measure of the knock resistance of the fuel, and was calculated using the California Air Resources Board (ARB) mathematical method. The Wobbe index is a measure of the interchangeability of fuel gases such as natural gas, LPG and butane, and is calculated by dividing the higher heating value of the fuel by its relative density. It has been shown in other programs conducted at SwRI that both the Wobbe Index and methane number directly affect NO_X. A link to a final report for one of these programs can be found at:

http://www.socalgas.com/business/gasQuality/documents/swri_final_report_cummins_johndeeredetroitdiesel.pdf.

TABLE 78. SUMMARY OF NORMAL EMITTER BUS TANK AND SWRI BLENDED NATURAL GAS FUEL ANALYSES
(No Statistical Analyses Were Performed On These Data)

Fuel Blend		Normal Emitter Bus Tank	SwRI Blended Sphere
Methane Number	-	101.4	88.5
Wobbe Index	BTU/scf	1331	1334
Methane	% vol	96.0	90.2
Ethane	% vol	1.8	4.5
Propane	% vol	0.3	1.9
N-Butane	% vol	0.1	0.0
Carbon Dioxide	% vol	1.04	0.00
Nitrogen	% vol	0.8	3.4
Total	% vol	100.00	100.00

If the methane number decreases, then NO_X is expected to increase. Conversely, if the Wobbe Index decreases, then NO_X is expected to decrease. Since the Wobbe Indices of both fuels are similar, we would not expect NO_X to change much due to the fuel change. But the methane numbers are very different and we do expect the NO_X would increase when operating on the SwRI blended fuel.

Although the hydrocarbon emissions rates of the repeatability tests were similar to the tests for record, the methane emissions were lower in the tests for record. This resulted in the repeatability test's non-methane hydrocarbon (NMHC) emissions to be much lower than the NMHC emissions from the tests for record. We suspect that the NMHC differences are due to the different fuels used. As with the low PM emitter, the high mileage bus's repeatability tests were also performed with the fuel in the bus as received from California. We did not analyze the high mileage natural gas bus's tank fuel but it is probably similar to the low-emitter's tank fuel which had more methane than the SwRI blend, which would reduce NMHC emissions from both vehicles during their repeatability tests.

9.5.1.1 Discussion of Regulated Emissions Results

Figures 74 through 78 show the average emission test results presented in Table 76. Note that long range precision was not thoroughly explored in the test design. Thus, statistical significance of comparisons across different temperatures, fuels, or lubricants cannot be rigorously verified. Average hydrocarbon emissions from the heavy-duty natural gas buses are shown in Figure 74. Hydrocarbon emission rates were similar from each vehicle. Average hydrocarbon rates on fresh oil with normal emitter were less than with aged oil, but the high-mileage bus's rates were very similar with both oils.

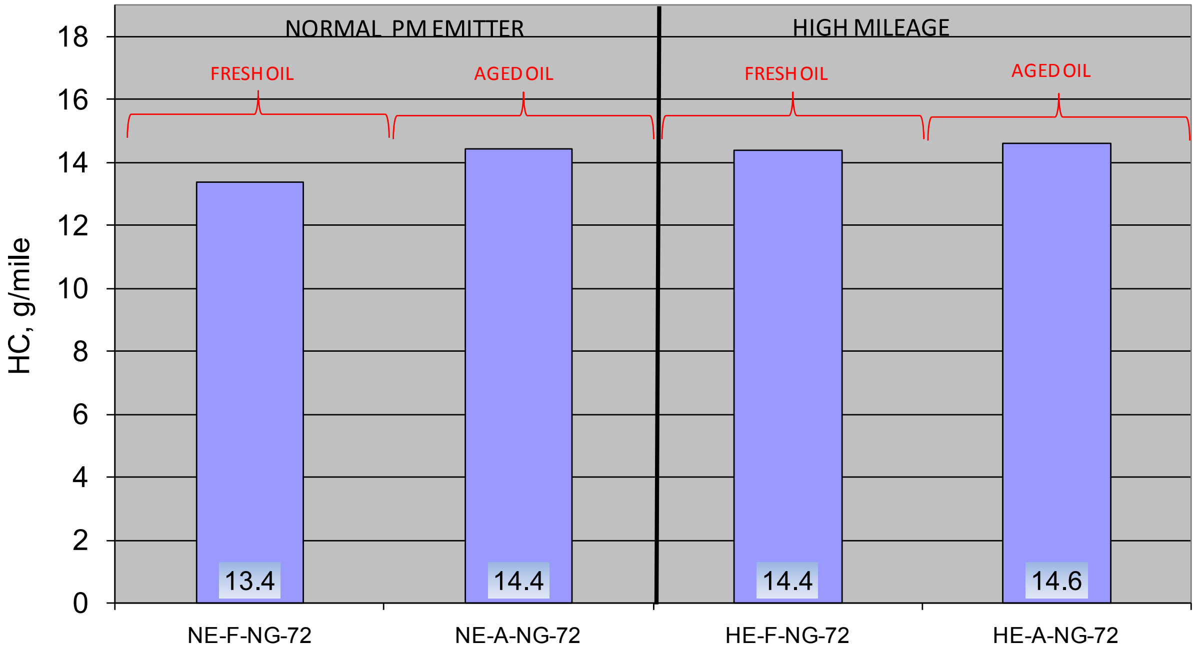

FIGURE 74. HYDROCARBON EMISSION RATES FROM THE NORMAL PM EMITTER AND HIGH MILEAGE NATURAL GAS BUSES (No Statistical Analyses Were Performed On These Data)

Average CO emissions from all the heavy-duty natural gas tests are shown in Figure 75. Both buses produced less CO emissions on fresh oil compared to aged oil. The normal PM emitter produced much less CO than the high mileage bus. The low emitter could have operated leaner, or its catalyst could be more efficient than the high-mileage bus. Average oxides of nitrogen emissions shown in Figure 76 also indicate leaner operation of the normal emitter since it produced higher NO_X emissions than the high-mileage bus. However, the two natural gas buses have different engines which also could explain the differences in their CO and NO_X emissions. NO_X emissions increased with the use of aged oil with both buses.

Fuel usage in pound per mile units from the heavy-duty natural gas vehicles is shown in Figure 77. The normal emitter exhibited worse fuel economy than the high-mileage bus. This is most likely attributable to the relative efficiency their engines. The normal emitter exhibited better fuel economy with aged oil compared to fresh oil, but the high mileage bus did not show any change in fuel economy with the change to aged oil.

Figure 78 shows the PM emissions from the heavy-duty natural gas buses. On fresh oil, the PM rates from both vehicles were very similar. On aged oil, PM rates from the normal emitter decreased but the high mileage vehicle's PM emissions increased. The reason why PM emissions trended in opposite directions when oil was switched from fresh to aged is unknown.

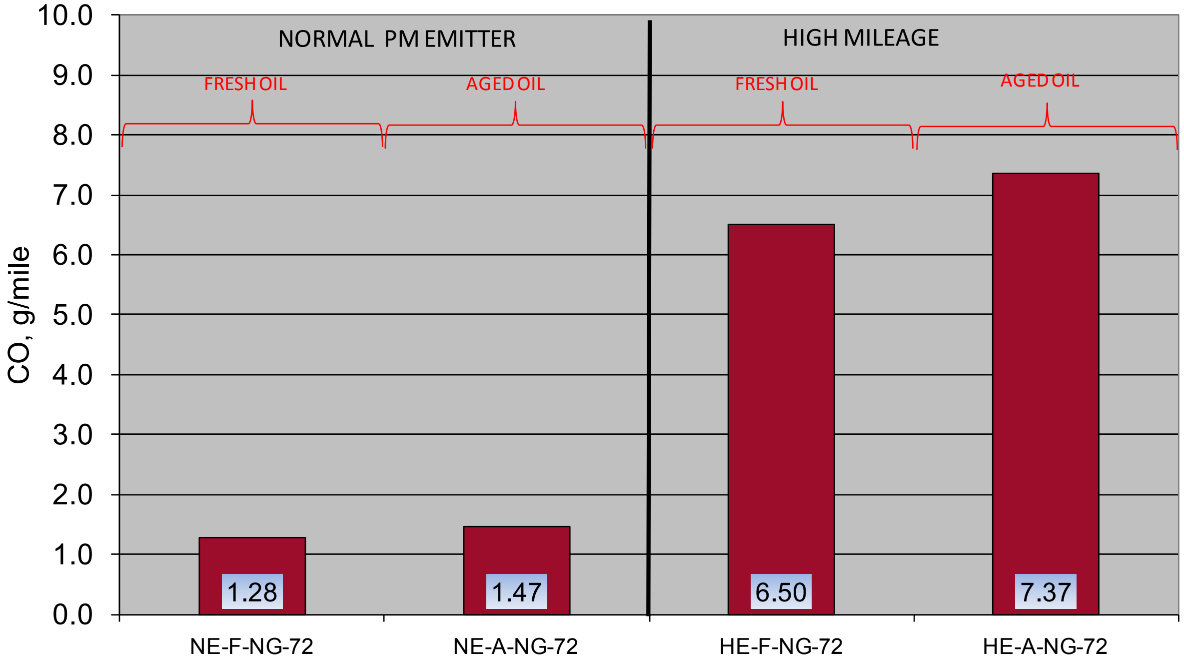

FIGURE 75. CARBON MONOXIDE EMISSION RATES FROM THE NORMAL PM EMITTER AND HIGH MILEAGE NATURAL GAS BUSES
(No Statistical Analyses Were Performed On These Data)

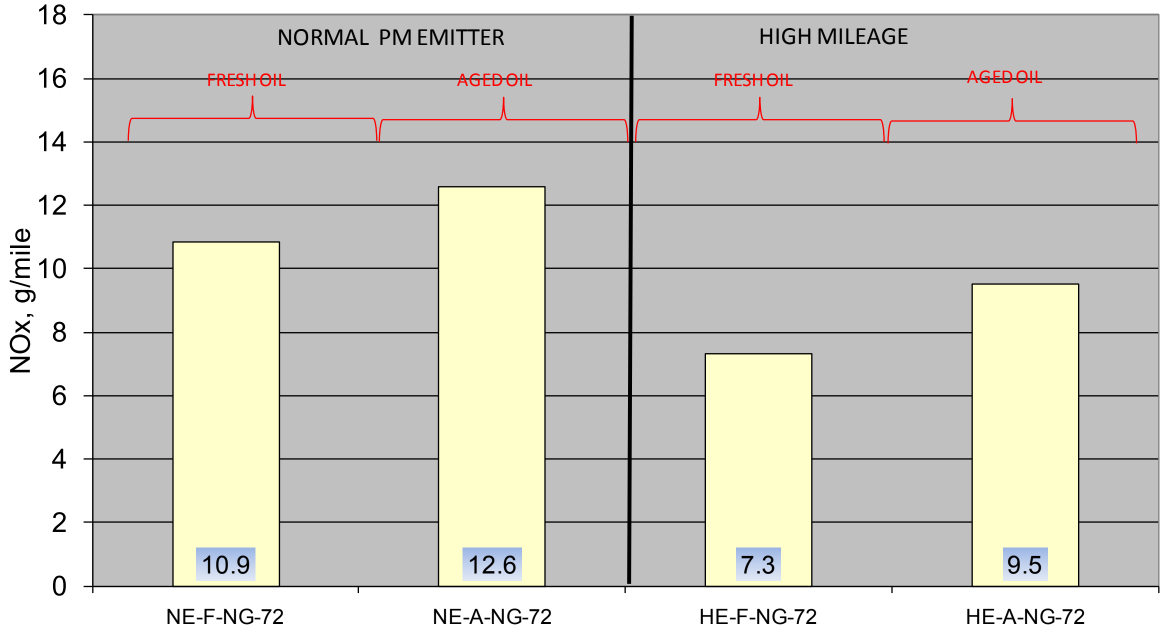

FIGURE 76. OXIDES OF NITROGEN EMISSION RATES FROM THE NORMAL PM EMITTER AND HIGH MILEAGE NATURAL GAS BUSES
(No Statistical Analyses Were Performed On These Data)

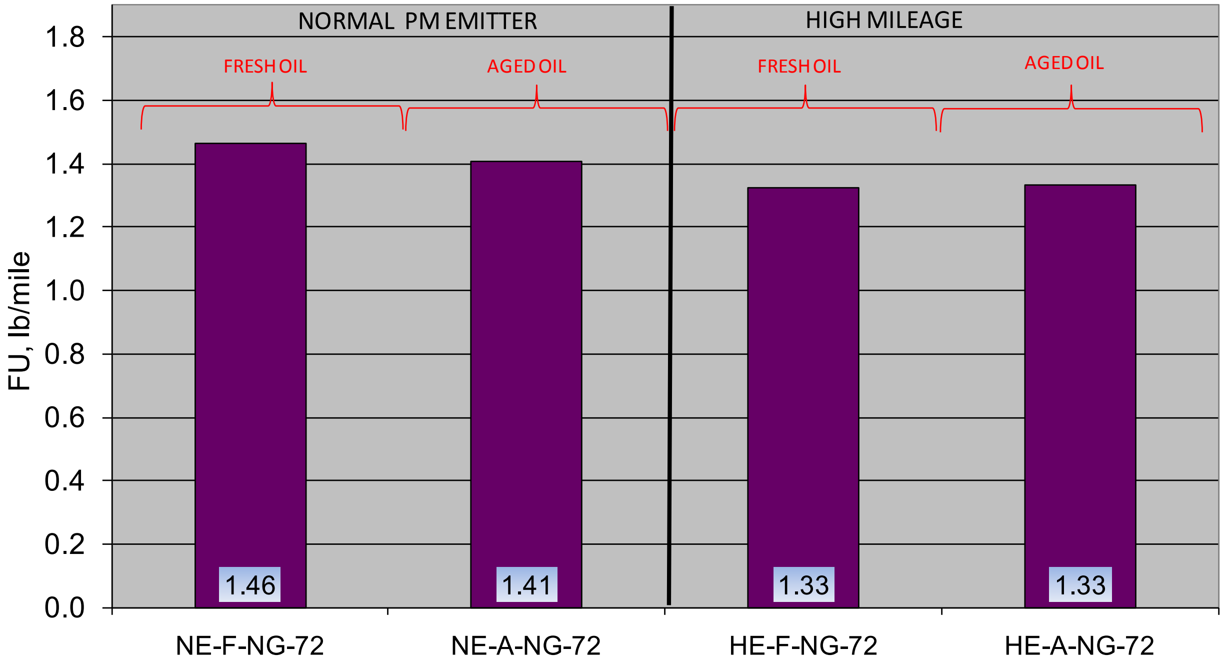

FIGURE 77. FUEL CONSUMPTION OF THE NORMAL PM EMITTER AND HIGH MILEAGE NATURAL GAS BUSES
(No Statistical Analyses Were Performed On These Data)

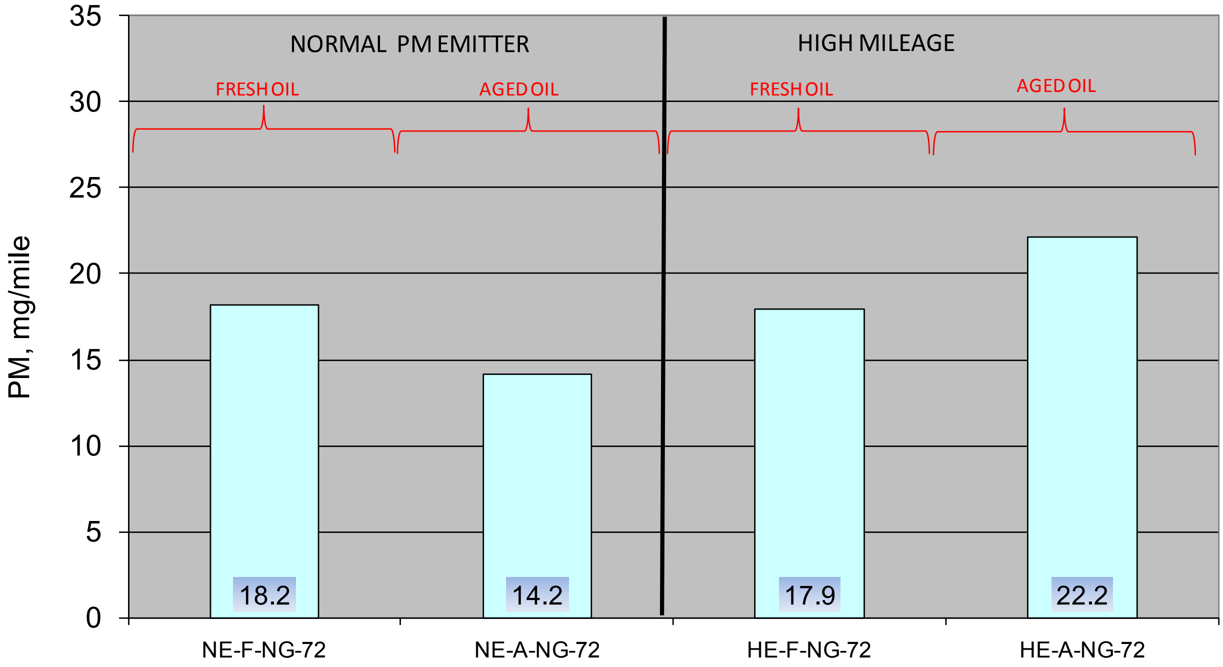

FIGURE 78. PARTICULATE MATTER EMISSION RATES FROM THE NORMAL PM EMITTER AND HIGH MILEAGE NATURAL GAS BUSES
(No Statistical Analyses Were Performed On These Data)

9.5.2 PM and SVOC Analyses

PM from the heavy-duty natural gas vehicle tests were characterized by analyzing them for elements, semi-volatile organic compounds (SVOC), elemental and organic carbon (EC/OC), sulfates, and soluble organic fraction (SOF) at DRI. In the following PM characterization subsections, Tables 79 through 86 present the results of these analyses. Data shown for PM in Tables 79 through 86 are the averages of the replicate tests performed in each configuration.

The spreadsheet of light-duty PM analyses results which was devised by Dr. Fujita to investigate the light-duty PM characterization results was used as a template for the heavy-duty natural gas PM characterization results. The spreadsheet includes the results from the individual tests, and is posted at an ftp site at SwRI for CLOSE participants. Dr. Lawrence Smith of SwRI used the spreadsheet data to identify elements and compounds of interest in the apportionment study presented in Section 9.6.

9.5.2.1 X-Ray Fluorescence (XRF)

PM sampled from the heavy-duty natural gas tests was analyzed by DRI for elements by XRF. Table 79 shows the average results in µg/mile of the replicate tests performed in each configuration, and the results of lubricant analysis in µg/gram. The configurations are identified in the top rows of the table, and elements measured are shown in the left column.

9.5.2.2 Inductively Coupled Plasma Mass Spectrometry (ICP-MS) Analysis

PM sampled from the heavy-duty natural gas tests was analyzed by DRI for eighteen elements by ICP-MS. Table 80 shows the average results from PM in µg/mile of the replicate tests performed in each configuration. Table 80 also shows the results of elemental analysis of the lubricants performed at EAI Inc. EAI measured five more elements in the lubricants than DRI measured in the particulate matter. Elements found in lubricants are presented in nanogram (ng) per gram of oil units. The configurations are identified in the top rows of the table, and elements measured are shown in the left column.

9.5.2.3 Polycyclic Aromatic Hydrocarbons

Exhaust emissions sampled from the heavy-duty natural gas tests were analyzed by DRI for polycyclic aromatic hydrocarbons (PAH). Table 81 shows the average results from PM in µg/mile of the replicate tests performed in each configuration. Table 81 also shows the results of lubricant analyses for PAHs in µg/gram units. Table 28 shows the codes for the PAH species in Table 81.

9.5.2.4 Alkanes

Exhaust emissions sampled from the heavy-duty natural gas tests were analyzed by DRI for alkanes. Table 82 shows the average results in µg/mile of the replicate tests performed in each configuration. Table 30 shows the codes for the alkane species in Table 82. Table 82 also shows the results of lubricant analyses for alkanes in µg/gram units.

9.5.2.5 Hopanes and Steranes

Exhaust emissions sampled from the heavy-duty natural gas tests were analyzed by DRI for hopanes and steranes. Table 83 shows the average results in µg/mile of the replicate tests performed in each configuration. Table 33 shows the codes for the hopanes and steranes species in Table 83. Table 83 also shows the results of lubricant analyses for hopanes and steranes in µg/gram units.

9.5.2.6 Particle-Phase Elemental and Organic Carbon

PM sampled from the heavy-duty natural gas tests was analyzed by DRI for elemental carbon and organic carbon (EC/OC). Table 84 shows the average results in mg/mile of the replicate tests performed in each configuration. The configurations are identified in the five left columns of the table, and EC/OC results are shown in the three right columns. In Table 84, EC is elemental carbon measured, OC is organic carbon, and TC is total carbon.

9.5.2.7 Particulate-Phase Sulfates

Particulate matter sampled from the heavy-duty natural gas tests was analyzed by DRI for sulfates. Table 85 shows the average results in µg/mile of the replicate tests performed in each configuration.

9.5.2.8 Particulate-Phase Soluble Organic Fraction

PM sampled from the heavy-duty natural gas tests was analyzed by DRI for soluble organic fraction (SOF). Table 86 shows the average results for the normal emitter and high emitter, in percent SOF, of the replicate tests performed in each configuration.

TABLE 79. SUMMARY AVERAGE HEAVY-DUTY NATURAL GAS VEHICLE PM AND LUBRICANT ELEMENTAL ANALYSIS BY XRF

(No Statistical Analyses Were Performed On These Data)

	Elemental Emission Rates, μg/mile				**Lubricant Elements, μg/gram**			
Test Number	**HD-NE-F-NG-72**	**HD-NE-A-NG-72**	**HD-HM-F-NG-72**	**HD-HM-A-NG-72**	**HD-NE-F-NG-72**	**HD-NE-A-NG-72**	**HD-HM-F-NG-72**	**HD-HM-A-NG-72**
Emitter	**Normal**	**Normal**	**High Mileage**	**High Mileage**	**Normal**	**Normal**	**High Mileage**	**High Mileage**
Oil	**Fresh**	**Aged**	**Fresh**	**Aged**	**Fresh**	**Aged**	**Fresh**	**Aged**
Fuel	**NG**	**NG**	**NG**	**NG**	**NG**	**NG**	**NG**	**NG**
Temp, ºF	**72**	**72**	**72**	**72**	**72**	**72**	**72**	**72**
Na	560	519	56	208	0	0	0	0
Mg	105	163	0	0	0	0	0	0
Al	0	0	44	40	0	0	0	0
Si	35	12	139	134	0	0	0	0
P	818	857	575	551	101	0	89	3
S	2618	1731	460	561	3046	2271	3147	2079
Cl	4	4	5	5	0	0	0	0
K	7	7	15	16	0	0	0	0
Ca	1823	1871	1220	1508	1828	1826	1823	1753
Sc	0	0	3	3	0	0	0	0
Ti	0	1	10	10	0	0	0	0
Va	1	0	0	0	0	0	0	0
Cr	25	30	18	43	1	1	1	2
Mn	7	18	4	30	0	0	0	0
Fe	1509	2737	539	546	10	23	2	27
Co	0	0	0	0	0	0	0	0
Ni	27	39	16	35	0	0	0	0
Cu	6	12	12	16	0	21	0	7
Zn	1102	1077	762	813	1152	582	1117	525
Ga	0	0	0	0	0	0	0	0
As	0	0	0	0	0	0	0	0
Se	0	0	0	0	0	0	0	0
Br	0	0	0	0	0	0	0	0
Rb	0	0	0	0	0	0	0	0
Sr	1	1	1	3	0	0	0	0
Yt	0	0	0	0	0	0	0	0
Zr	1	0	5	3	0	0	0	0
Nb	0	0	0	0	0	0	0	0
Mo	30	79	20	112	35	292	33	276
Pd	0	0	0	0	0	0	0	0
Ag	0	0	0	0	0	0	0	0
Cd	0	0	1	0	0	0	0	0
In	0	1	0	1	0	0	0	0
Sn	0	0	0	0	0	0	0	0
Sb	1	0	0	0	0	0	0	0
Cs	0	0	0	0	0	0	0	0

TABLE 79 (CONT'D). SUMMARY AVERAGE HEAVY-DUTY NATURAL GAS VEHICLE PM AND LUBRICANT ELEMENTAL ANALYSIS BY XRF

(No Statistical Analyses Were Performed On These Data)

	Elemental Emission Rates, μg/mile				Lubricant Elements, μg/gram			
Test Number	**HD-NE-F-NG-72**	**HD-NE-A-NG-72**	**HD-HM-F-NG-72**	**HD-HM-A-NG-72**	**HD-NE-F-NG-72**	**HD-NE-A-NG-72**	**HD-HM-F-NG-72**	**HD-HM-A-NG-72**
Emitter	**Normal**	**Normal**	**High Mileage**	**High Mileage**	**Normal**	**Normal**	**High Mileage**	**High Mileage**
Oil	**Fresh**	**Aged**	**Fresh**	**Aged**	**Fresh**	**Aged**	**Fresh**	**Aged**
Fuel	**NG**	**NG**	**NG**	**NG**	**NG**	**NG**	**NG**	**NG**
Temp, ºF	**72**	**72**	**72**	**72**	**72**	**72**	**72**	**72**
Ba	0	6	4	0	0	0	0	0
La	0	5	0	0	0	0	0	0
Ce	0	0	0	0	0	0	0	0
Sm	0	2	4	0	0	0	0	0
Eu	4	0	0	0	0	0	0	0
Tb	0	0	1	8	0	0	0	0
Hf	0	0	0	0	0	0	0	0
Ta	0	0	0	0	0	0	0	0
Wo	0	0	0	0	0	0	0	0
Ir	0	0	0	0	0	0	0	0
Au	0	0	0	0	0	0	0	0
Hg	0	0	0	0	0	0	0	0
Tl	0	0	0	0	0	0	0	0
Pb	1	1	2	5	1	7	0	6

TABLE 80. RESULTS OF HEAVY-DUTY NATURAL GAS PM AND LUBRICANTS ELEMENTAL ANALYSIS BY ICP-MS
(No Statistical Analyses Were Performed On These Data)

Test Number	Average Particulate Elements, µg/mile				Lubricant Elements, ng/gram			
	HD-NE-F-NG-72	**HD-NE-A-NG-72**	**HD-HM-F-NG-72**	**HD-HM-A-NG-72**	**HD-NE-F-NG**	**HD-NE-A-NG**	**LO-223360**	**LO-223291**
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	As-received	As-received
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	NG	NG	NG	NG	NG	NG	NG	NG
Temp, ºF	72.0	72.0	72.0	72.0	72	72	72	72
Mg	226.8	224.1	46.5	33.0	10792	22435	5165	13118
Al	13.6	10.6	176.0	90.9	771	1558	471	1412
Ca	826.6	849.7	522.9	529.0	1492876	1484968	1498063	1383799
Va	0.1	0.2	0.2	0.1	35	21	34	21
Cr	8.8	11.9	5.1	16.8	179	274	24	254
Mn	1.5	5.2	6.3	22.8	187	236	60	219
Fe	959.0	1452.9	619.6	328.6	6375	15223	1790	18074
Ni	18.5	28.6	11.7	20.0	240	300	74	418
Cu	3.9	9.6	5.2	8.1	508	19973	22	9644
Zn	782.1	805.3	538.9	509.7	923229	495975	942587	424717
Mo	22.1	62.0	20.3	80.0	31565	267178	32171	293420
Ag	0.1	0.1	0.0	0.1	5	193	<LOD[a]	114
Cd	0.0	0.0	0.0	0.0	0	0	0	0
Sn	0.2	0.3	0.1	0.5	0	0	0	0
Ba	1.3	1.5	11.7	10.9	22	76	12	68
Ce	0.8	2.1	20.4	12.4	0	0	0	0
Hg	0.0	0.0	0.0	0.0	0	0	0	0
Pb	0.9	1.8	2.5	4.0	631	6254	34	5455
W	NM[b]	NM	NM	NM	7	41	5	52
P	NM	NM	NM	NM	747579	386806	787657	336946
S	NM	NM	NM	NM	3378529	2461678	3375411	2275117
Ti	NM	NM	NM	NM	<LOD	35	29	30
Sr	NM	NM	NM	NM	497	536	464	449

[a] Less than Level of Detection
[b] Not measured

TABLE 81. HEAVY-DUTY NATURAL GAS VEHICLE AVERAGE POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST AND LUBRICANTS

(No Statistical Analyses Were Performed On These Data)

Test Number	PAHs, µg/mile				Lubricant PAHs, µg/gram			
	HD-NE-F-NG-72	**HD-NE-A-NG-72**	**HD-HM-F-NG-72**	**HD-HM-A-NG-72**	**HD-NE-F-NG**	**HD-NE-A-NG**	**HD-HM-F-NG**	**HD-HM-A-NG**
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	NG	NG	NG	NG	NG	NG	NG	NG
Temp, ºF	72	72	72	72	72	72	72	72
Media [a]	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction [b]	Yes	Yes	Yes	Yes	NA	NA	NA	NA
naphth	60.9	14.5	63.0	161.1	29.6	30.7	31.9	25.9
quinoline	1.4	0.0	4.6	6.1	0.0	0.0	0.0	0.0
mnaph2	57.2	0.0	95.7	119.5	25.8	29.7	30.3	26.2
mnaph1	33.8	0.0	54.0	72.6	12.7	13.2	16.2	13.8
biphen	4.0	0.7	3.9	14.0	0.6	0.7	0.7	0.9
m_2bph	0.0	0.0	26.4	44.0	0.0	0.2	0.0	0.0
dmn267	16.3	0.0	19.5	25.1	4.7	5.6	6.9	6.9
dm1367	24.4	0.0	32.6	39.1	6.0	9.6	11.6	11.6
d14523	8.5	0.0	16.8	15.6	0.6	1.5	2.4	2.4
enap12	6.9	0.0	17.2	22.1	2.4	2.2	1.7	1.7
acnapy	2.1	0.4	7.2	13.7	0.0	0.0	0.0	0.0
dmn12	1.6	0.0	4.8	6.2	0.0	0.2	0.0	0.6
dmn18	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
acnape	0.1	0.0	0.4	1.9	7.1	0.0	0.0	0.0
m_3bph	0.0	0.0	23.4	41.4	0.0	1.7	1.4	1.8
m_4bph	0.0	0.0	7.2	15.1	0.0	0.5	5.3	0.6
dbzfur	1.9	1.1	2.8	6.6	0.0	0.0	0.0	0.0
em_12n	5.3	3.7	16.8	23.5	0.0	0.3	0.0	0.2
tmi235n	6.2	0.6	11.3	9.4	0.4	0.8	4.1	3.1
btmnap	4.0	0.0	10.7	9.8	0.9	2.1	3.9	3.4
atmnap	12.6	0.2	14.3	17.0	0.0	1.1	0.6	1.9
ctmnap	1.4	0.0	10.2	9.6	0.0	0.8	3.2	3.0
em_21n	0.1	0.0	0.6	0.4	0.0	0.0	0.0	0.0
etmnap	1.9	0.0	5.9	6.5	1.1	1.0	2.8	1.7
tm245n	0.9	0.0	2.5	3.1	0.0	0.1	0.6	0.4

TABLE 81 (CONT'D). HEAVY-DUTY NATURAL GAS VEHICLE AVERAGE POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST AND LUBRICANTS

(No Statistical Analyses Were Performed On These Data)

Test Number	PAHs, µg/mile				Lubricant PAHs, µg/gram			
	HD-NE-F-NG-72	HD-NE-A-NG-72	HD-HM-F-NG-72	HD-HM-A-NG-72	HD-NE-F-NG	HD-NE-A-NG	HD-HM-F-NG	HD-HM-A-NG
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	NG	NG	NG	NG	NG	NG	NG	NG
Temp, °F	72	72	72	72	72	72	72	72
Media [a]	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction [b]	Yes	Yes	Yes	Yes	NA	NA	NA	NA
ftmnap	2.2	0.0	6.9	6.3	0.6	1.2	3.3	2.8
fluore	0.4	0.0	5.2	6.5	0.0	0.1	0.6	0.7
tm145n	0.0	0.0	2.2	2.4	0.0	0.2	0.4	0.7
jtmnap	2.8	0.4	3.7	2.3	0.0	0.2	0.6	0.4
a_mfluo	0.0	0.0	1.0	0.9	0.2	0.5	2.0	2.7
b_mfluo	0.0	0.0	0.4	0.4	0.0	0.0	0.4	0.2
m_1fluo	0.5	0.0	1.5	0.8	0.2	0.2	1.8	1.2
fl9one	0.0	0.0	5.9	14.5	0.0	0.0	0.0	0.0
phenan	0.0	0.0	7.0	11.5	0.6	2.6	4.4	4.7
anthra	0.0	0.0	1.1	2.0	0.1	0.7	2.3	2.4
xanone	0.0	0.0	0.4	1.3	0.0	0.0	0.1	0.2
acquone	0.0	0.1	0.5	0.0	0.0	0.0	0.0	0.0
m_2phen	1.2	0.0	1.0	2.3	1.1	3.2	3.2	6.0
m_3phen	0.0	0.0	2.1	2.4	1.0	4.0	3.7	6.6
pnapone	0.2	0.1	3.6	5.2	0.0	0.3	0.6	0.6
m_2anth	0.0	0.0	0.3	0.2	0.0	2.0	4.1	4.8
m_45phen	0.0	0.0	0.1	2.4	0.4	0.6	0.7	0.6
m_9phen	0.0	0.0	0.9	3.6	0.0	1.2	1.7	2.5
mpht_1	0.3	0.2	0.8	0.8	0.0	1.7	1.2	2.0
anthron	0.0	0.0	0.0	1.8	0.0	2.0	1.1	3.9
m_9ant	0.0	0.0	0.1	0.0	0.2	0.1	0.0	0.2
nap2phen	0.0	0.0	0.0	0.4	0.2	0.5	0.8	0.7
anrquone	0.0	0.0	0.7	1.3	0.0	0.2	0.0	0.3
a_dmph	0.0	0.1	0.3	0.8	0.2	3.1	1.2	1.5
b_dmph	0.0	0.0	0.0	0.2	0.0	2.0	0.4	0.9
dm17ph	0.0	0.0	0.0	0.1	0.5	2.7	1.4	2.2
dm36ph	0.0	0.0	0.1	0.3	0.1	1.2	0.0	1.6

TABLE 81 (CONT'D). HEAVY-DUTY NATURAL GAS VEHICLE AVERAGE POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST AND LUBRICANTS

(No Statistical Analyses Were Performed On These Data)

Test Number	PAHs, µg/mile				Lubricant PAHs, µg/gram			
	HD-NE-F-NG-72	**HD-NE-A-NG-72**	**HD-HM-F-NG-72**	**HD-HM-A-NG-72**	**HD-NE-F-NG**	**HD-NE-A-NG**	**HD-HM-F-NG**	**HD-HM-A-NG**
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	NG	NG	NG	NG	NG	NG	NG	NG
Temp, °F	72	72	72	72	72	72	72	72
Media [a]	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction [b]	Yes	Yes	Yes	Yes	NA	NA	NA	NA
d_dmph	0.0	0.0	0.1	0.2	0.2	0.9	1.7	1.5
e_dmph	0.0	0.0	0.0	0.7	0.1	2.3	0.8	3.2
c_dmph	0.0	0.0	0.1	0.3	0.8	5.0	3.5	6.8
fluora	0.0	0.0	0.9	1.3	0.1	0.4	0.3	0.7
pyrene	0.5	0.0	1.3	2.3	0.2	5.6	1.8	8.2
antal9	0.0	0.0	0.0	0.0	0.5	1.7	1.1	2.5
retene	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2
bafluo	0.0	0.0	0.1	0.0	0.7	1.2	0.4	2.8
bbfluo	0.0	0.0	0.0	0.0	0.2	0.6	0.7	0.7
bmpyfl	0.0	0.0	0.1	0.0	0.8	1.4	0.5	3.3
c1mflpy	0.0	0.0	0.0	0.0	0.1	0.5	0.7	0.4
m_13fl	0.0	0.0	0.1	0.1	0.8	1.0	0.5	2.6
m_4pyr	0.0	0.0	0.1	0.8	1.1	6.6	1.3	12.0
cmpyfl	0.0	0.0	0.0	0.0	0.3	1.1	1.2	1.3
dmpyfl	0.0	0.0	0.0	0.2	0.4	10.8	1.2	15.8
m_1pyr	0.0	0.0	0.0	0.1	0.5	4.9	0.7	7.4
bntiop	0.0	0.0	0.0	0.2	0.5	0.5	0.0	0.6
bzcphen	0.0	0.0	0.0	0.1	0.3	0.3	0.3	0.4
bghifl	0.0	0.0	0.2	0.4	0.2	0.8	0.6	0.2
phant9	0.0	0.0	0.3	0.1	0.1	0.2	0.0	0.2
cp_cdpyr	0.3	0.0	0.4	0.1	0.1	0.3	0.4	0.2
baanth	0.0	0.1	0.0	0.1	0.1	2.8	0.8	2.8
chr_tr	0.1	0.0	0.0	0.5	0.5	1.8	0.8	4.3
bzanthr	0.1	0.1	0.1	0.6	1.1	1.7	0.9	1.7
baa7_12	0.0	0.0	0.0	0.3	0.8	3.8	1.3	2.1
m_3chr	0.0	0.0	0.0	0.2	0.3	0.9	0.7	2.4
chry56m	0.0	0.0	0.0	0.0	0.7	1.0	0.8	0.6

TABLE 81 (CONT'D). HEAVY-DUTY NATURAL GAS VEHICLE AVERAGE POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST AND LUBRICANTS
(No Statistical Analyses Were Performed On These Data)

Test Number	PAHs, µg/mile				Lubricant PAHs, µg/gram			
	HD-NE-F-NG-72	HD-NE-A-NG-72	HD-HM-F-NG-72	HD-HM-A-NG-72	HD-NE-F-NG	HD-NE-A-NG	HD-HM-F-NG	HD-HM-A-NG
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	NG	NG	NG	NG	NG	NG	NG	NG
Temp, ºF	72	72	72	72	72	72	72	72
Media [a]	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction [b]	Yes	Yes	Yes	Yes	NA	NA	NA	NA
m_7baa	0.0	0.0	0.0	0.0	0.9	0.8	0.7	0.5
dmban712	0.0	0.0	0.0	1.7	0.3	0.3	0.9	0.2
bbjkfl	0.0	0.0	0.0	0.4	0.3	0.3	0.1	0.4
bafl	0.0	0.0	0.0	0.0	0.2	0.2	0.1	0.0
bepyrn	0.0	0.0	0.1	0.4	0.2	0.5	0.2	0.2
bapyrn	0.0	0.0	0.0	0.1	0.4	0.5	0.2	0.5
peryle	0.2	0.0	0.0	0.1	0.4	0.2	0.0	0.4
m_7bpy	0.1	0.1	0.1	0.0	0.2	0.2	0.2	0.2
bpy910dih	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
incdfl	0.0	0.0	0.0	0.1	0.6	0.5	0.9	0.5
dbahacr	0.0	0.0	0.0	0.0	0.6	0.2	0.1	0.1
dbajacr	0.0	0.0	0.0	0.0	0.2	0.3	0.4	0.5
in123pyr	0.0	0.0	0.1	0.1	0.4	0.4	0.4	0.3
dbahacan	0.0	0.0	0.0	0.0	0.7	0.7	1.8	0.7
dbajan	0.0	0.0	0.0	0.0	0.7	0.9	0.4	0.4
bbchr	0.0	0.0	0.0	0.0	0.5	0.6	0.7	0.7
pic	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.5
bghipe	0.1	0.0	0.6	0.7	0.6	0.5	1.0	0.7
anthan	0.0	0.0	0.1	0.0	0.3	0.2	1.1	0.7
dbalpyr	0.0	0.0	0.0	0.0	0.2	0.3	0.2	1.4
corone	0.0	0.0	0.2	0.3	0.3	0.2	0.0	0.4
dbaepyr	0.0	0.0	0.0	0.1	0.0	0.9	0.0	0.2
dbaipyr	0.0	0.0	0.0	0.1	0.5	0.3	0.0	0.0
dbahpyr	0.0	0.0	0.0	0.1	0.3	0.4	0.0	0.0
dbbkfl	0.0	0.0	0.0	0.0	0.5	0.7	0.0	0.9
dbth	0.0	0.0	0.0	0.4	0.4	0.4	0.4	0.4

[a] Filter + XAD cartridge samples or oil samples.

[b] Test samples were corrected by subtracting the average tunnel blank measurement.

TABLE 82. HEAVY-DUTY NATURAL GAS VEHICLE AVERAGE ALKANES IN EXHAUST AND LUBRICANTS

(No Statistical Analyses Were Performed On These Data)

Test Number	Alkanes Emission Rates, µg/mile				Lubricant Alkanes, µg/gram			
	HD-NE-F-NG-72	HD-NE-A-NG-72	HD-HM-F-NG-72	HD-HM-A-NG-72	HD-NE-F-NG	HD-NE-A-NG	HD-HM-F-NG	HD-HM-A-NG
Source	Exhaust	Exhaust	Exhaust	Exhaust	Oil	Oil	Oil	Oil
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	NG	NG	NG	NG	NG	NG	NG	NG
Temp, ºF	72	72	72	72	72	72	72	72
Media [a]	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction [b]	Yes	Yes	Yes	Yes	NA	NA	NA	NA
dodec	216.9	0.0	0.0	71.3	0.0	0.3	0.9	0.4
norfarn	62.3	0.0	0.3	42.8	15.1	0.0	0.0	0.0
tridec	116.1	0.0	0.0	114.4	0.0	0.4	1.4	1.3
hpycyhx	13.8	1.0	0.0	13.4	0.0	0.0	0.0	0.0
farnes	51.4	0.5	0.0	31.7	0.0	0.0	0.0	0.0
tdec	553.2	0.0	24.0	164.0	2.2	4.0	5.1	4.0
ocycyhx	4.5	0.0	0.0	11.5	0.0	0.0	0.1	0.0
pentad	92.5	11.7	38.5	132.5	1.7	5.4	4.8	4.1
noycyhx	8.7	1.1	2.4	13.2	0.1	0.0	0.2	0.1
hexad	15.9	4.4	25.1	82.9	14.8	21.9	21.5	17.1
norprst	7.4	7.8	13.5	33.2	0.5	0.4	3.1	0.7
decyhx	0.0	2.1	4.6	8.8	0.2	0.2	0.6	0.1
heptad	11.1	0.0	22.2	62.1	42.1	67.6	63.7	63.8
heptdpris	7.6	2.3	16.2	32.2	2.2	5.1	8.9	2.1
dec1yhx	0.2	0.0	0.6	1.5	0.9	2.0	4.6	1.9
octad	6.8	0.0	16.9	31.3	29.6	38.9	46.1	39.5
phytan	4.7	0.0	12.8	21.9	18.1	15.9	30.7	15.2
dec2yhx	0.1	0.1	3.5	2.5	5.8	1.5	9.2	4.7
nonad	4.9	0.5	12.4	16.6	39.4	60.0	62.6	55.3
dec3yhx	0.0	0.0	1.4	1.4	9.4	11.4	12.0	10.7
eicosa	1.4	0.0	7.1	10.2	67.4	113.7	100.9	107.2
dec4yhx	0.0	0.0	0.3	1.1	28.7	24.2	33.4	30.7
heneic	0.0	0.0	4.7	7.7	94.1	111.1	130.1	121.9
dec5yhx	0.0	0.0	1.0	1.1	53.0	75.9	83.3	69.2
docosa	0.0	0.0	3.7	4.7	78.0	107.8	102.4	109.5
dec6yhx	0.1	0.1	0.3	0.5	12.1	5.5	15.2	51.1

TABLE 82 (CONT'D). HEAVY-DUTY NATURAL GAS VEHICLE AVERAGE ALKANES IN EXHAUST AND LUBRICANTS
(No Statistical Analyses Were Performed On These Data)

Test Number	Alkanes Emission Rates, µg/mile				Lubricant Alkanes, µg/gram			
	HD-NE-F-NG-72	HD-NE-A-NG-72	HD-HM-F-NG-72	HD-HM-A-NG-72	HD-NE-F-NG	HD-NE-A-NG	HD-HM-F-NG	HD-HM-A-NG
Source	Exhaust	Exhaust	Exhaust	Exhaust	Oil	Oil	Oil	Oil
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	NG	NG	NG	NG	NG	NG	NG	NG
Temp, ºF	72	72	72	72	72	72	72	72
Media [a]	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction [b]	Yes	Yes	Yes	Yes	NA	NA	NA	NA
tricosa	0.0	0.0	4.3	2.4	61.9	87.0	76.9	100.8
dec7yhx	0.2	0.0	0.4	3.5	76.0	121.1	102.6	117.5
tetcos	0.0	0.0	0.0	1.1	51.9	56.6	37.6	82.9
dec8yhx	0.0	0.0	4.2	9.2	33.5	7.6	11.9	72.2
pencos	0.0	0.0	3.3	6.6	75.0	138.4	152.6	159.2
hexcos	0.0	0.0	2.8	1.7	110.6	102.7	185.1	94.1
dec9yhx	0.0	0.0	0.8	0.9	9.0	10.2	27.0	7.7
hepcos	0.0	0.1	5.6	2.3	35.4	25.1	102.3	90.8
cyhxeic	0.0	0.0	0.4	0.4	76.9	57.1	48.3	64.5
octcos	0.0	0.0	3.5	2.6	52.0	38.3	21.2	120.4
noncos	0.0	0.0	2.0	2.3	41.9	74.0	32.2	22.4
cyhxhen	0.2	0.3	0.5	0.1	29.0	22.4	4.8	10.9
tricont	0.0	0.0	1.0	1.9	27.4	8.9	15.3	22.2
htricont	0.0	0.0	1.1	3.1	21.1	7.5	46.4	1.4
dtricont	0.0	0.0	0.8	1.7	6.3	24.1	8.3	6.6
ttricont	0.0	0.0	0.4	1.6	2.9	4.2	16.8	3.7
tetricont	0.0	0.0	0.2	0.0	7.4	4.5	29.4	20.5
ptricont	0.0	0.0	0.0	0.2	10.0	0.1	1.1	3.4
hxtricont	0.0	0.0	0.0	0.0	2.0	2.6	4.4	7.1
hptricont	0.0	0.0	0.0	0.0	11.0	10.4	2.3	5.8
otricont	0.0	0.0	0.1	0.1	5.8	2.3	6.9	4.8
ntricont	0.0	0.0	0.0	0.1	4.2	3.0	0.7	5.7
tecont	0.0	0.0	0.2	0.1	4.6	2.0	4.4	8.1
hxtric74	4.6	2.2	8.0	8.1	380.2	317.4	372.2	370.9
ucm	1735	515	5473	8027	179758	191638	190729	206337

[a] Filter + XAD cartridge samples or oil samples.

[b] Test samples were corrected by subtracting the average tunnel blank measurement.

TABLE 83. HEAVY-DUTY NATURAL GAS VEHICLE AVERAGE HOPANES AND STERANES IN EXHAUST AND LUBRICANTS
(No Statistical Analyses Were Performed On These Data)

Test Number	Hopanes and Steranes Emission Rates, µg/mile				Lubricant Hopanes and Steranes, µg/gram			
	HD-NE-F-NG-72	HD-NE-A-NG-72	HD-HM-F-NG-72	HD-HM-A-NG-72	HD-NE-F-NG-72	HD-NE-A-NG-72	HD-HM-F-NG-72	HD-HM-A-NG-72
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	NG	NG	NG	NG	NG	NG	NG	NG
Temp, ºF	72	72	72	72	72	72	72	72
Media [a]	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction [b]	Yes	Yes	Yes	Yes	NA	NA	NA	NA
hop15	0.0	0.1	0.6	0.9	31.7	32.6	47.0	51.7
hop17	0.2	0.2	2.4	2.8	98.2	121.0	164.0	94.6
hop19	0.0	0.5	1.7	2.0	59.9	77.1	94.5	62.1
hop20	0.0	0.0	0.0	0.0	1.7	2.9	0.0	2.0
hop21	0.0	0.9	1.5	2.0	44.6	56.1	89.2	49.6
hop22	0.0	0.4	0.6	0.8	29.6	40.7	78.9	29.2
hop23	0.1	0.1	0.1	0.0	4.4	7.7	11.2	5.0
hop24	0.1	0.1	0.5	0.8	24.7	29.3	70.6	24.6
hop25	0.1	0.2	0.4	0.6	14.3	24.0	67.2	19.5
hop26	0.1	0.1	0.3	0.4	12.6	15.8	34.9	17.3
hop27	0.0	0.0	0.2	0.3	9.0	11.9	56.9	16.7
ster42	0.1	0.0	0.1	0.1	9.7	7.2	4.1	6.5
ster43	0.1	0.0	1.3	0.6	32.2	31.2	35.0	29.3
ster44	0.0	0.0	0.8	0.3	15.5	15.6	15.0	16.6
ster45_40	0.1	0.1	0.4	0.4	27.1	26.4	18.2	21.6
ster46	0.0	0.0	0.3	0.1	3.5	3.7	2.2	4.3
ster47	0.0	0.0	0.3	0.3	15.6	15.4	16.2	17.7
ster48_41	0.0	0.0	0.1	0.0	9.5	10.3	8.5	6.6
ster49	0.0	0.0	0.1	0.1	2.1	1.8	4.2	2.2
ster50	0.0	0.0	0.2	0.2	8.9	9.1	8.2	8.9
ster51	0.0	0.0	1.2	0.3	17.6	19.6	16.4	18.8
ster52	0.0	0.1	0.2	0.2	12.6	13.9	11.2	13.2
ster53	0.1	0.0	0.1	0.3	11.8	12.9	14.5	11.6

[a] Filter + XAD cartridge samples or oil samples.
[b] Test samples were corrected by subtracting the average tunnel blank measurement.

TABLE 84. HEAVY-DUTY NATURAL GAS VEHICLE AVERAGE ELEMENTAL CARBON AND ORGANIC CARBON RATES

(No Statistical Analyses Were Performed On These Data)

					CARBON EMISSION RATE, mg/mile		
Test Number	Emitter	Oil	Fuel	Temp, ºF	EC	OC	TC
HD-NE-F-NG-72	Normal	Fresh	Natural Gas	72	0.96	7.26	8.22
HD-NE-A-NG-72	Normal	Aged	Natural Gas	72	1.52	7.63	9.14
HD-HM-F-NG-72	High Mileage	Fresh	Natural Gas	72	0.46	16.84	17.30
HD-HM-A-NG-72	High Mileage	Aged	Natural Gas	72	1.20	22.71	23.90

TABLE 85. AVERAGE SULFATE EMISSIONS FROM HEAVY-DUTY NATURAL GAS VEHICLES

(No Statistical Analyses Were Performed On These Data)

Test Number	Emitter	Oil	Fuel	Temp	Average Sulfate, µg/mile
HD-NE-F-NG-72	Normal	Fresh	Natural Gas	72	6531
HD-NE-A-NG-72	Normal	Aged	Natural Gas	72	4205
HD-HM-F-NG-72	High Mileage	Fresh	Natural Gas	72	1086
HD-HM-A-NG-72	High Mileage	Aged	Natural Gas	72	1147

TABLE 86. HEAVY-DUTY NATURAL GAS VEHICLE AVERAGE SOLUBLE ORGANIC FRACTION

(No Statistical Analyses Were Performed On These Data)

Test Name	Lubricant	Vehicle	Fuel	Ambient Temperature, ºF	Average SOF, %
HD-NE-F-NG-72	Fresh	Normal Emitter	Natural Gas	72	9%
HD-NE-A-NG-72	Aged	Normal Emitter	Natural Gas	72	15%
HD-HM-F-NG-72	Fresh	High Mileage	Natural Gas	72	66%
HD-HM-A-NG-72	Aged	High Mileage	Natural Gas	72	72%

9.5.2.9 Particle Number and Size Distribution Emission Test Results

Figures 79 and 80 show the exhaust PN concentration for the heavy-duty natural gas normal emitter (HD-NG-NE). The data are shown for the fresh and aged oil at 72°F. The data are plotted as an average concentration for the cold-start and for one subsequent hot-start of the HD UDDS. The exhaust PN concentration ranged from about $6x10^6$ part./cm³ to $15x10^6$ part./cm³. This is comparable in range to the diesel MD-NE, but as can be seen later, the particle size distribution is vastly different. More PN emissions were observed during the hot-start portion of the cycle, compared to the cold-start. Fresh oil produced higher PN emissions than the aged oil, particularly volatile PN. This trend was observed previously with the gasoline LD-NE. Figures 81 and 82 show the percent ratio of solid and volatile PN concentration to total PN concentration. Twenty five to fifty-five percent of the number of particles emitted from the HD-NG-NE were solid in nature.

Figures 83 and 84 show the exhaust PN concentration for the HD-NG high mileage emitter (HM). The exhaust PN concentration ranged from $10x10^6$ part./cm³ to $55x10^6$ part./cm³. This highest PN concentration is higher than the PN concentration observed with the MD NE and HE. However, it was 63 percent lower than the highest PN concentration observed with the light duty HE. Fresh oil showed higher PN emissions than aged oil under cold-start. Under hot-start, the PN emission was comparable between the fresh and the aged oil. Figures 85 and 86 show that over 80 percent of the PN were volatile particles. This is similar to what was observed previously with the gasoline LD-HE.

It is known that heavy-duty natural gas engines produce very little PM when the engine is tuned properly and lube oil consumption is low. The high volatile PN emissions observed in this study are likely due to sulfuric acid and volatile and semi-volatile hydrocarbon particle formation during dilution and cooling of hot exhaust. The origin of sulfuric acid is from the presence of sulfur in the fuel (if any) and lube oil. Sulfur is oxidized in combustion and in the exhaust over an oxidation catalyst to produce SO_3. SO_3 reacts with water in the exhaust to form sulfuric acid. Sulfuric acid nucleates into particles during exhaust cooling and dilution.

The origin of volatile and semi-volatile hydrocarbon is mainly due to unburned and partially burned lube oil. The origin of solid particles in natural gas engines can be due to multiple factors. First, soot formation in natural gas combustion is a plausible scenario, but perhaps unlikely with the lean burn natural gas engines tested in this program. Another mechanism is soot formation by pyrolysis of semi-volatiles in the lube oil. This mechanism is more plausible in stoichiometric natural gas engines with a lack of excess oxygen rather than in lean burn natural gas engines. A third plausible mechanism for solid particle emissions from natural gas engines is metal oxides and/or sulfated ash emissions derived from the lube oil. The presence of these particles typically shows up in the nuclei mode part of the size distribution, as shown below.

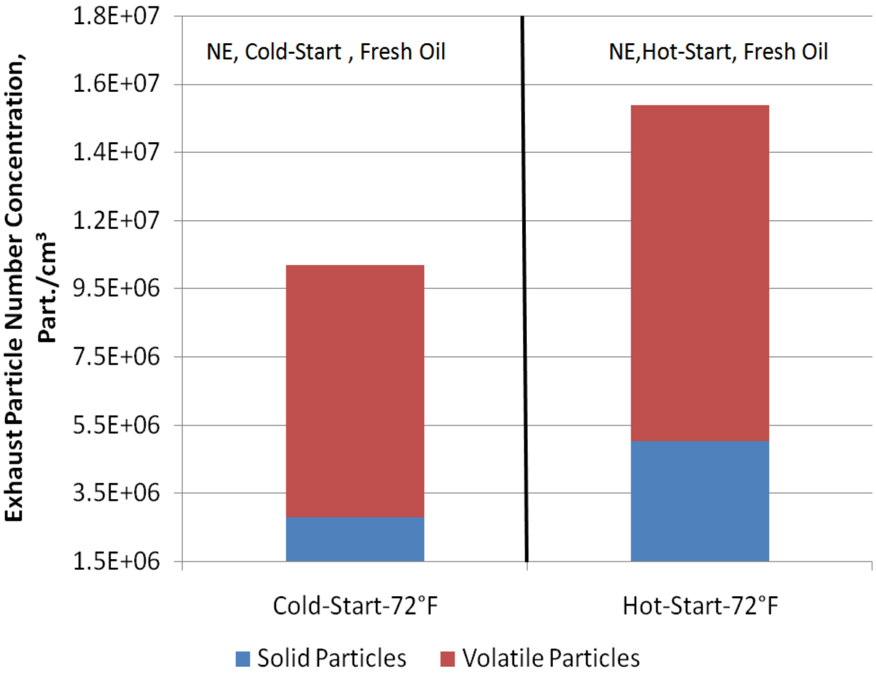

FIGURE 79. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (NATURAL GAS, NORMAL EMITTER, FRESH OIL) (No Statistical Analyses Were Performed On These Data)

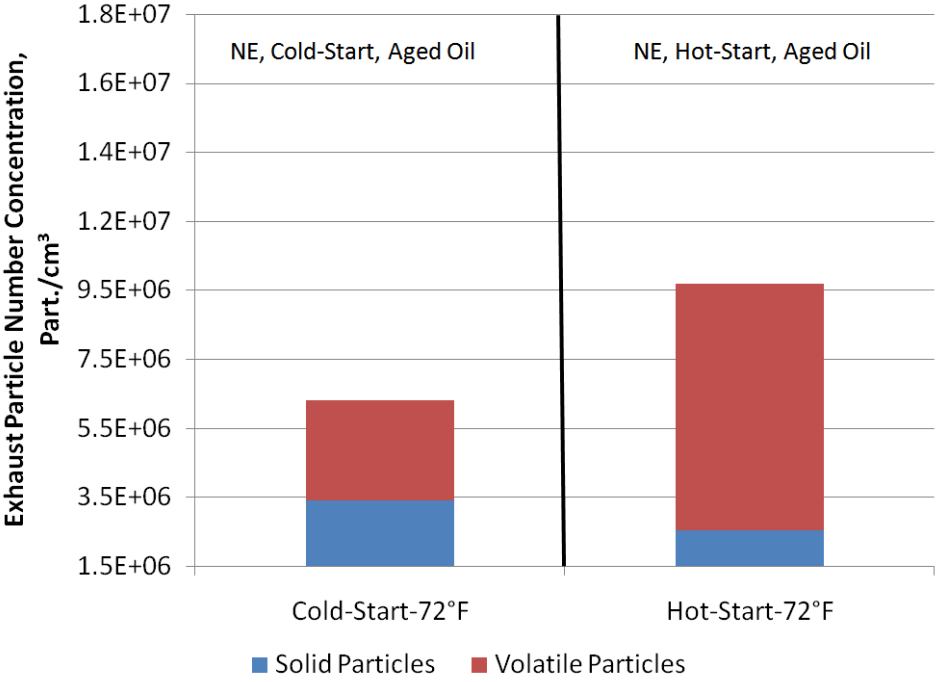

FIGURE 80. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (NATURAL GAS, NORMAL EMITTER, AGED OIL) (No Statistical Analyses Were Performed On These Data)

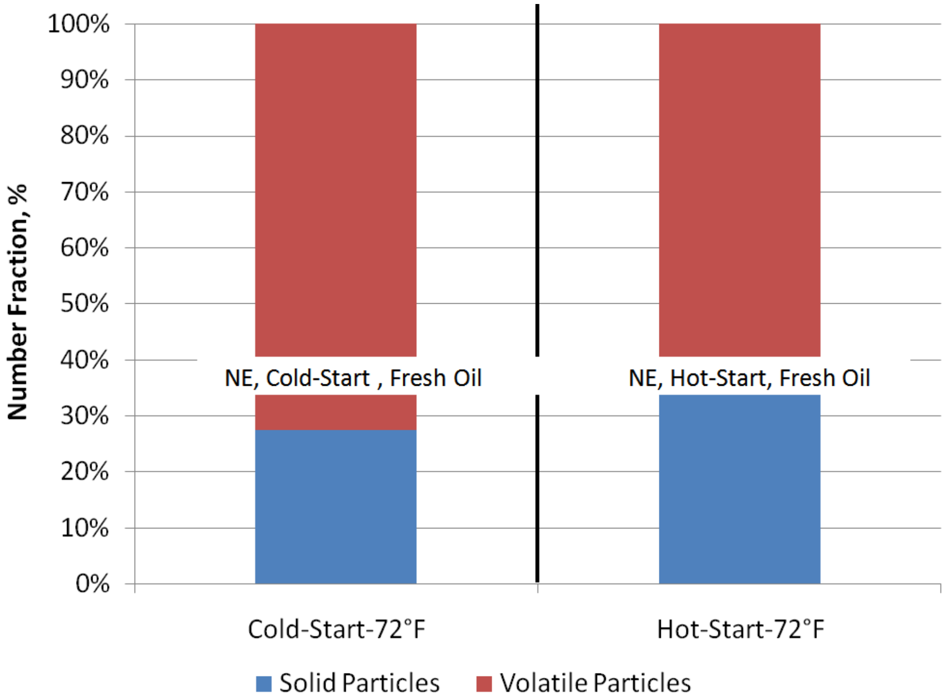

FIGURE 81. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (NATURAL GAS, NORMAL EMITTER, FRESH OIL) (No Statistical Analyses Were Performed On These Data)

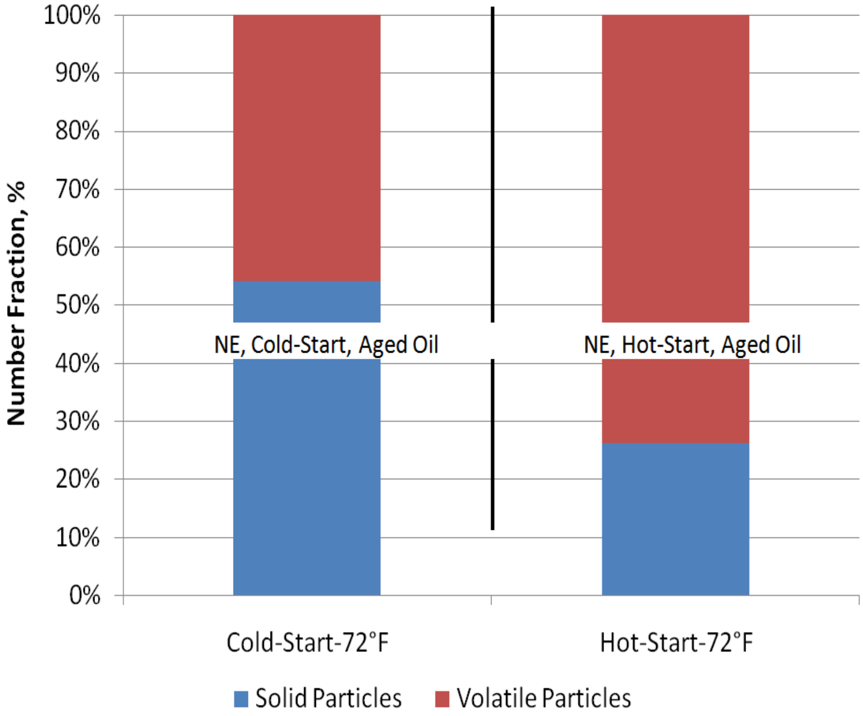

FIGURE 82. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (NATURAL GAS, NORMAL EMITTER, AGED OIL) (No Statistical Analyses Were Performed On These Data)

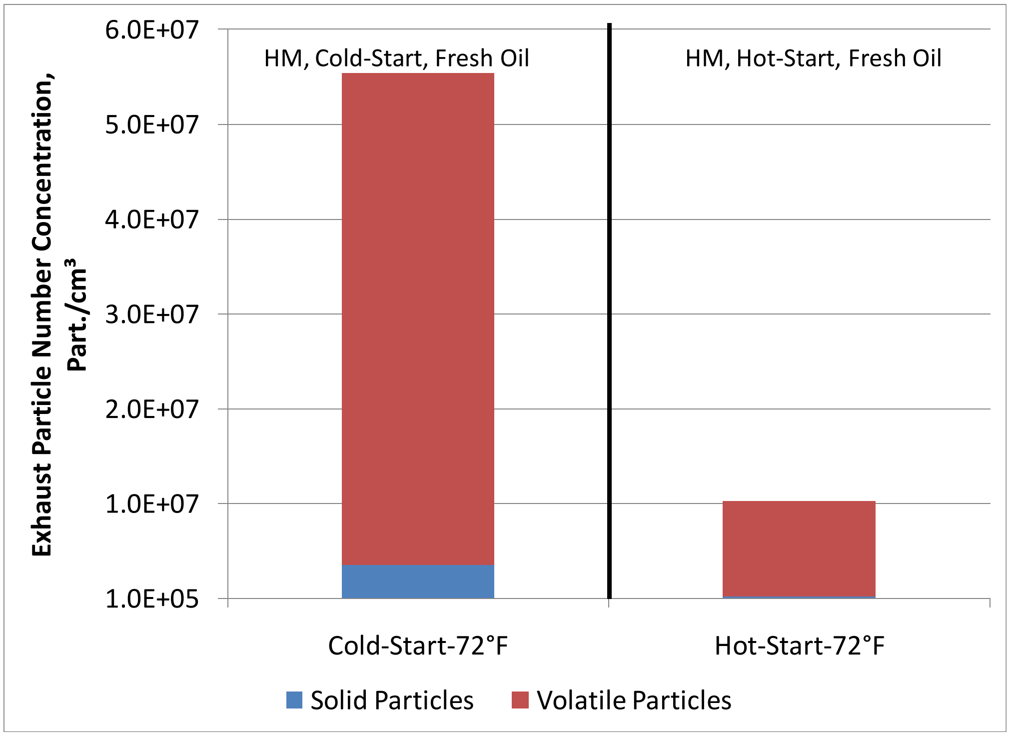

FIGURE 83. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (NATURAL GAS, HIGH MILEAGE EMITTER, FRESH OIL) (No Statistical Analyses Were Performed On These Data)

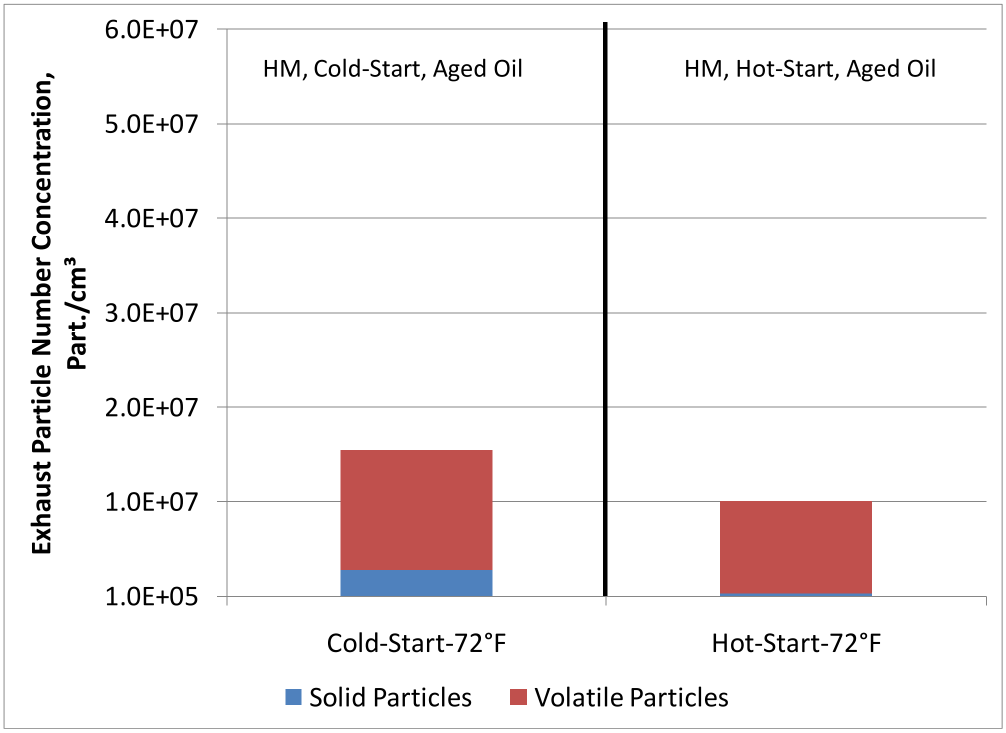

FIGURE 84. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (NATURAL GAS, HIGH MILEAGE EMITTER, AGED OIL) (No Statistical Analyses Were Performed On These Data)

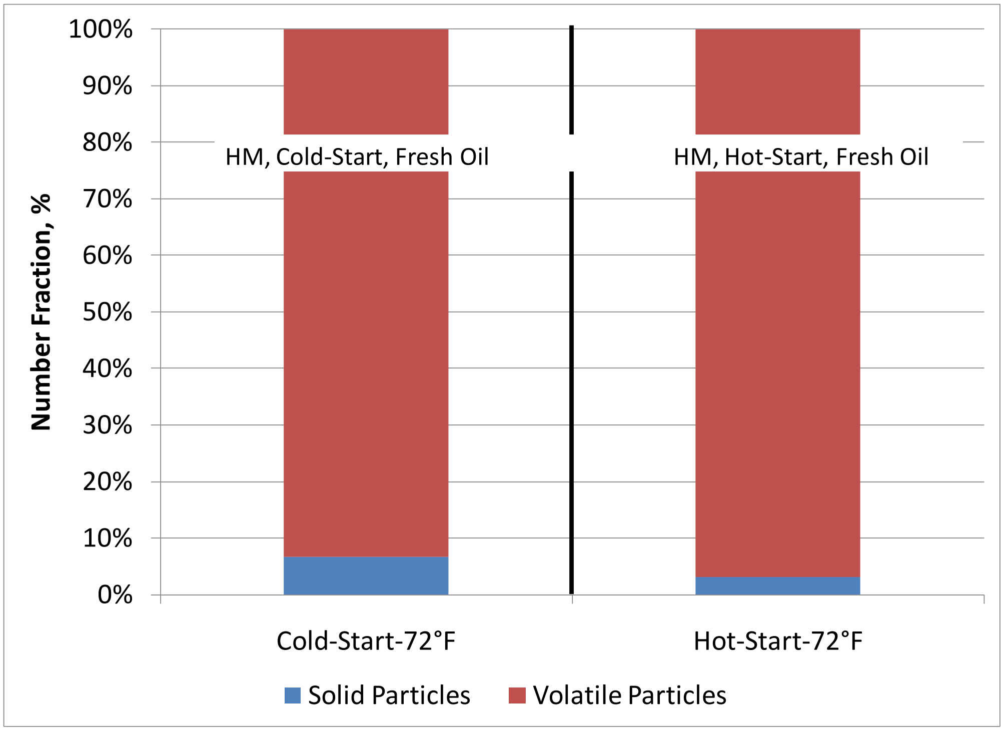

FIGURE 85. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (NATURAL GAS, HIGH MILEAGE EMITTER, FRESH OIL) (No Statistical Analyses Were Performed On These Data)

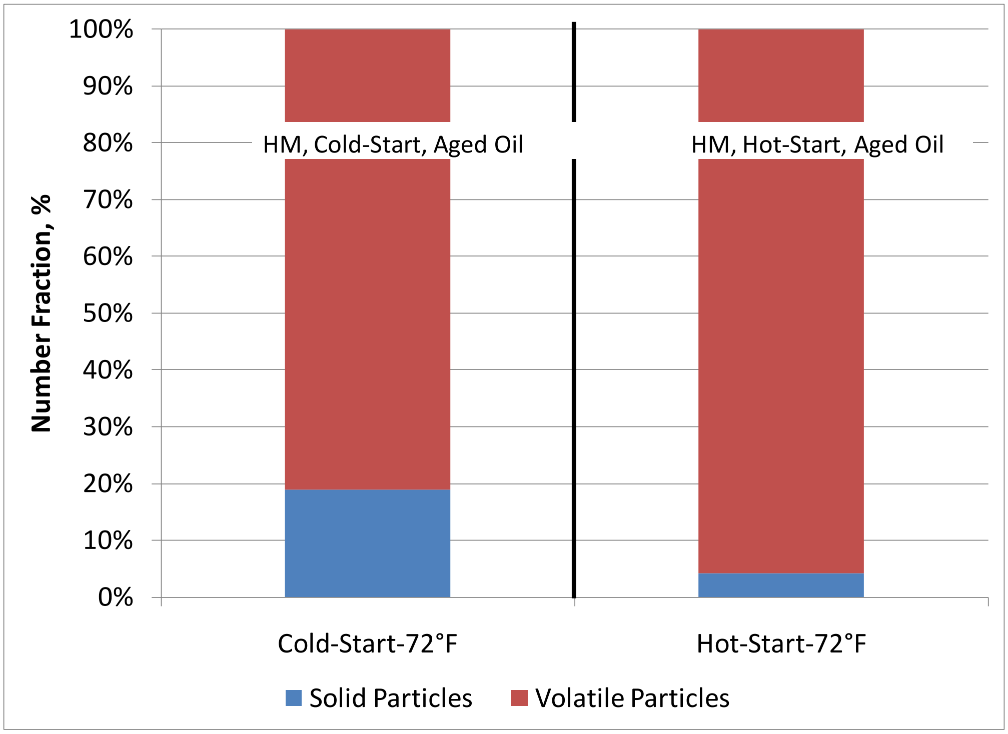

FIGURE 86. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (NATURAL GAS, HIGH MILEAGE EMITTER, AGED OIL) (No Statistical Analyses Were Performed On These Data)

Figures 87 and 88 show a typical size distribution for the HD-NG-NE using the fresh and aged oil. The data are shown for the cold-start and hot-start portions of testing. The total and solid distributions seem to exhibit a similar monomodal lognormal size distribution structure that consists of a nuclei mode. The nuclei mode peaks at 10 nm. Similar size distributions are observed with the HD-NG-HM, as shown in Figures 89 and 90. The cold start with fresh oil showed a higher concentration and growth of particles, but the growth was not as strong as what was seen with the gasoline LD-HE. In the case of the LD-HE, volatile particle size reached 50 to 60 nm in diameter with a higher number concentration, compared to the HD-NG-HM. The reduction in volatile nuclei PN emissions with the aged oil, compared to fresh oil, could be related to the loss of lube oil volatile material that plays a role in particle nucleation and/or growth. This phenomenon is worth investigating further in future research. The solid size distributions for the HD-NG vehicles have a small peak at 10 nm diameter. The solid particles are likely to be ash particles from the lube oil, but further work is needed to investigate the nature of the nuclei mode solid particles emitted from the HD-NG-HM.

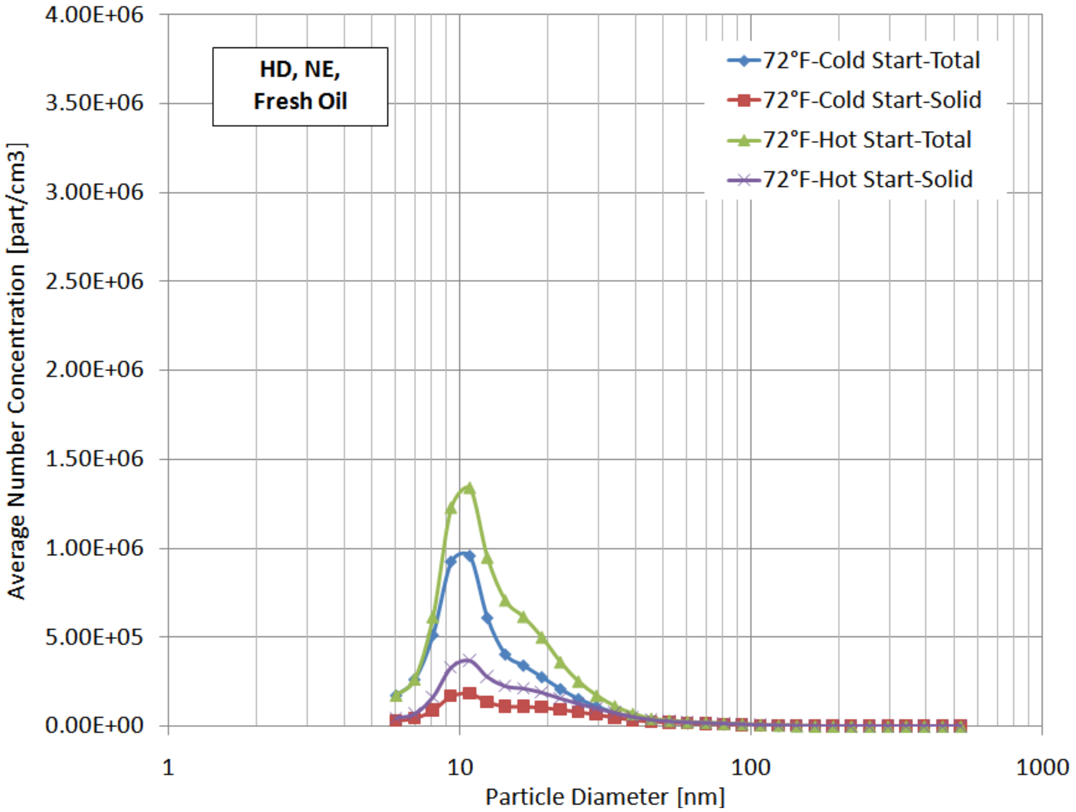

FIGURE 87. NUMBER-WEIGHTED SIZE DISTRIBUTION (NATURAL GAS, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

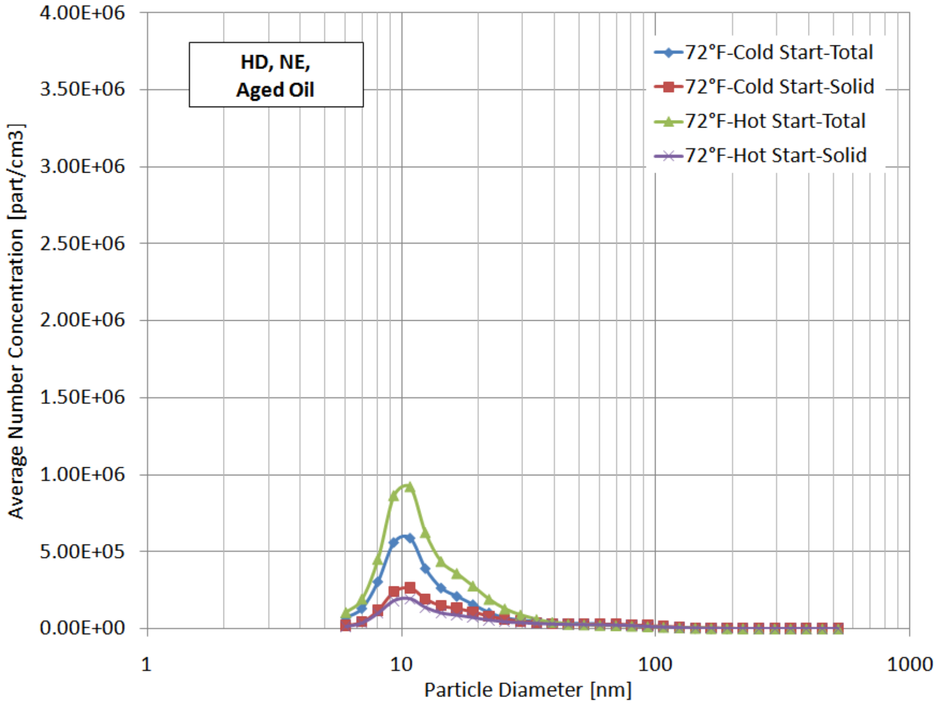

FIGURE 88. NUMBER-WEIGHTED SIZE DISTRIBUTION (NATURAL GAS, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

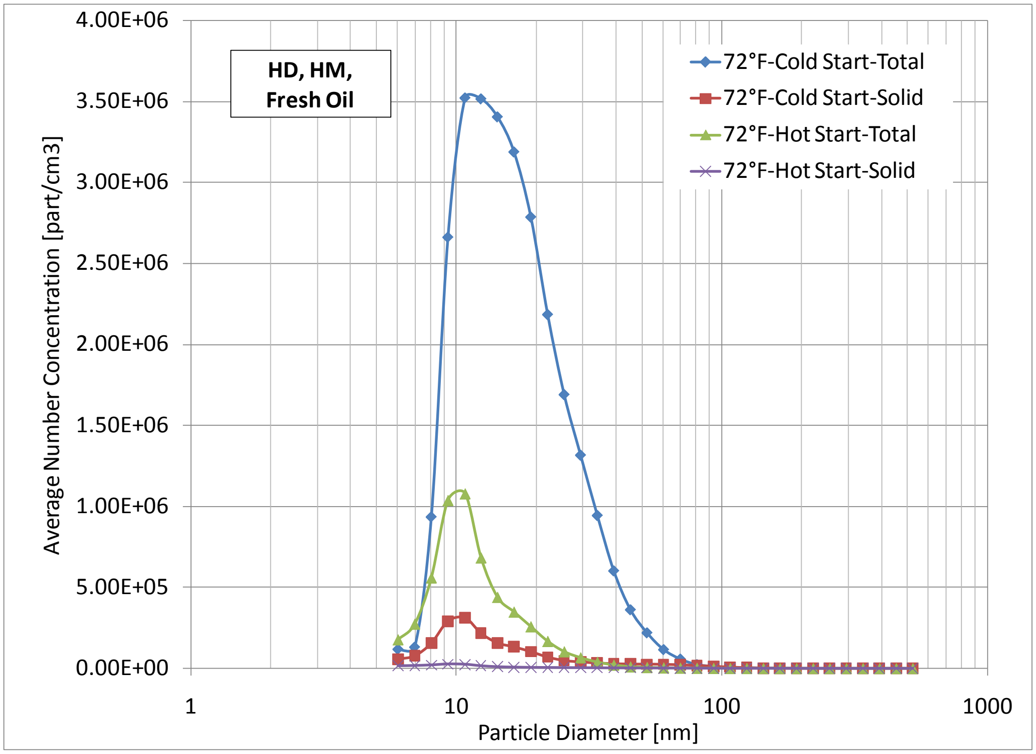

FIGURE 89. NUMBER-WEIGHTED SIZE DISTRIBUTION (NATURAL GAS, HIGH MILEAGE EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

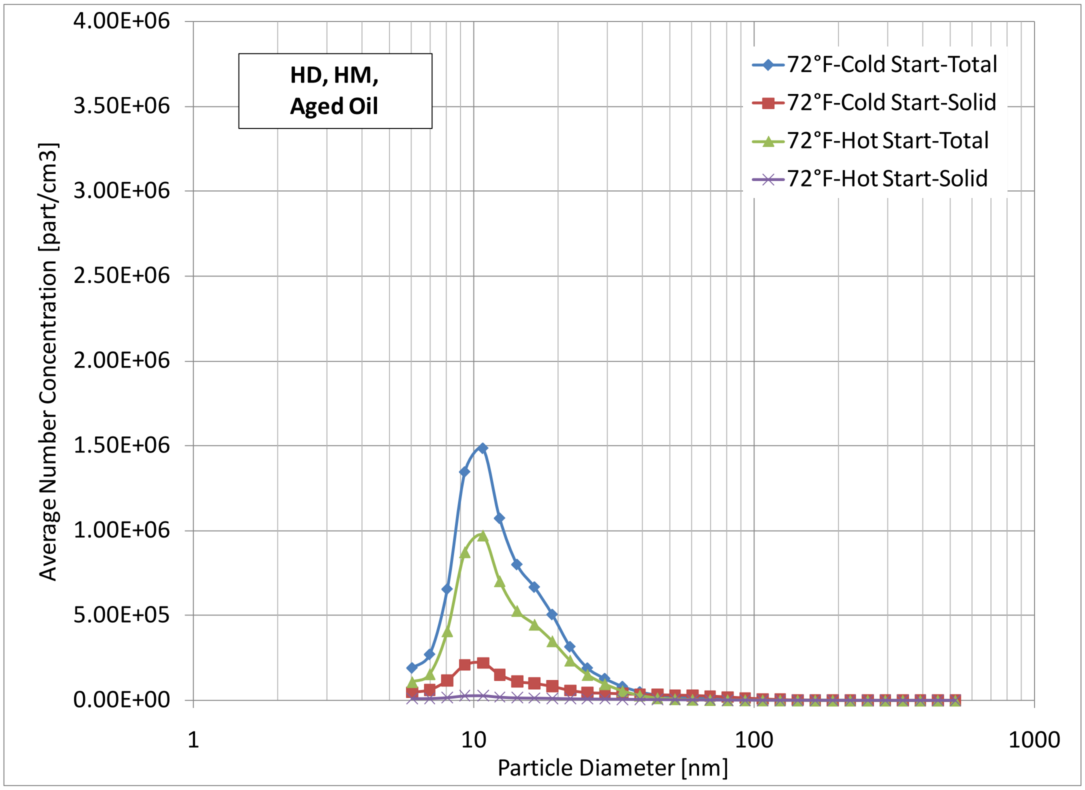

FIGURE 90. NUMBER-WEIGHTED SIZE DISTRIBUTION (NATURAL GAS, HIGH MILEAGE EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

9.6 PM Apportionment Summary

For the heavy-duty vehicle evaluations, two natural gas-fueled vehicles and two diesel-fueled vehicles were tested in duplicate using the Heavy-Duty Urban Dynamometer Driving Schedule with two crankcase oils (a “fresh oil” and an “aged oil”). The vehicles were tested either with natural gas or with diesel fuel as appropriate. A total of four tests (two with each of two oils) were conducted on each of the four vehicles. All four vehicles were equipped with catalytic converters. Two of the vehicles (one diesel-fueled and one natural gas-fueled) had been operated for considerably more mileage (100 to 150 thousand miles) than the other vehicle in the set and were designated as the high mileage (HM), while the lower mileage vehicles were designated as normal emitters (NE). It should be noted that the measured exhaust emission rates did not necessarily follow this designation. The same set of analyses that were conducted on the medium-duty vehicles’ exhaust were also conducted for the heavy-duty vehicles. More details related to the description of the vehicles, test cycle, fuels, lubricating oil, and analytical procedures can be found in Section 6 and in previous subsections of this section (9.1 through 9.4).

The same approach to analyzing the data that was followed for the medium-duty vehicles was also followed for the heavy-duty vehicles. Because each of the two sets of vehicles not only used different fuels, but also different lubricating oils; the evaluations were divided into two subparts, one for the natural gas-fueled vehicles and one for the diesel-fueled vehicles.

9.6.1 Regulated Emissions and Fuel Economy

Regulated emissions and fuel economy data for each set of duplicate tests conducted on each of the two natural gas-fueled vehicles were averaged and are presented in Table 87.

TABLE 87. REGULATED EMISSIONS AND FUEL ECONOMY FOR HEAVY-DUTY NATURAL GAS-FUELED VEHICLES (No Statistical Analyses Were Performed On These Data)

	NE		HM	
	Fresh Oil	**Aged Oil**	**Fresh Oil**	**Aged Oil**
HC, g/mi	13.37	14.44	14.39	14.63
CO, g/mi	1.28	1.47	6.50	7.37
NO_x, g/mi	10.86	12.57	7.34	9.52
PM, mg/mi	18	14	18	22
Fuel Usage, lbs/mi	1.46	1.41	1.33	1.33
***Results are the average of duplicate tests**				

The largest numerical difference in the regulated emissions between the two test vehicles was in the carbon monoxide emissions which were nominally lower for the NE than for the HM (possibly due to a more active catalyst on the lower mileage NE). Hydrocarbons, carbon monoxide, and oxides of nitrogen emissions nominally increased with the use of the aged oil, but PM emissions had opposing trends for the two test vehicles.

9.6.2 Estimates for Vehicle Oil Consumption Rates

As was carried out for the medium-duty vehicles, elements found in both the exhaust PM and in the oil were utilized to calculate oil consumption rates for the two vehicles. There was, however, a disparity in the exhaust emission rates for the elements with the two methods of analysis, XRF and ICP-MS. The XRF results for many of the elements were, in general, found to be twice or more the level of those determined by ICP-MS. When no obvious solution for this disparity could be found, it was decided to calculate oil consumption rates using both sets. As was utilized for the medium-duty NE, calcium was selected for the calculations. Table 88 lists average emission rates and oil concentrations for calcium along with calculated oil consumption rates. Zinc (XRF and ICP-MS) and phosphorus (XRF) data gave oil consumption rates similar to those determined with calcium for both vehicles with the fresh oil, but nearly twice the calcium determined rate for both vehicles with the aged oil. These higher rates were primarily due to similar exhaust emission for the elements with both oil, but the aged oil containing only one half the amount of zinc and phosphorus as did the fresh oil.

TABLE 88. ESTIMATED OIL CONSUMPTION RATES USING BOTH XRF & ICP-MS DATA*

(No Statistical Analyses Were Performed On These Data)

	NE	HM
Calcium Emissions, XRF, µg/mi	1848	1364
Calcium Emissions, ICP-MS, µg/mi	838	526
Calcium Oil Concentration, XRF, µg/g	1807	1807
Calcium Oil Concentration, ICP-MS, µg/g	1465	1465
Oil Consumption Rate, XRF, mg/mi**	1023	755
Oil Consumption Rate, ICP-MS, mg/mi**	572	359

* Values in this table are averages for four tests, two with each oil
** An oil consumption rate of 833 mg/mi equals 1 quart per 1000 miles

As can be seen in Table 88, both XRF and ICP-MS results predict a higher oil consumption rate for the NE. Sulfur from the oil (the natural gas fuel was a synthetic blend and did not contain sulfur) was found in the NE PM exhaust at levels four times higher than those found for the HM. This difference in sulfur is not consistent with the difference in calculated oil consumption rates using the calcium emissions and could occur as a result of a more active catalyst on the NE (as was suggested earlier) converting more of the sulfur in the oil to sulfate. PM sulfate levels were five times higher for the NE than for the HM.

9.6.3 Wear Elements

No unusual trends were noted for the typical wear elements observed in exhaust PM. As was the case for the elements originating in the oil, the two methods of analysis, XRF and ICP-MS, gave different results for the wear elements in the exhaust. Both methods indicate higher concentrations of the wear element in the exhaust of the NE (1.3 to 2.3 mg/mi) as compared to the HM (0.7 mg/mi with both analytical methods).

9.6.4 Carbon Analyses for "Elemental" and "Organic" Content of PM

Elemental, organic, and total carbon content results from TOR analyses of the PM filters from the natural gas-fueled vehicle tests are presented in Table 89. The measured total PM results for each vehicle are also shown for comparison. While total PM and EC results are similar for the two vehicles, the organic carbon from the HM is more than twice that for the NE. Recall that the oil consumption rate as determined from elemental Ca was actually higher for the NE.

TABLE 89. TOTAL, ELEMENTAL, AND ORGANIC CARBON EMISSIONS
(No Statistical Analyses Were Performed On These Data)

	Emissions, mg/mi			
	NE		HM	
	Fresh Oil	**Aged Oil**	**Fresh Oil**	**Aged Oil**
EC	1.0	1.5	0.5	1.2
OC	7.3	7.6	16.8	22.7
TC	8.2	9.1	17.3	23.9
PM	18	14	18	22

As was done with the MD vehicles, an attempt was made to account for the total PM mass by combining the measured carbon mass with a sum of oil and wear derived element masses (Table 90). Sulfur and phosphorus were assumed to be present as sulfate and phosphate and the organic carbon mass was assumed to contain 1.5 hydrogen atoms per carbon atom. As can be seen in the table, both vehicles have similar PM emission rates, but the make-up of the PM is very different. The NE is composed of only 40 percent organic related material (OC plus hydrogen), while the HM is made up of 80 percent organic material.

TABLE 90. CARBON AND OTHER ELEMENT TOTALS COMPARED TO TOTAL PM
(No Statistical Analyses Were Performed On These Data)

	Emissions, mg/mi			
	NE		HM	
	Fresh Oil	**Aged Oil**	**Fresh Oil**	**Aged Oil**
Total Carbon	8.2	9.1	17.3	23.9
Elements*	14.8	13.4	5.8	6.6
Hydrogen Mass for OC**	0.9	1.0	2.1	2.9
Total	23.9	23.5	25.2	33.4
Measured PM	18	14	18	22

*Element totals from XRF analysis. Mass for sulfur and phosphorus assumed to be sulfate and phosphate.
**Mass for 1.5 hydrogen per carbon assumed

9.6.5 Estimation of Unburned Oil Content

The oils used in this part of the study also contained a hexatriacontane-d74 tracer, which along with the total measured hopanes and steranes, were used to calculate unburned oil concentrations in the exhaust PM. Average PM hexatriacontane-d74 exhaust emission rates were found to be 4.3 µg/mi for the NE and 8.1 µg/mi for the HM. When the emission rates were divided by the average concentration of the hexatriacontane-d74 in the oil, 360 µg/g, unburned oil emission rates of 11.9 mg/mi for the NE and 22.5 mg/mi for the HM were obtained. Average emission rates for the total hopanes and steranes measured in this study were 1.3 µg/mi for the NE and 12.0 µg/mi for the HM. When the average total hopane and sterane concentration in the test oils, 624 µg/g, was used to calculate unburned oil concentrations, average emission rates of 2.1 mg/mi for the NE and 19.2 mg/mi for the HM were obtained. A third estimate for the unburned oil contribution to PM was made using an unresolved complex mixture total (UCM) obtained during the GC-MS alkane analysis. The PM emission rate for UCM was found to be 1.1 mg/mi for the NE and 4.7 mg/mi for the HM. The oils, on average, were found to contain 0.196 g/g oil of this unresolved material. Dividing the PM emission rate by the average oil concentration of the UCM gives a third estimate for the unburned oil contribution to PM, 5.6 mg/mi for the NE and 24.0 mg/mi for the HM.

Table 91 presents a comparison of these calculated unburned oil estimates to the organic carbon (OC) component of the PM. There appears to be good agreement of unburned oil estimates with the total OC for the HM, indicating that the OC is primarily unburned oil and that any one of the three methods could be utilized to make this prediction. For the NE, the use of hextriacontane-d74 over-estimates the OC of the PM, while the hopanes and steranes under estimate the OC. The UCM provides the best estimate of the three methods. The relative amount of the heavy hexatriacontane-d74 material is apparently increased in the NE PM by the volatilization of the lighter oil components (as was noted for the medium-duty HE vehicle), while the lighter hopanes and steranes are lost and are diminished in concentration.

TABLE 91. COMPARISON OF UNBURNED OIL ESTIMATES TO OC
(No Statistical Analyses Were Performed On These Data)

	Average Emission Rate for Normal Emitter, mg/mi	Average Emission Rate for High Mileage Emitter, mg/mi
Hexatriacontane-d74	11.9	22.5
Hopanes and Steranes	2.1	19.2
UCM	5.6	24.0
OC	7.5	19.8

9.6.6 PAH PM Emissions

As one may expect for these natural gas-fueled vehicles, the total PM PAH emission rates were extremely low (compared to the diesel-fueled vehicles); 0.6 µg/mi for the NE and 7.7 µg/mi for the HM. The lower level of these combustion products in the NE exhaust was probably due to its more active catalyst. There was only a small numerical difference in total PM PAH compounds between the tests with fresh (0.9 µg/mi) and aged (0.3 µg/mi) oil for the NE, but a more perceivable difference was noted for the HM, 3.1 µg/mi for fresh oil and 12.4 µg/mi for aged oil. The aged oil did contain higher concentrations of PAH compounds than did the fresh oil.

Only two PAH compounds were found on all eight PM filters analyzed in this part of the study, benzo(ghi)perylene and coronene. These PAHs are two of the three PAHs used in the light-duty gasoline-fueled part of this study as markers for fuel-generated EC. In this case, however, these PAH markers did not trend with the EC emissions. The HM, which had slightly lower EC emissions (0.8 mg/mi) than the NE (1.2 mg/mi) had much higher PM emission rates for these two compounds, 878 ng/mi, than did the NE, 82 ng/mi. Once again, this difference is thought to be due to the more active catalyst on the NE.

9.6.7 Summary

The following are some of the observations made from the analyses of the emissions data.

- Carbon monoxide emissions were nominally lower for the NE compared to the HM, perhaps indicating a more active catalyst on the lower mileage NE.
- XRF and ICP-MS analyses gave different emission rates for the oil derived elements and subsequently different calculated oil consumption rates for the two vehicles. Both methods gave higher oil consumption rates for the NE than for the HM.
- Sulfate PM emissions were nearly 5 times higher for the NE than for the HM, once again indicating a more active catalyst for the NE.
- OC emission rates indicate that as much as 99 percent of the consumed oil was burned or partially burned in either the combustion chamber or in the vehicles catalyst for the NE, while 95 to 98 percent of the consumed oil was burned or partially burned for the HM.
- Both vehicles had similar PM emission rates, but the make-up of the PM was very different. The HM PM consisted of nearly 80 percent organic material, while the NE PM consisted of only 40 percent organic material.
- Three different methods gave calculated unburned oil estimates for the HM that were in good agreement with the OC component of PM, indicating that the OC is primarily unburned oil and that any one of the three methods could be used to make this predication.
- The hexatriacontane-d74 method over-predicted the unburned oil component of the NE PM, while hopane and sterane totals under-predicted this component, indicating an increase in the relative amount of the heavier oil components in the PM.
- Both vehicles had relatively low PAH emission rates (0.6 to 7.7 µg/mi) compared to the diesel-fueled vehicles (500 µg/mi).
- High molecular weight PAH compounds found in light-duty exhaust (benzo(ghi)perylene and coronene) were also found in the exhaust of the natural gas-fueled heavy-duty vehicles. The HM had lower PM emissions than the NE, but more than 10 times the level of these two PAH compounds. The more active catalyst on the NE may have been instrumental in the lower levels of these PAHs in the exhaust.

9.7 Heavy-Duty Natural Gas Vehicles Major Technical Findings

Fresh and Aged Oil

The normal emitter produced similar PM emissions compared to the high-mileage vehicle on fresh oil and fresh lube produced more PM emissions than aged lube.

Low and High Particulate Matter (High Mileage) Emitter

No trend in PM emissions was evident between the low emitter and the high-mileage vehicle. PM emission rates ranged from 14 to 22 mg/mi.

Normal (72°F) and Low (20°F) Temperature

No low temperature tests were performed with the HD natural gas vehicles.

Particle Number and Size Distributions

Particle Number

- From the NE, the exhaust PN concentration ranged from about $6x10^6$ part./cm³ to $15x10^6$ part./cm³.This is comparable in range to the diesel MD NE, but the particle size distribution is vastly different.
- More PN emissions were observed from the NE during the hot-start portion of the cycle, compared to the cold-start.
- The NE on fresh oil produced higher PN emissions than with the aged oil, particularly volatile PN. This trend was observed previously with the gasoline LD NE.
- Twenty-five to fifty-five percent of the number of particles emitted from the HD NG NE were solid in nature.
- For the HD NG high mileage emitter, the exhaust PN concentration ranged from $10x10^6$ part./cm³ to $55x10^6$ part./cm³. This PN concentration is higher than the PN concentration observed with the MD NE and HE. However, it was 63 percent lower than the highest PN concentration observed with the light duty HE.
- Fresh oil in the HM showed higher PN emissions than aged oil under cold-start. Under hot-start, the PN emission was comparable between the fresh and the aged oil.
- Over 80 percent of the HM PN emissions were volatile particles. This is similar to what was observed previously with the gasoline LD HE.

Particle Size Distribution

- For the HD NG NE with both fresh and aged oil, the total and solid distributions seem to exhibit a similar monomodal lognormal size distribution structure that consists of a nuclei mode. The nuclei mode peaks at 10 nm. Similar size distributions are observed with the HD NG HM.
- The cold start with fresh oil showed a higher concentration and growth of particles, compared to the aged oil, but the growth was not as strong as what was seen with the gasoline LD HE. In the case of the LD HE, volatile particle size reached 50 to 60 nm in diameter with higher number concentration, compared to the HD NG HM.
- The reduction in volatile nuclei PN emissions with the aged oil, compared to fresh oil, could be related to the loss of lube oil volatile material that plays a role in particle nucleation and/or growth. This phenomenon is worth investigating in future research.
- The solid size distributions for the HD NG vehicles have a small peak at 10 nm diameter. The solid particles are likely to be ash particles from the lube oil, but further work is needed to investigate the nature of the nuclei mode solid particles emitted from the HD NG HM.

HD Natural Gas PM Apportionment

- Carbon monoxide emissions were nominally lower for the NE compared to the HM, perhaps indicating a more active catalyst on the lower mileage NE.
- XRF and ICP-MS analyses gave different emission rates for the oil derived elements and subsequently different calculated oil consumption rates for the two vehicles. Both methods gave higher oil consumption rates for the NE than for the HM.
- Sulfate PM emissions were nearly 5 times higher for the NE than for the HM, once again indicating a more active catalyst for the NE.
- OC emission rates indicate that as much as 99 percent of the consumed oil was burned or partially burned in either the combustion chamber or in the vehicle's catalyst for the NE, while 95 to 98 percent of the consumed oil was burned or partially burned for the HM.
- Both vehicles had similar PM emission rates, but the make-up of the PM was very different. The HM PM consisted of nearly 80 percent organic material, while the NE PM consisted of only 40 percent organic material.
- Three different methods gave calculated unburned oil estimates for the HM that were in good agreement with the OC component of PM, indicating that the OC is primarily unburned oil and that any one of the three methods could be used to make this predication.
- The hexatriacontane-d74 method over-predicted the unburned oil component of the NE PM, while hopane and sterane totals under-predicted this component, indicating an increase in the relative amount of the heavier oil components in the PM.
- Both vehicles had relatively low PAH emission rates (0.6 to 7.7 μg/mi) compared to the diesel-fueled vehicles (~500 μg/mi).
- High molecular weight PAH compounds found in light-duty exhaust (benzo(ghi)perylene and coronene) were also found in the exhaust of the natural gas-fueled heavy-duty vehicles. The HM had lower PM emissions that the NE, but more than 10 times the level of these two PAH compounds. The more active catalyst on the NE may have been instrumental in producing the lower levels of these PAHs in the exhaust.

10.0 HEAVY-DUTY DIESEL VEHICLE TESTS

10.1 Vehicle Selection and Description

Vehicle selection was made in collaboration with the CLOSE Project Management Team. SwRI identified potential candidate vehicles for testing and made vehicle recommendations to the CLOSE Project Management Team. We then waited for technical approval prior to procuring the test vehicles. One vehicle from each of the following categories was recruited:

10.1.1 Heavy-Duty Diesel Vehicle Selection Criteria

- Normal-emitting diesel vehicle: This heavy-duty vehicle was to be equipped with a diesel engine having an advertised displacement of at least 7.2 liters and a minimum rated torque of 660 ft-lbs. The engine/vehicle was to be a model year 2002 or newer with fewer than 270,000 miles on the odometer. The vehicle was not to be equipped with a PM filter or trap, or an oxidation catalyst. It was expected that this vehicle would be a 60,000-lb capacity Class 8 on-highway tractor leased from a local agency.

- High-emitter diesel vehicle: This heavy-duty vehicle was to be equipped with a diesel engine and to have an advertised displacement of at least 7.2 liters and a minimum rated torque of 660 ft-lbs. The engine/vehicle was to be a model year 1996 or older and known to emit high levels of PM, have high lubrication oil consumption, and/or have visible smoke related to lubrication oil. It was thought that this vehicle would be solicited from a governmental fleet, and expected to be near the end of its useful life.

10.1.2 Heavy-Duty Diesel Vehicle Selection and Description

As with the heavy-duty natural gas vehicles, SwRI spent months searching for heavy-duty diesel vehicle candidates. SwRI was invited to inspect heavy-duty vehicles at City Public Service (CPS) Company, which is the electrical utility in the San Antonio area. These vehicles were used as construction and repair support vehicles for CPS and were up for sale. SwRI was informed that the vehicles had been released from service and could be used in the CLOSE program as heavy-duty diesel PM emission test vehicles.

All the vehicles were 1993 to 1998 models. SwRI inspected six CPS vehicles and made a report to the CLOSE project sponsors with candidate recommendations. The report on the CPS vehicles is included in Appendix E. However, when we contacted City Public Service for more information on the vehicles, we found that they had all been sold.

SwRI then found a contact at VIA Metropolitan Transit, which is San Antonio's city bus company. We were informed that VIA would lease two candidate heavy-duty diesel buses to SwRI for the project. VIA offered SwRI a 1988 TMC bus with a DDC 6V/71N, V6 engine that had 736,871 miles as a candidate high PM emissions vehicle.

The CLOSE sponsors rejected the first candidate heavy-duty diesel bus with high PM emissions because its two-stroke DDC engine was deemed to be of too old a design. We requested that VIA search for more high PM emission diesel buses. We visited VIA in order to observe three candidate high PM emission buses. VIA had not found any buses with smoky exhausts. The HM candidates were chosen by VIA because they all had high blowby rates. Because blowby is caused by poor piston ring seals, we expected that these vehicles would also allow more oil past the rings into the combustion chamber and exhaust.

SwRI went to VIA's maintenance yard and observed three candidate high PM buses. None of the buses were observed to have high smoke emissions. The second candidate high PM emissions bus we chose (Bus #842) had some light, white smoke during acceleration under load, and slight smoke at idle. This bus was already idling upon SwRI's arrival at VIA, so we did not observe a cold engine start. There was no smoke visible during a hot-start of #842. The other two buses had less smoke than #842.

Information regarding the second candidate high PM emissions diesel bus was furnished to the CLOSE sponsors along with information on a newer bus in good working order that was of the same make and model as the candidate high PM emitter. The CLOSE participants approved both VIA heavy-duty diesel buses as candidates for testing.

SwRI and VIA signed an agreement to lease (at no cost) the two approved diesel buses for heavy-duty emissions testing. After testing the first low-PM emissions diesel bus, we asked VIA to prepare the second candidate high PM emissions bus (#842), but when they started it the engine failed. VIA found another bus (#839) for the project that had high blowby emissions like bus #842. Bus #839 is the same make and model as bus #842, and is the same make and model as the first low PM emitter (#946) we tested. Information regarding the third candidate diesel high PM emissions bus #839 was furnished to the CLOSE sponsors. The CLOSE Project sponsors approved the use of bus #839 as a high mileage PM emitter. Table 92 describes the two heavy-duty diesel buses selected for emissions testing.

TABLE 92. DESCRIPTION OF HEAVY-DUTY DIESEL BUSES

	Normal Emitter	**High Mileage**
Bus Number	946	839
Year	2001	2001
Make	NABI	NABI
Model	40 LFW - 05	40 LFW - 05
Mileage	461,403	569,240
VIN #	1N90400521A140336	1N9040051YA140614
License #	814-486	806-354
Engine	2001 Cummins	2001 Cummins
Engine Model	CUM 8.3 ISC	CUM 8.3 ISC
Engine Displacement	8.3L, 506 ci	8.3L, 506 ci
Engine oil spec.	15W-40	15W-40
Oil consumption, miles/quart	971	145

10.1.3 Gaseous and PM Emissions Check-out Tests

When the low-PM emission heavy duty bus #942 was delivered, its emission rate repeatability was assessed over three hot-start HDDC cycles before changing its oil or fuel. Table 93 shows a statistical summary of the three replicate tests performed with bus #942. Repeatability of all emission rates was very good with a maximum covariance of 5 percent for hydrocarbons. The CLOSE Project sponsors accepted bus #942 for continued testing.

TABLE 93. RESULTS OF THREE REPEATABILITY CHECK EMISSION TESTS PERFORMED WITH THE HEAVY-DUTY NORMAL PM EMITTING DIESEL BUS AS RECEIVED

(No Statistical Analyses Were Performed On These Data)

Emissions	Average	Standard Deviation	Covariance
HC, g/mile	0.59	0.03	5%
CO, g/mile	5.87	0.07	1%
NO_X, g/mile	16.69	0.10	1%
PM, g/mile	0.764	0.02	3%
Fuel Economy, lb/mile	1.47	0.04	3%

These tests are not part of the particle characterization tests.
Tests were performed at a nominal 72°F, with commercial fuel and lubricant as received.
Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

Before starting emissions tests for record and before changing its oil or fuel, SwRI also performed an emissions repeatability assessment with bus #839, the candidate high blowby and higher mileage diesel bus from VIA. Emissions were measured over three hot-start HDDC cycles. Table 94 shows a statistical summary of the three replicate tests performed with bus #839. Repeatability of all emission rates was also very good with a maximum emission rate covariance of 4 percent with CO emissions, and #839 was approved for further tests. Note that the PM emission rates from the high-mileage diesel bus are less than from the normal emitter.

TABLE 94. RESULTS OF THREE REPEATABILITY CHECK EMISSION TESTS PERFORMED WITH THE HEAVY-DUTY HIGH-MILEAGE DIESEL BUS AS RECEIVED

(No Statistical Analyses Were Performed On These Data)

Emissions	Average	Standard Deviation	Covariance
HC, g/mile	0.65	0.014	2%
CO, g/mile	5.96	0.250	4%
NO_X, g/mile	15.27	0.17	1%
PM, g/mile	0.696	0.01	1%
Fuel Economy, lb/mile	1.57	0.01	0.5%

These tests are not part of the particulate characterization tests.
Tests were performed at a nominal 72°F, with commercial fuel and lubricant as received.
Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

Because the HD natural gas and HD diesel vehicles did not exhibit higher PM emissions, they are designated as high mileage or HM.

10.2 Lubricants

The heavy-duty vehicles were tested with both fresh and aged lubricants. Their description and the supplier's analyses are included in Section 5.1 in Tables 3 and 7. The drain and fill procedure is described in Section 5.1. Degreening of the lubricants was accomplished by operating the heavy-duty vehicles for 150 miles on the road or on the chassis dynamometer. Oil samples include the fresh and aged oils as received, and one oil sample each taken after completion of all tests on fresh and then aged oils from the normal- and high-mileage emitter. For example, the normal emitter was operated over multiple emission tests with fresh oil and a sample was taken from the crankcase drain oil, and then the normal emitter was operated over multiple emissions tests with aged oil and a sample was taken from the crankcase drain oil. Thus two oil samples were taken from the normal-emitter (fresh and aged oil), and two oil samples were taken from the high-mileage emitter.

10.3 Fuels

Fuel systems on all vehicles were flushed with the test fuels prior to the initiation of testing. The heavy-duty diesel vehicles were fueled directly from an underground tank dedicated to the project. Analyses results for the TxLED diesel used for heavy-duty tests are included in Section 5.2.3.

10.4 Emission Test Procedures

This is a pilot study of exhaust emissions effects from the use of different fuels and lubricants with some tests conducted at different temperatures. It is important to note that the scope of work in this study is limited to short-term effects on emissions when a fuel or lubricant was changed. The fuels and lubricants used in this study could have long-term effects on emissions which were not measured.

10.4.1 Driving Cycle

The heavy-duty diesel vehicles were operated over the same test cycle as described in Section 9.4.1 for the natural gas vehicles.

- Normal-Emitting Diesel Vehicle: With SwRI's single-dilution sampling system, sufficient sample was collected over replicate cold- and hot-start HDDCs totaling approximately 20 miles. Thus a total of 8 HDDCs were performed in order to collect all 4 PM samples (2 HCCDs per sample × 2 oils × 2 replicate samples per oil). One additional cold- and hot-start HDDC was run for the DDP particle number and size determination.

- High-Mileage Diesel Vehicle: In order to parallel the testing of the normal-emitting diesel vehicle, SwRI tested this vehicle over the same number of replicate cold- and hot-start HDDCs as the normal emitter.

10.4.2 Chassis Dynamometer

The same dynamometer was used for testing the diesel buses as the natural gas buses. It is described in Section 9.4.2.

10.5 Heavy-Duty Diesel Vehicles Emission Test Results

10.5.1 Regulated Gaseous and PM Emissions

Average results from both of the heavy-duty diesel vehicles are shown in Table 95. Average regulated gaseous emissions, PM emissions, and fuel consumption rates while operating the vehicles with fresh and aged oil are included. Standard deviations and covariances of the replicate tests are also provided (each replicate being comprised of one cold start and one hot start HDDC tests). All heavy-duty emission tests were conducted at a nominal 72ºF ambient temperature. Repeatability of the emissions from the replicate tests was good. Hydrocarbon rates measured from the normal emitter (NE) bus on aged oil showed the greatest variability between the two replicate tests with a covariance of 15 percent. NO_X emissions from the NE also exhibited higher variability with a covariance of 11 percent on fresh oil. In addition, hydrocarbon emissions from the high mileage (HM) bus with high blowby on aged oil showed a covariance of 11 percent, but all other emission rates exhibited lower variability with covariances below 10 percent.

10.5.1.1 Discussion of Regulated Emissions Results

Figures 91 through 95 display the emission tests results shown in Table 95. Note that long range precision was not thoroughly explored in the test design. Thus, statistical significance of comparisons across different temperatures, fuels, or lubricants cannot be rigorously verified. Hydrocarbon emissions from both heavy-duty diesel buses are shown in Figure 91. The high-mileage high blowby bus averaged higher HC emissions than the low emitter but the variability was such that the standard deviations of the averages overlapped. HC emissions on aged oil were also higher than with fresh oil, but again, variability was high and the standard deviations overlapped.

TABLE 95. AVERAGE REGULATED EMISSIONS FROM HEAVY-DUTY DIESEL VEHICLES
(No Statistical Analyses Were Performed On These Data)

	72° F - Average of Duplicate Tests[a]											
	Normal Emitter						High Mileage					
	Fresh Oil			Aged Oil			Fresh Oil			Aged Oil		
	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation	Average	Standard Deviation	Coefficient of Variation
HC, g/mile	0.61	0.05	8%	0.65	0.10	15%	0.66	0.03	4%	0.71	0.08	11%
CO, g/mile	6.50	0.44	7%	6.20	0.36	6%	5.41	0.42	8%	5.49	0.11	2%
NOx, g/mile	17.65	1.93	11%	19.97	0.40	2%	18.20	0.72	4%	19.07	0.57	3%
PM, g/mile[b]	0.86	0.06	7%	0.78	0.02	2%	0.66	0.02	3%	0.64	0.01	1%
Fuel Usage, lb/mile	1.58	0.06	4%	1.59	0.04	3%	1.65	0.01	1%	1.68	0.02	1%

[a] Each replicate test consisted of one cold HDDC cycle and one hot HDDC cycle.

[b] PM as determined from phase-by-phase filter samples collected during each of two duplicate tests.

Note: Standard deviations reflect only short term variability within each group of successive UDCs (standard deviation, σn-1, where n is the number of replicate UDC tests). Longer range precision was not rigorously explored in the test design. Thus, the statistical significance of comparisons across different temperatures, fuels or lubricants cannot be rigorously verified.

Figure 92 shows the carbon monoxide emissions from the heavy-duty diesel tests. CO emissions were lower from the high-mileage bus, but there was no trend in CO emissions comparing fresh to aged lubricant tests. Figure 93 shows that oxides of nitrogen emissions from both diesel buses were very similar, and it appears that aged oil tests had higher average NO_X emissions than fresh oil tests, although there is some overlap of the standard deviation around the mean. Figure 94 shows the fuel usage in pound per mile units from the heavy-duty diesel buses, and the normal PM emitter exhibited better fuel economy than the high mileage diesel bus. There was no trend in fuel usage comparing fresh to aged oil tests.

PM emissions from the heavy-duty diesel tests are shown in Figure 95. The high-mileage high blowby diesel bus had lower PM emissions than the vehicle designated as the normal PM emitter. This result was expected since the repeatability tests had already shown the same data. From both buses, operation on aged oil produced lower PM emissions than on fresh oil. PM characterization results are presented in the next sections.

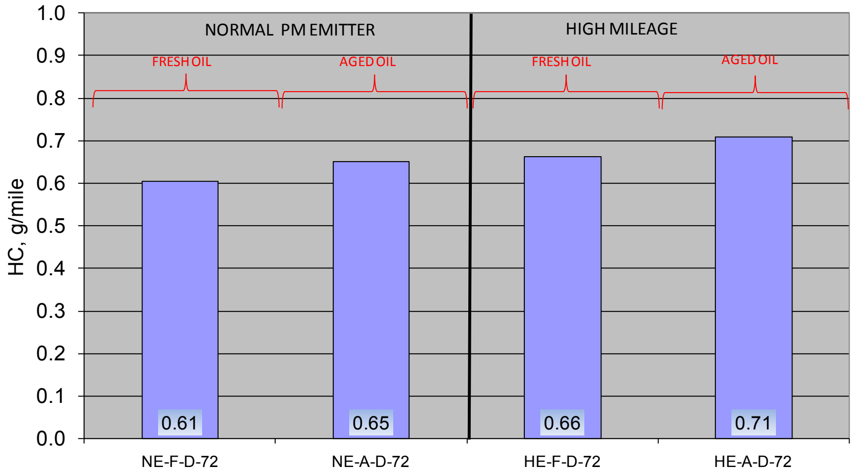

FIGURE 91. HYDROCARBON EMISSION RATES FROM THE NORMAL PM EMITTER AND HIGH MILEAGE DIESEL BUSES
(No Statistical Analyses Were Performed On These Data)

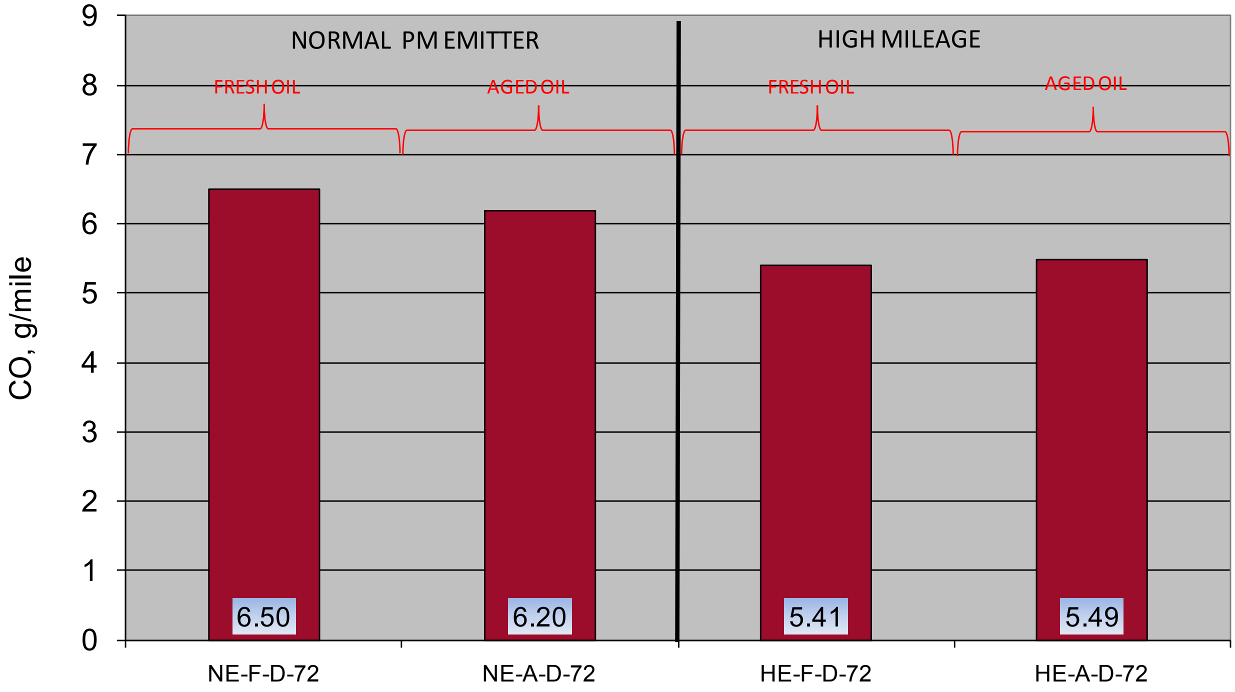

FIGURE 92. CARBON MONOXIDE EMISSION RATES FROM THE NORMAL PM EMITTER AND HIGH MILEAGE DIESEL BUSES
(No Statistical Analyses Were Performed On These Data)

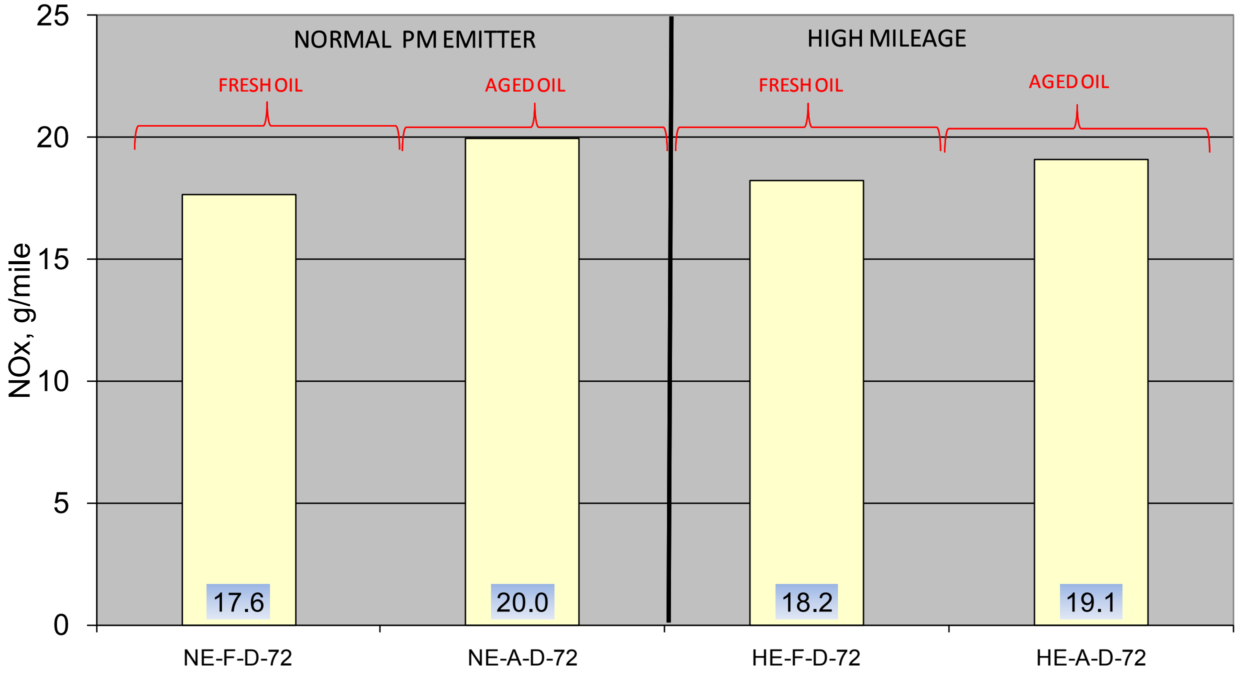

FIGURE 93. OXIDES OF NITROGENEMISSION RATES FROM THE NORMAL PM EMITTER AND HIGH MILEAGE DIESEL BUSES
(No Statistical Analyses Were Performed On These Data)

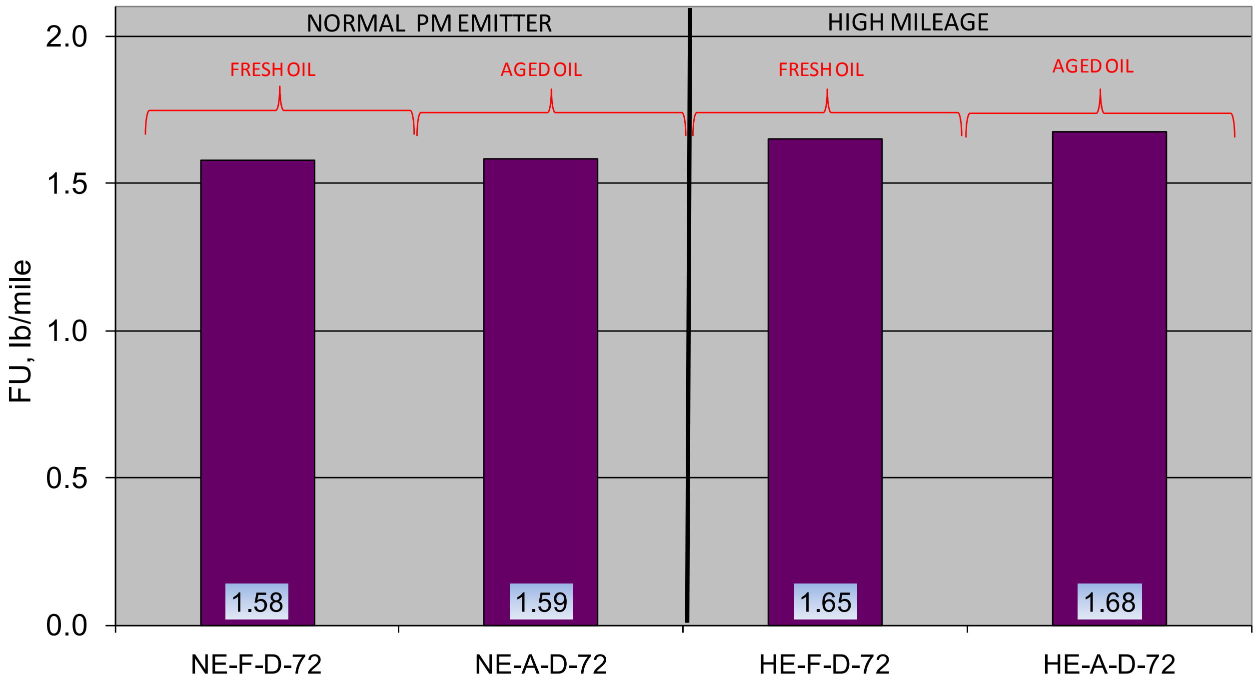

FIGURE 94. FUEL CONSUMPTION OF THE NORMAL PM EMITTER AND HIGH MILEAGE DIESEL BUSES
(No Statistical Analyses Were Performed On These Data)

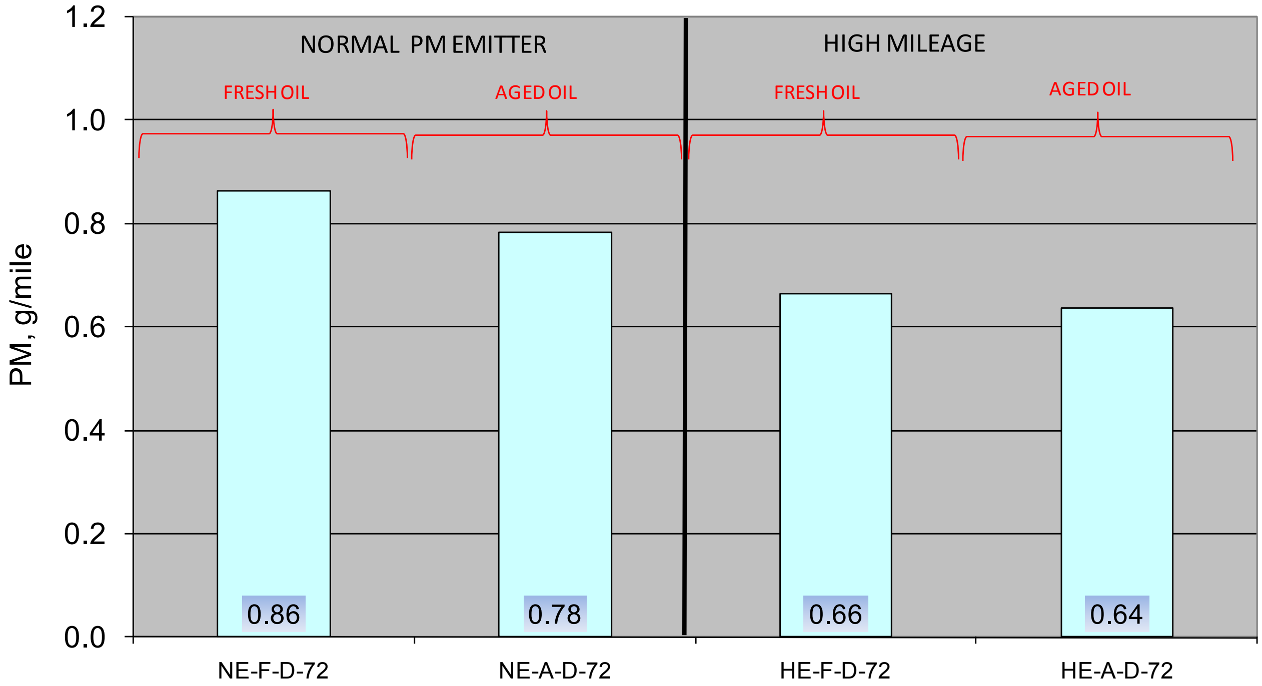

FIGURE 95. PARTICULATE MATTER EMISSION RATES FROM THE NORMAL PM EMITTER AND HIGH MILEAGE DIESEL BUSES
(No Statistical Analyses Were Performed On These Data)

10.5.2 PM and SVOC Analyses

PM from the heavy-duty diesel vehicle tests was analyzed for elements, semi-volatile organic compounds (SVOC), elemental and organic compounds (EC/OC), sulfates, and soluble organic fraction (SOF) at DRI. In the following PM characterization subsections, Tables 96 through 103 present the results of these characterizations along with analyses of heavy-duty fuel and lubricants. PM analysis data shown in Tables 96 through 103 are the averages of the replicate tests performed in each configuration.

The spreadsheet of light-duty PM and SVOC analyses results which was devised by Dr. Fujita to investigate the light-duty PM characterization results was used as a template for the heavy-duty PM characterization results. The spreadsheet includes the results from the individual tests, and is posted at an SwRI ftp site. Dr. Lawrence Smith of SwRI used the spreadsheet data to identify elements and compounds of interest in the apportionment study presented in Section 10.6.

10.5.2.1 X-Ray Fluorescence (XRF)

Particulate matter sampled from the heavy-duty diesel tests was analyzed by DRI for elements by XRF. Table 96 shows the average results in µg/mile of the replicate tests performed in each configuration. In addition, Table 96 presents the results of the lubricant analyses for elements by XRF. The configurations are identified in the top rows of the table, and elements measured are shown in the left column.

10.5.2.2 Inductively Coupled Plasma Mass Spectrometry (ICP-MS) Analysis

PM sampled from the heavy-duty diesel tests was analyzed by DRI for eighteen elements by ICP-MS. Table 97 shows the average results from PM in µg/mile of the replicate tests performed in each configuration. Table 97 also shows the results of elemental analysis of the lubricants and diesel fuel performed at EAI Inc. EAI measured five more elements than DRI measured in the particulate matter. Elements found in lubricants and fuel are presented in nanogram (ng) per gram of oil units. The configurations are identified in the top rows of the table, and elements measured are shown in the left column.

10.5.2.3 Polycyclic Aromatic Hydrocarbons

PM and SVOCs sampled from the heavy-duty diesel tests were analyzed by DRI for polycyclic aromatic hydrocarbons (PAH). Table 98 shows the average results from the exhaust in µg/mile of the replicate tests performed in each configuration. Table 98 also shows the results of lubricant analyses for PAHs in µg/gram units. Table 28 shows the codes for the PAH species in Table 98.

TABLE 96. AVERAGE HEAVY-DUTY DIESEL PM ELEMENTAL ANALYSIS BY XRF (No Statistical Analyses Were Performed On These Data)

	Elemental Emission Rates, µg/mi				Lubricant Elements, µg/gram			
Test Number	**HD-NE-F-D-72**	**HD-NE-A-D-72**	**HD-HM-F-D-72**	**HD-HM-A-D-72**	**HD-NE-F-D-72**	**HD-NE-A-D-72**	**HD-HM-F-D-72**	**HD-HM-A-D-72**
Emitter	**Normal**	**Normal**	**High Mileage**	**High Mileage**	**Normal**	**Normal**	**High Mileage**	**High Mileage**
Oil	**Fresh**	**Aged**	**Fresh**	**Aged**	**Fresh**	**Aged**	**Fresh**	**Aged**
Fuel	**Diesel**	**Diesel**	**Diesel**	**Diesel**	**Diesel**	**Diesel**	**Diesel**	**Diesel**
Temp, ºF	**72**	**72**	**72**	**72**	**72**	**72**	**72**	**72**
Na	0	16	1478	0	0	0	0	0
Mg	0	0	658	0	0	0	0	0
Al	25	48	287	128	0	0	0	0
Si	211	68	379	51	0	0	0	0
P	2504	955	2819	1200	181	118	147	153
S	1396	725	1851	876	2948	3049	2930	3130
Cl	647	260	518	238	0	0	0	0
K	48	55	46	4	0	0	0	0
Ca	5064	2870	5045	2397	2601	2701	2646	2713
Sc	0	0	0	0	0	0	0	0
Ti	13	14	27	7	0	0	0	0
Va	3	0	3	1	0	0	0	0
Cr	50	59	46	10	0	4	3	4
Mn	34	24	1	30	0	1	0	1
Fe	3860	2203	2107	982	2	59	5	62
Co	0	3	0	0	0	0	0	0
Ni	8	31	3	1	0	0	0	0
Cu	130	77	168	81	0	0	0	0
Zn	3174	1414	3681	1454	1495	1461	1495	1475
Ga	0	0	0	0	0	0	0	0
As	0	0	0	0	0	0	0	0
Se	0	0	0	0	0	0	0	0
Br	0	0	0	0	0	0	0	0
Rb	0	0	0	0	0	0	0	0
Sr	4	2	5	6	0	0	0	0
Yt	0	0	3	0	0	0	0	0
Zr	1	20	10	12	0	0	0	0
Nb	0	1	7	3	0	0	0	0
Mo	59	32	85	1	0	1	0	1
Pd	0	10	0	0	0	0	0	0
Ag	6	7	0	0	0	0	0	0
Cd	0	1	0	0	0	0	0	0
In	4	5	0	0	0	0	0	0
Sn	0	0	0	0	0	0	0	0
Sb	0	0	13	11	0	0	0	0
Cs	0	0	0	0	0	0	0	0
Ba	0	0	0	20	0	0	0	0
La	9	0	0	15	0	0	0	0
Ce	34	6	17	44	0	0	0	0

TABLE 96 (CONT'D). AVERAGE HEAVY-DUTY DIESEL PM ELEMENTAL ANALYSIS BY XRF

(No Statistical Analyses Were Performed On These Data)

	Elemental Emission Rates, µg/mi				Lubricant Elements, µg/gram			
Test Number	**HD-NE-F-D-72**	**HD-NE-A-D-72**	**HD-HM-F-D-72**	**HD-HM-A-D-72**	**HD-NE-F-D-72**	**HD-NE-A-D-72**	**HD-HM-F-D-72**	**HD-HM-A-D-72**
Emitter	**Normal**	**Normal**	**High Mileage**	**High Mileage**	**Normal**	**Normal**	**High Mileage**	**High Mileage**
Oil	**Fresh**	**Aged**	**Fresh**	**Aged**	**Fresh**	**Aged**	**Fresh**	**Aged**
Fuel	**Diesel**	**Diesel**	**Diesel**	**Diesel**	**Diesel**	**Diesel**	**Diesel**	**Diesel**
Temp, °F	**72**	**72**	**72**	**72**	**72**	**72**	**72**	**72**
Sm	38	62	87	81	0	0	0	0
Eu	0	0	81	0	0	0	0	0
Tb	0	0	72	0	0	0	0	0
Hf	0	0	0	0	0	0	0	0
Ta	0	0	0	11	0	0	0	0
Wo	0	32	0	0	0	0	0	0
Ir	0	0	0	0	0	0	0	0
Au	0	0	0	0	0	0	0	0
Hg	0	0	1	0	0	0	0	0
Tl	0	1	0	1	0	0	0	0
Pb	0	17	2	18	0	5	0	5

TABLE 97. RESULTS OF HEAVY-DUTY DIESEL PM, LUBRICANTS, AND FUEL ELEMENTAL ANALYSIS BY ICP-MS

(No Statistical Analyses Were Performed On These Data)

TEST NUMBER	AVERAGE PARTICULATE ELEMENTS, µg/mile				LUBRICANT AND FUEL ELEMENTS, ng/gram		
	HD-NE-F-D-72	HD-NE-A-D-72	HD-HM-F-D-72	HD-HM-A-D-72	HD-NE-F-D-72	HD-NE-A-D-72	EM-7006-F
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	Both
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Both
Fuel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Temp	72	72	72	72	72	72	72
Mg	685.21	120.97	1031.60	161.23	9744	7593	<LOD[a]
Al	673.32	0.00	0.00	801.60	1583	10068	<LOD
Ca	4360.75	4007.91	1316.24	1452.06	2283753	2307237	<LOD
Va	0.07	0.01	0.00	0.18	22	24	<LOD
Cr	29.99	13.38	31.10	45.31	51	2021	<LOD
Mn	19.13	19.15	35.73	21.95	84	690	<LOD
Fe	2447.64	2312.70	1238.99	1069.12	1727	41393	14
Ni	13.21	4.69	27.33	32.46	109	593	<LOD
Cu	140.10	87.03	46.65	108.00	92	4546	<LOD
Zn	2420.67	1880.71	1281.79	2177.55	1295948	1213750	<LOD
Mo	40.40	23.01	7.74	39.70	387	1340	<LOD
Ag	13.66	10.06	2.19	7.98	<LOD	20	<LOD
Cd	0.00	0.04	0.04	0.01	0	0	0
Sn	0.00	0.50	1.11	0.87	0	0	0
Ba	8.61	3.17	1.62	2.01	21	1675	<LOD
Ce	38.60	19.25	3.64	155.45	0	0	0
Hg	0.00	0.00	0.00	0.00	0	0	0
Pb	4.61	4.75	5.71	7.35	65	4870	<LOD
W	NM[b]	NM	NM	NM	<LOD	16	<LOD
P	NM	NM	NM	NM	1100160	956503	<LOD
S	NM	NM	NM	NM	3842501	3755101	7775
Ti	NM	NM	NM	NM	40	77	<LOD
Sr	NM	NM	NM	NM	748	830	<LOD

[a] Less than Level of Detection

[b] Not measured

TABLE 98. HEAVY-DUTY DIESEL AVERAGE POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST AND LUBRICANTS

(No Statistical Analyses Were Performed On These Data)

Test Number	Exhaust PAHs, µg/mile				Lubricant PAHs, µg/gram			
	HD-NE-F-D-72	HD-NE-A-D-72	HD-HM-F-D-72	HD-HM-A-D-72	HD-NE-F-D-72	HD-NE-A-D-72	HD-HM-F-D-72	HD-HM-A-D-72
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Temp, °F	72	72	72	72	72	72	72	72
Media[a]	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction[b]	Yes	Yes	Yes	Yes	NA	NA	NA	NA
naphth	62.85	123.66	196.89	83.47	28.11	34.98	27.90	28.25
quinoline	16.96	0.00	0.00	0.00	0.00	0.00	0.00	0.00
mnaph2	82.11	25.88	124.96	109.25	25.69	31.69	21.58	26.39
mnaph1	93.49	71.99	115.74	111.09	12.26	15.89	11.24	13.37
biphen	59.53	36.65	20.95	53.98	1.20	2.11	1.25	2.04
m_2bph	246.64	0.00	0.00	0.00	0.00	0.00	0.00	0.87
dmn267	114.55	53.39	56.17	100.59	6.13	10.56	6.71	7.31
dm1367	233.42	115.34	151.63	228.94	10.49	17.53	9.09	14.28
d14523	69.16	32.55	23.18	63.51	2.74	4.38	1.48	2.65
enap12	105.26	12.64	1.72	18.63	1.93	2.82	2.26	2.99
acnapy	14.24	21.28	15.98	18.03	0.00	0.00	0.00	0.00
dmn12	9.71	19.67	4.07	10.62	0.39	1.02	0.16	0.80
dmn18	1.53	0.00	0.21	0.00	0.00	0.00	0.00	0.00
acnape	0.00	7.36	0.00	0.00	0.00	0.12	0.00	0.00
m_3bph	244.87	0.00	0.00	0.00	2.08	3.60	2.65	4.77
m_4bph	99.78	0.00	0.00	0.00	0.81	0.98	0.27	0.91
dbzfur	4.49	11.35	5.88	8.65	0.00	0.08	0.08	0.15
em_12n	9.61	21.31	13.17	20.98	0.54	1.13	0.23	0.45
tmi235n	32.18	25.49	21.48	55.94	3.28	9.90	0.55	7.01
btmnap	55.50	19.15	28.20	51.28	3.12	11.58	2.85	7.65
atmnap	177.41	21.65	30.10	41.13	1.62	9.12	1.05	6.32
ctmnap	60.07	28.41	35.82	64.48	3.78	9.94	3.43	7.76
em_21n	2.88	1.71	0.00	0.00	0.00	0.08	0.00	0.04
etmnap	30.16	17.58	21.03	34.42	1.66	6.61	1.29	6.02
tm245n	15.86	4.17	4.21	4.84	0.15	0.94	0.39	0.30
ftmnap	24.51	11.64	15.75	29.28	2.01	6.38	1.60	3.94
fluore	16.42	13.99	7.72	6.22	0.66	3.68	1.09	1.06
tm145n	3.83	3.07	2.39	4.33	0.54	0.39	0.23	0.15
jtmnap	17.11	17.15	1.49	8.41	0.27	3.91	0.16	4.01

TABLE 98 (CONT'D). HEAVY-DUTY DIESEL AVERAGE POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST AND LUBRICANTS

(No Statistical Analyses Were Performed On These Data)

Test Number	Exhaust PAHs, µg/mile				Lubricant PAHs, µg/gram			
	HD-NE-F-D-72	**HD-NE-A-D-72**	**HD-HM-F-D-72**	**HD-HM-A-D-72**	**HD-NE-F-D-72**	**HD-NE-A-D-72**	**HD-HM-F-D-72**	**HD-HM-A-D-72**
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Temp, °F	72	72	72	72	72	72	72	72
Media[a]	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction[b]	Yes	Yes	Yes	Yes	NA	NA	NA	NA
a_mfluo	4.00	11.29	10.60	5.91	0.77	2.66	0.90	4.17
b_mfluo	0.72	0.97	2.40	2.26	0.15	0.55	0.00	1.33
m_1fluo	15.07	14.06	25.95	29.62	1.16	0.70	0.31	5.00
fl9one	50.56	48.93	86.81	77.99	0.08	0.35	0.08	0.64
phenan	145.30	104.45	183.64	181.18	1.54	8.30	0.70	8.33
anthra	7.03	7.48	12.96	15.20	0.31	1.76	0.12	1.48
xanone	0.78	0.54	0.00	0.00	0.08	7.79	0.00	8.48
acquone	6.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00
m_2phen	30.09	27.43	42.25	56.18	1.04	10.45	0.78	11.36
m_3phen	35.23	32.07	48.91	62.06	1.35	14.79	0.43	13.48
pnapone	0.72	9.17	1.26	1.15	0.42	2.31	0.35	1.67
m_2anth	1.56	1.18	2.70	3.40	0.42	0.67	0.43	2.54
m_45phen	7.63	4.07	10.43	10.56	0.66	2.31	0.43	1.14
m_9phen	19.21	18.21	30.94	38.89	0.54	8.30	1.09	7.69
mpht_1	8.04	18.37	1.63	0.08	0.62	7.51	0.98	3.14
anthron	0.00	0.00	2.52	0.00	0.00	15.30	1.44	16.24
m_9ant	0.62	4.34	1.07	1.63	0.46	0.70	0.23	0.64
nap2phen	7.50	5.36	13.34	13.18	0.27	0.16	0.23	1.17
anrquone	0.72	2.07	0.00	0.00	0.27	2.00	0.04	0.19
a_dmph	12.76	0.00	15.65	26.70	0.35	6.89	0.55	5.72
b_dmph	4.56	14.07	7.19	9.88	0.50	3.48	0.23	3.98
dm17ph	27.61	7.23	12.92	17.01	0.46	7.94	0.16	8.56
dm36ph	4.59	4.92	6.53	9.89	0.31	4.58	0.31	3.82
d_dmph	29.62	7.58	12.85	16.83	0.50	4.97	0.39	4.58
e_dmph	21.06	2.40	2.92	3.60	0.54	4.46	0.08	3.67
c_dmph	31.01	16.00	27.68	37.74	0.89	12.95	0.78	13.29
fluora	25.10	16.46	31.64	25.83	0.15	0.82	0.47	0.34
pyrene	27.26	21.18	40.39	39.95	0.81	5.87	0.27	6.93
antal9	0.00	0.00	1.07	0.00	1.70	3.87	1.44	2.39

TABLE 98 (CONT'D). HEAVY-DUTY DIESEL AVERAGE POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST AND LUBRICANTS

(No Statistical Analyses Were Performed On These Data)

Test Number	Exhaust PAHs, µg/mile				Lubricant PAHs, µg/gram			
	HD-NE-F-D-72	HD-NE-A-D-72	HD-HM-F-D-72	HD-HM-A-D-72	HD-NE-F-D-72	HD-NE-A-D-72	HD-HM-F-D-72	HD-HM-A-D-72
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Temp, °F	72	72	72	72	72	72	72	72
Media[a]	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction[b]	Yes	Yes	Yes	Yes	NA	NA	NA	NA
retene	0.00	0.00	0.76	1.70	0.23	0.08	0.20	0.15
bafluo	1.98	0.11	3.32	3.78	1.50	1.06	1.13	2.57
bbfluo	0.41	0.00	0.10	0.22	0.62	0.47	1.17	1.44
bmpyfl	0.00	1.79	0.00	0.00	1.70	1.25	1.76	2.99
c1mflpy	0.00	1.72	0.00	0.00	0.00	0.98	0.27	0.64
m_13fl	5.59	1.60	8.23	9.37	1.70	1.21	1.29	1.44
m_4pyr	6.46	3.80	3.94	8.99	0.81	3.05	0.66	6.06
cmpyfl	0.00	0.34	0.00	0.00	1.12	0.82	2.03	2.54
dmpyfl	0.00	4.51	0.00	0.00	0.54	2.74	0.47	6.25
m_1pyr	0.00	1.01	0.00	0.18	0.77	2.23	0.55	3.37
bntiop	0.43	0.00	0.22	0.06	0.77	0.39	0.74	0.53
bzcphen	0.59	0.38	0.89	0.79	0.23	0.90	0.35	0.30
bghifl	4.90	3.05	10.40	9.53	0.00	0.63	0.31	0.27
phant9	0.30	0.25	0.21	0.19	0.12	0.35	0.16	0.11
cp_cdpyr	4.09	0.14	1.37	1.39	0.00	0.67	0.23	0.49
baanth	0.94	1.36	1.92	2.54	0.46	0.67	0.55	0.38
chr_tr	4.45	0.69	0.00	0.00	0.31	0.90	0.55	0.95
bzanthr	2.92	1.41	4.58	5.31	0.77	0.90	1.76	1.44
baa7_12	0.00	0.00	0.23	0.58	0.93	1.17	6.67	2.35
m_3chr	0.00	0.00	0.29	0.09	0.00	0.51	0.43	0.23
chry56m	0.00	0.00	0.00	0.00	0.50	0.67	0.51	0.38
m_7baa	0.00	0.00	0.00	0.00	0.42	0.51	0.55	0.42
dmban712	0.44	0.00	23.90	16.56	0.50	0.23	0.23	0.72
bbjkfl	0.49	0.36	0.45	0.07	0.00	0.23	0.12	0.49
bafl	0.38	0.00	0.21	0.40	0.00	0.16	0.04	0.11
bepyrn	0.40	0.00	0.83	0.61	0.19	0.23	0.20	0.42
bapyrn	0.14	0.18	0.42	0.36	0.00	0.23	0.16	0.23
peryle	0.00	0.18	0.00	0.00	0.35	0.47	0.16	0.53

TABLE 98 (CONT'D). HEAVY-DUTY DIESEL AVERAGE POLYCYCLIC AROMATIC HYDROCARBONS IN EXHAUST AND LUBRICANTS
(No Statistical Analyses Were Performed On These Data)

Test Number	Exhaust PAHs, µg/mile				Lubricant PAHs, µg/gram			
	HD-NE-F-D-72	HD-NE-A-D-72	HD-HM-F-D-72	HD-HM-A-D-72	HD-NE-F-D-72	HD-NE-A-D-72	HD-HM-F-D-72	HD-HM-A-D-72
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Temp, °F	72	72	72	72	72	72	72	72
Media[a]	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction[b]	Yes	Yes	Yes	Yes	NA	NA	NA	NA
m_7bpy	1.15	0.00	0.00	0.00	0.00	0.04	0.23	0.19
bpy910dih	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
incdfl	0.07	0.00	0.01	0.03	0.35	1.37	1.60	0.72
dbahacr	0.00	0.00	0.00	0.00	0.00	0.59	0.51	0.23
dbajacr	0.00	0.00	0.00	0.00	0.00	0.43	0.59	0.49
in123pyr	0.00	0.00	0.01	0.00	0.85	0.74	0.74	0.42
dbahacan	0.00	0.00	0.00	0.00	1.00	0.67	0.90	0.76
dbajan	0.00	0.00	0.00	0.00	0.66	0.27	0.90	0.23
bbchr	0.00	0.00	0.01	0.00	1.39	0.35	0.74	0.30
pic	0.00	0.00	0.00	0.00	0.00	1.25	3.12	1.36
bghipe	0.23	0.00	0.02	0.18	1.16	0.55	1.87	0.23
anthan	0.00	0.00	0.03	0.03	0.19	0.63	1.21	0.42
dbalpyr	0.00	0.00	0.00	0.00	0.35	0.00	0.23	0.72
corone	0.01	0.00	0.00	0.00	0.00	0.67	0.39	0.23
dbaepyr	0.02	0.00	0.00	0.00	0.00	0.00	0.35	0.15
dbaipyr	0.02	0.00	0.00	0.00	0.00	0.90	0.00	0.00
dbahpyr	0.00	0.00	0.02	0.00	0.00	0.78	0.00	0.23
dbbkfl	0.00	0.00	0.00	0.00	0.19	0.23	0.31	0.49
dbth	5.24	2.96	1.43	1.82	0.39	0.39	0.39	0.47

[a] Filter and XAD cartridge samples

[b] Test samples were corrected by subtracting a tunnel blank measurement

10.5.2.4 Alkanes

Exhaust samples from the heavy-duty diesel tests were analyzed by DRI for alkanes. Table 99 shows the average results in µg/mile of the replicate tests performed in each configuration. Table 30 shows the codes for the alkane species in Table 99. Table 99 also shows the results of lubricant analyses for alkanes in µg/gram units.

10.5.2.5 Hopanes and Steranes

Exhaust samples from the heavy-duty diesel tests were analyzed by DRI for hopanes and steranes. Table 100 shows the average results in µg/mile of the replicate tests performed in each configuration. Table 33 shows the codes for the hopanes and steranes species in Table 100. Table 100 also shows the results of lubricant analyses for hopanes and steranes in µg/gram units.

10.5.2.6 Particle-Phase Elemental and Organic Carbon

PM samples from the heavy-duty diesel tests were analyzed by DRI for elemental carbon and organic carbon (EC/OC). Table 101 shows the average results in mg/mile of the replicate tests performed in each configuration. The configurations are identified in the five left columns of the table, and EC/OC results are shown in the three right columns. In Table 101, EC is elemental carbon measured, OC is organic carbon, and TC is total carbon.

10.5.2.7 Particle-Phase Sulfates

PM samples from the heavy-duty diesel tests were analyzed by DRI for sulfates. Table 102 shows the average results in µg/mile of the replicate tests performed in each configuration.

10.5.2.8 Particle-Phase Soluble Organic Fraction

PM samples from the heavy-duty diesel tests were analyzed by DRI for soluble organic fraction (SOF). Table 103 shows the average results for the normal emitter and high mileage, in percent SOF, of the replicate tests performed in each configuration.

TABLE 99. HEAVY-DUTY DIESEL AVERAGE ALKANES IN EXHAUST AND LUBRICANTS
(No Statistical Analyses Were Performed On These Data)

	EXHAUST ALKANES EMISSION RATES, µg/mile				LUBRICANT ALKANES, µg/gram			
TEST NUMBER	**HD-NE-F-D-72**	**HD-NE-A-D-72**	**HD-HM-F-D-72**	**HD-HM-A-D-72**	**HD-NE-F-D-72**	**HD-NE-A-D-72**	**HD-HM-F-D-72**	**HD-HM-A-D-72**
Source	Exhaust	Exhaust	Exhaust	Exhaust	Oil	Oil	Oil	Oil
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Temp	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0
Media	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction	Yes	Yes	Yes	Yes	NA	NA	NA	NA
dodec	2245.5	278.5	66.8	417.0	13.6	14.8	1.3	9.8
norfarn	1012.8	568.0	457.5	801.6	6.3	8.1	1.6	3.8
tridec	2190.1	1086.1	1168.5	1831.2	22.3	32.1	8.2	22.9
hpycyhx	218.6	83.4	108.6	206.3	1.0	3.2	0.4	1.9
farnes	524.8	381.4	296.9	536.6	4.8	10.1	2.2	9.7
tdec	2270.1	894.4	684.7	1550.0	35.9	67.4	17.7	57.6
ocycyhx	231.7	89.5	70.8	145.5	1.3	6.7	0.2	5.5
pentad	1488.4	771.8	736.0	1437.5	48.4	127.7	31.1	124.6
noycyhx	174.6	149.2	23.4	95.0	4.4	8.6	0.4	14.2
hexad	1030.9	689.0	504.9	1155.7	64.0	212.0	44.4	227.5
norprst	403.4	348.7	184.6	480.7	25.6	117.3	12.8	113.4
decyhx	77.6	73.6	30.2	79.4	2.8	10.4	1.1	20.0
heptad	837.1	535.7	380.6	905.4	102.3	380.6	98.2	376.6
heptdpris	648.5	461.8	345.7	817.5	44.8	152.4	24.8	167.8
dec1yhx	53.0	47.6	22.6	34.9	5.3	25.8	5.8	25.4
octad	534.1	578.6	370.7	579.8	60.5	368.4	52.6	385.6
phytan	274.6	250.5	184.3	288.4	36.5	203.2	29.4	203.6
dec2yhx	30.8	27.2	20.4	19.2	6.8	36.4	5.1	35.4
nonad	604.6	597.0	465.9	515.4	59.4	427.9	49.5	445.1
dec3yhx	17.8	12.4	11.9	15.8	8.6	21.1	8.3	25.1
eicosa	492.9	532.7	370.9	393.9	70.9	413.2	75.1	409.3
dec4yhx	12.9	15.2	6.1	8.0	18.1	57.3	10.5	43.3
heneic	268.4	303.2	224.7	240.9	66.0	371.2	44.8	404.6
dec5yhx	7.4	1.9	0.5	6.8	5.7	85.4	7.9	98.0
docosa	38.6	134.3	62.3	92.0	109.5	308.1	129.9	280.2
dec6yhx	0.0	0.9	0.5	0.0	12.1	45.8	11.6	15.3
tricosa	0.0	100.1	4.8	0.8	149.4	197.3	138.5	234.7
dec7yhx	1.7	39.9	12.9	28.6	16.6	144.5	39.0	165.6
tetcos	0.4	80.6	0.0	0.0	54.0	167.4	132.0	196.1
dec8yhx	34.1	0.5	91.4	81.7	29.8	22.3	19.4	31.5
pencos	0.0	81.8	0.0	0.0	241.6	122.4	92.9	294.9
hexcos	5.1	37.0	16.5	0.0	110.0	138.6	103.6	187.3
dec9yhx	0.6	6.9	6.3	0.0	3.9	12.0	20.5	26.4
hepcos	8.6	0.0	0.5	0.0	165.6	38.0	12.0	100.8
cyhxeic	0.1	4.4	0.1	3.0	23.3	147.8	21.3	81.3
octcos	0.0	0.0	9.1	0.0	55.1	57.4	55.1	55.1
noncos	5.2	0.2	8.2	0.0	44.5	10.7	63.8	58.0
cyhxhen	0.6	2.3	4.4	0.0	12.4	19.0	27.8	10.1
tricont	0.0	0.0	0.0	0.0	54.9	93.9	13.8	6.4
htricont	0.0	5.1	16.6	0.0	33.1	2.5	2.2	7.5
dtricont	0.0	3.5	10.9	0.0	13.8	3.8	6.4	18.6
ttricont	0.0	1.7	0.0	0.0	2.9	4.9	0.0	2.1
tetricont	0.0	1.1	0.0	0.0	28.8	13.8	15.3	9.7
ptricont	0.2	2.0	0.0	0.0	4.1	2.9	3.3	0.0
hxtricont	0.6	2.0	0.0	0.0	0.7	0.0	0.5	0.0
hptricont	0.0	0.0	0.6	0.0	4.3	6.0	4.1	1.7
otricont	0.2	0.0	0.0	0.0	1.0	1.8	3.7	1.7
ntricont	1.2	0.0	0.5	1.1	2.9	1.2	4.8	2.1
tecont	1.1	0.0	0.0	0.1	0.0	1.6	2.1	2.5
hxtric74	24.6	36.0	16.7	9.4	218.5	145.1	196.5	109.3
ucm	64923.7	28867.3	37983.3	48942.2	223690.1	243031.9	276126.3	243855.9

TABLE 100. HEAVY-DUTY DIESEL AVERAGE HOPANES AND STERANES IN EXHAUST AND LUBRICANTS

(No Statistical Analyses Were Performed On These Data)

	PARTICULATE HOPANES AND STERANES EMISSION RATES, µg/mile				LUBRICANT HOPANES AND STERANES, µg/gram			
TEST NUMBER	**HD-NE-F-D-72**	**HD-NE-A-D-72**	**HD-HM-F-D-72**	**HD-HM-A-D-72**	**HD-NE-F-D-72**	**HD-NE-A-D-72**	**HD-HM-F-D-72**	**HD-HM-A-D-72**
Emitter	Normal	Normal	High Mileage	High Mileage	Normal	Normal	High Mileage	High Mileage
Oil	Fresh	Aged	Fresh	Aged	Fresh	Aged	Fresh	Aged
Fuel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel	Diesel
Temp, F°	72	72	72	72	72	72	72	72
Media	F+XAD	F+XAD	F+XAD	F+XAD	Oil	Oil	Oil	Oil
TB Correction	Yes	Yes	Yes	Yes	NA	NA	NA	NA
hop15	1.28	0.65	0.96	1.69	11.55	24.28	12.39	23.08
hop17	4.65	5.55	4.63	9.03	28.60	61.65	37.05	65.80
hop19	5.60	5.32	3.25	2.83	20.98	38.58	25.56	40.44
hop20	0.11	0.00	0.00	0.11	1.50	2.70	1.91	3.06
hop21	1.48	2.22	2.17	3.56	13.83	29.64	21.05	29.63
hop22	1.34	2.03	0.99	0.58	9.45	19.64	10.30	19.01
hop23	0.11	0.00	0.80	0.59	1.06	0.00	0.00	2.71
hop24	1.01	1.32	0.94	0.79	7.25	15.69	12.06	16.13
hop25	0.00	0.00	0.23	0.00	5.57	10.08	5.37	8.88
hop26	0.64	0.69	0.77	0.54	5.09	9.39	5.89	12.08
hop27	0.50	0.37	0.14	0.33	2.62	9.58	4.45	8.52
ster42	0.63	1.40	0.73	0.90	1.62	5.48	3.01	5.42
ster43	1.60	0.19	3.50	1.83	11.40	23.50	12.12	23.73
ster44	5.80	1.77	1.42	0.76	5.24	10.76	4.56	12.95
ster45_40	2.15	0.32	0.37	0.69	9.18	17.26	8.71	17.61
ster46	0.48	1.35	1.20	0.34	1.80	2.53	2.33	3.58
ster47	0.96	0.19	0.00	0.22	5.15	12.50	6.61	12.55
ster48_41	0.39	0.05	0.00	4.49	2.38	4.64	2.75	4.60
ster49	0.42	0.59	0.61	0.09	1.74	1.92	2.46	1.94
ster50	0.56	0.00	0.50	0.31	2.07	6.20	4.63	5.40
ster51	0.61	0.17	2.33	1.13	5.25	10.89	4.69	12.39
ster52	0.61	0.07	0.82	0.91	3.82	8.14	4.45	8.34
ster53	0.69	0.00	0.54	0.00	3.30	4.80	4.67	5.44

TABLE 101. HEAVY-DUTY DIESEL AVERAGE ELEMENTAL CARBON AND ORGANIC CARBON RATE

(No Statistical Analyses Were Performed On These Data)

					CARBON EMISSION RATES, mg/mile		
TEST NUMBER	**EMITTER**	**OIL**	**FUEL**	**TEMP**	**EC**	**OC**	**TC**
HD-NE-F-D-72	Normal	Fresh	Diesel	72	828	123	952
HD-NE-A-D-72	Normal	Aged	Diesel	72	712	132	844
HD-HE-F-D-72	High Mileage	Fresh	Diesel	72	569	122	691
HD-HE-A-D-72	High Mileage	Aged	Diesel	72	584	131	715

TABLE 102. AVERAGE SULFATE EMISSIONS FROM HEAVY-DUTY DIESEL VEHICLES
(No Statistical Analyses Were Performed On These Data)

TEST NUMBER	Vehicle	Oil	Fuel	Temp	Average Sulfate, µg/mile
HD-NE-F-D-72	Normal Emitter	Fresh	Diesel	72°F	1685
HD-NE-A-D-72	Normal Emitter	Aged	Diesel	72°F	1181
HD-HM-F-D-72	High Mileage	Fresh	Diesel	72°F	2987
HD-HM-A-D-72	High Mileage	Aged	Diesel	72°F	456

TABLE 103. HEAVY-DUTY DIESEL VEHICLE AVERAGE SOLUBLE ORGANIC FRACTION
(No Statistical Analyses Were Performed On These Data)

TEST NAME	Lubricant	Vehicle	Fuel	Ambient Temperature, °F	Average SOF, %
HD-NE-F-D-72	Fresh	Normal Emitter	Diesel	72	14%
HD-NE-A-D-72	Aged	Normal Emitter	Diesel	20	13%
HD-HM-F-D-72	Fresh	High Mileage	Diesel	72	18%
HD-HM-A-D-72	Aged	High Mileage	Diesel	20	16%

10.5.2.9 Particle Number and Size Distribution Emission Test Results

Figures 96 and 97 show the exhaust PN concentration for the heavy-duty diesel normal emitter (HD-D-NE). The data are shown for the fresh and aged oil at 72°F. The data are plotted as an average concentration for one cold-start and one subsequent hot-start of the HD UDDS. The exhaust PN concentration ranged from about $12x10^6$ part./cm³ to $18x10^6$ part./cm³. This is comparable to the MD-NE and the HD-NG-NE, but the PN composition and size distribution are different from those emitted from the HD-NG-NE and similar to those emitted from MD-NE, as shown later in this section. No notable differences were observed between cold-start and hot-start and fresh and aged oils. Figures 98 and 99 show the percent ratio of solid and volatile PN concentration to total PN concentration. Seventy to ninety percent of the number of particles emitted from the HD-D-NE were solid in nature. This is much different from the HD-NG-NE that was dominated by volatile particles. It is also slightly different from the MD-NE that had more volatile PN than that observed with the HD-D-NE. While total PN emission is similar between HD-D-NE and HD-NG-NE, the solid or soot PN emission from the HD-D-NE is much higher than that observed with HD-NG-NE. This suggests that fuel is the major contributor of PN in HD-D, while lube oil is the major contributor of PN in HD-NG. Even if the oil consumption is similar between the two vehicle types, the absence of soot or solid particle surface area in the HD-NG vehicles promotes sulfuric acid and hydrocarbon particle nucleation and growth. This phenomenon was observed and discussed in previous work (CRC Project E-66 Phase 1 & 2, www.crcao.com). Essentially, the presence of soot during dilution and cooling acts as a surface area available for adsorption/condensation of volatile material. In the absence of such surface area, the path for particle nucleation is enhanced. Also, the same phenomenon can explain the lack of PN emissions from the HD-D vehicles between fresh and aged oil, compared to HD-NG vehicles. The soot present in diesel exhaust dominates PN emission, and changes in lube oil volatility or properties have a minor influence on PN.

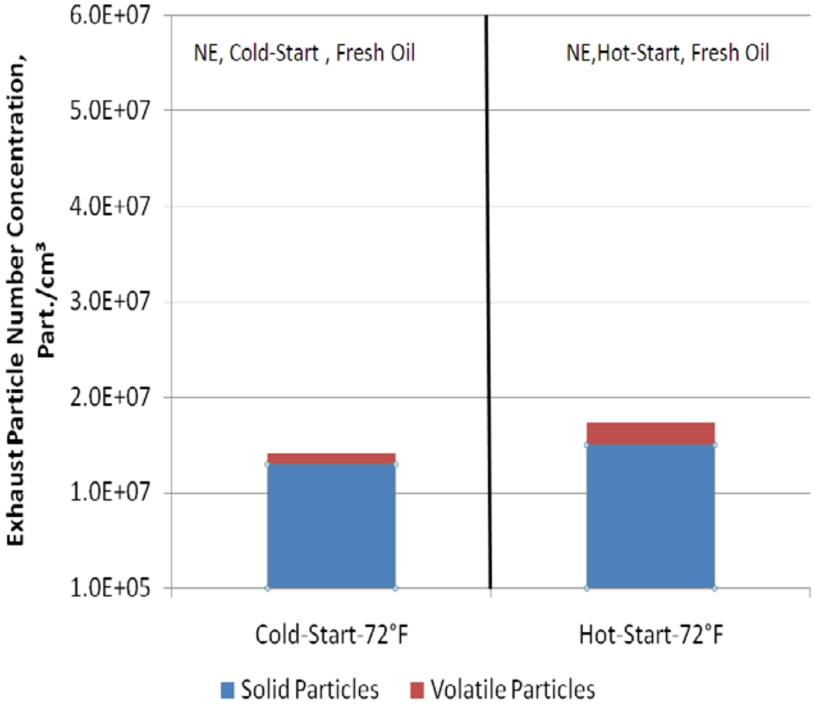

FIGURE 96. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (DIESEL, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

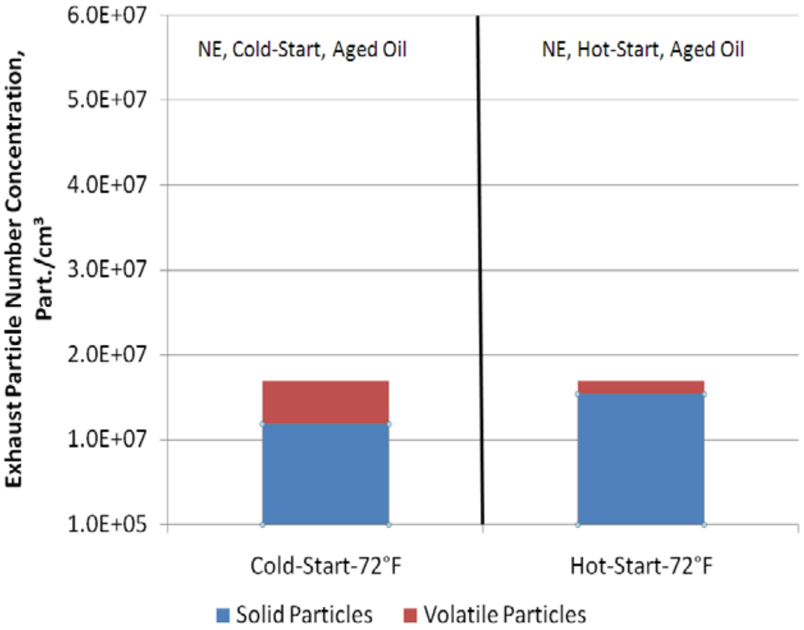

FIGURE 97. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (DIESEL, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

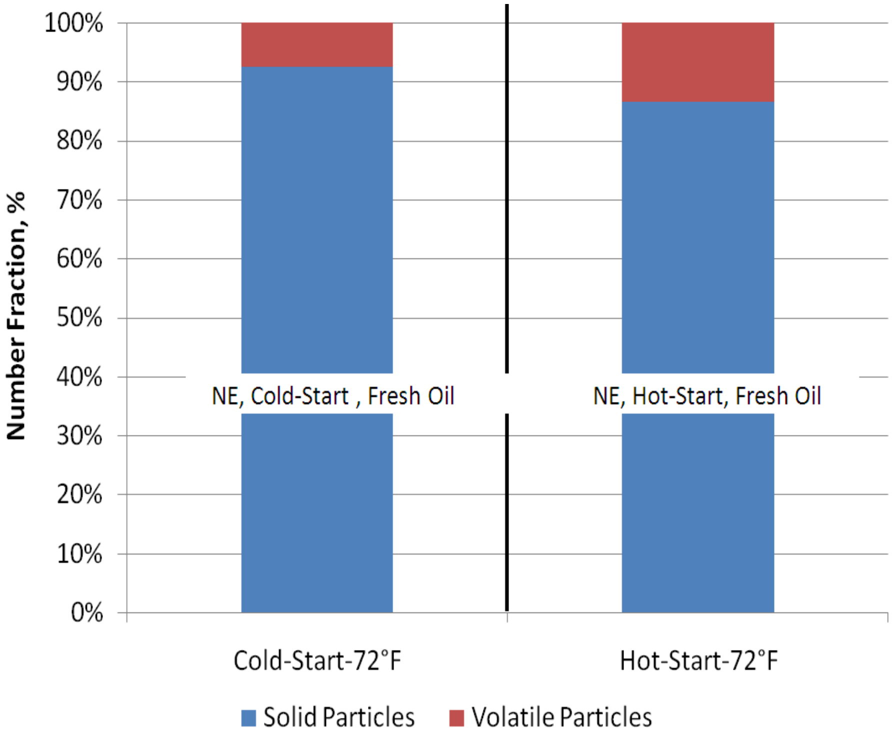

FIGURE 98. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (DIESEL, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

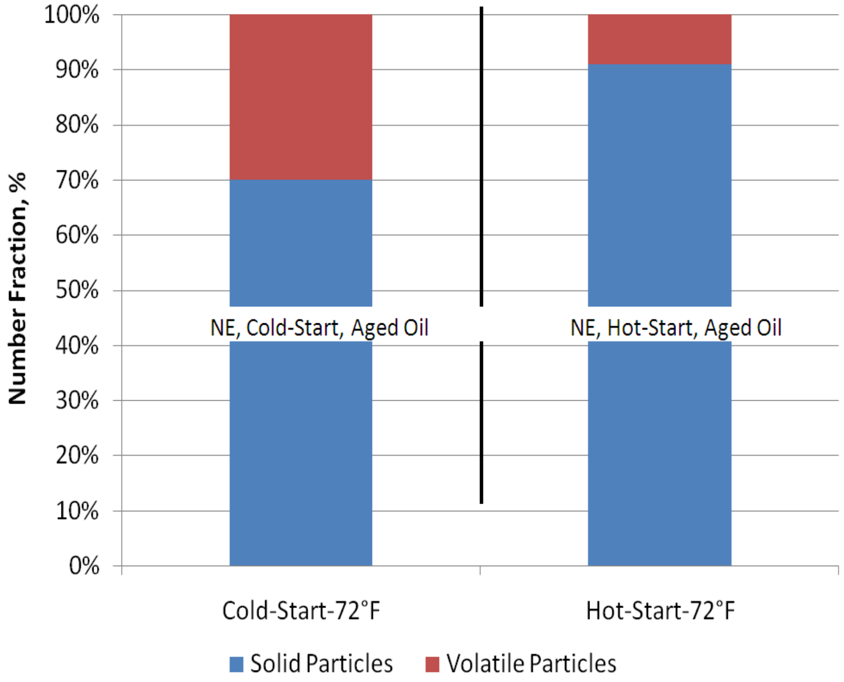

FIGURE 99. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (DIESEL, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

Figures 100 and 101 show the exhaust PN concentration for the HD-D high mileage (HM) vehicle. The exhaust PN concentration ranged from 10x10^6 part./cm³ to 16x10^6 part./cm³. This concentration range is similar to that of the HD-D-NE and the MD-NE and MD-HE, but much lower than that of the LD-HE and the HD-NG-HM. This further demonstrates that when soot dominates PN emission, lube oil contribution to PN is minimized. It is interesting to note that among the vehicles tested, LD-HE and HD-NG-HM had the highest PN emission. Figures 102 and 103 show that over 70 percent of the PN emitted from the HD-D-HM was solid. This is similar to the HD-D-NE vehicle but drastically different from the LD-HE and the HD-NG-HM vehicle, where over 70 percent of PN was volatile. Furthermore, this is slightly different from the MD-HE vehicle, where more volatile fraction of the PN was observed. However, in general, the volatile PN fraction for the HD and MD diesel vehicles were comparable, suggesting little influence of lube oil aging and oil/consumption on PN emissions.

Figures 104 and 105 show a typical size distribution for the HD-D-NE using the fresh and aged oil. The data are shown for the cold-start and hot-start portions of the test cycles using TxLED fuel at 72°F. The total and solid distributions exhibit a similar monomodal lognormal size distribution structure that consists of an accumulation mode. The accumulation mode peaks between 50 nm and 70 nm, similar to what was observed with the MD-NE. For the HD-D-HM, as shown in Figures 106 and 107, the total and solid particle size distributions were very similar to that for the HD-D-NE. No notable differences in the size distributions were observed between the fresh oil and aged oil, the cold-start and hot-start, or the NE and HM.

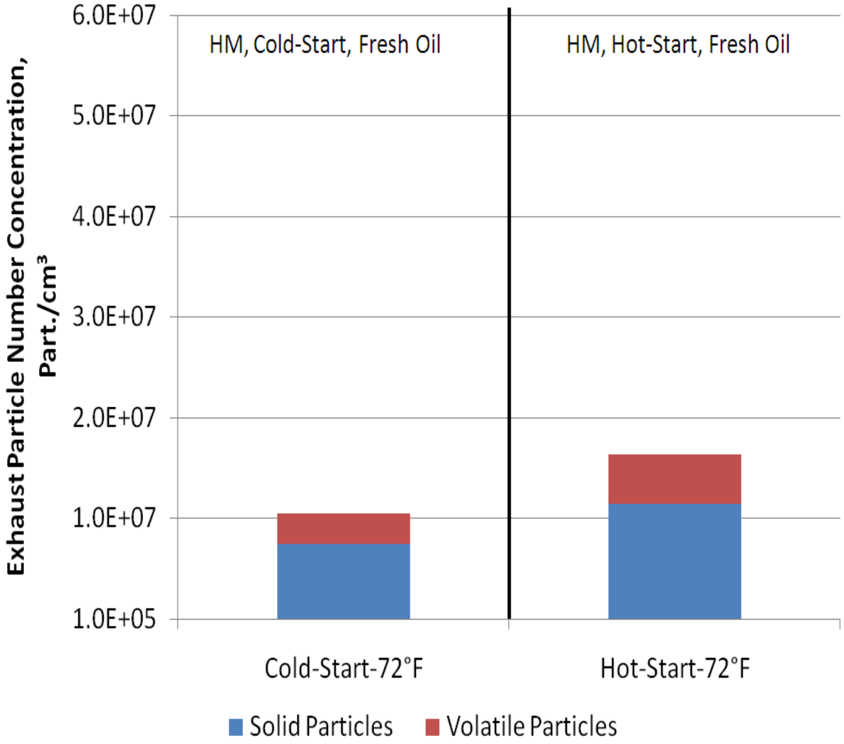

FIGURE 100. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (DIESEL, HIGH MILEAGE VEHICLE, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

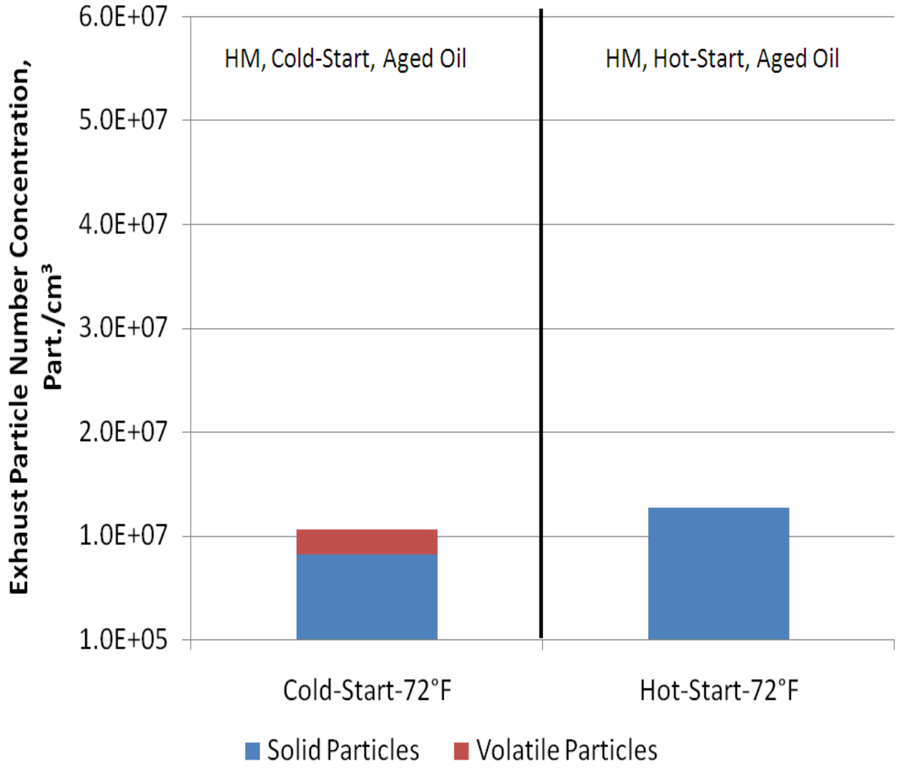

FIGURE 101. SOLID AND VOLATILE PARTICLE NUMBER CONCENTRATION (DIESEL, HIGH MILEAGE VEHICLE, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

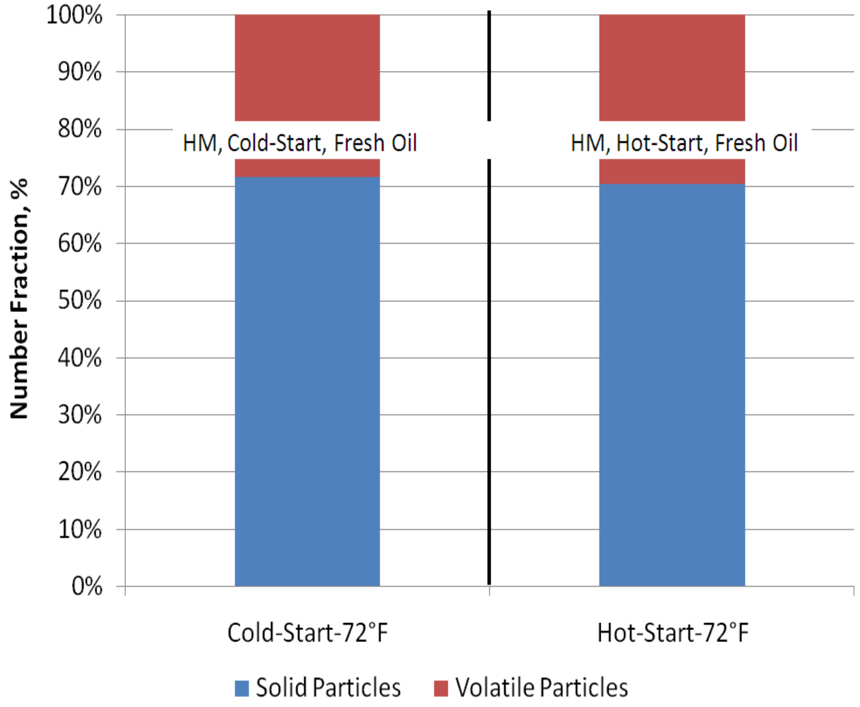

FIGURE 102. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (HD DIESEL, HIGH MILEAGE VEHICLE, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

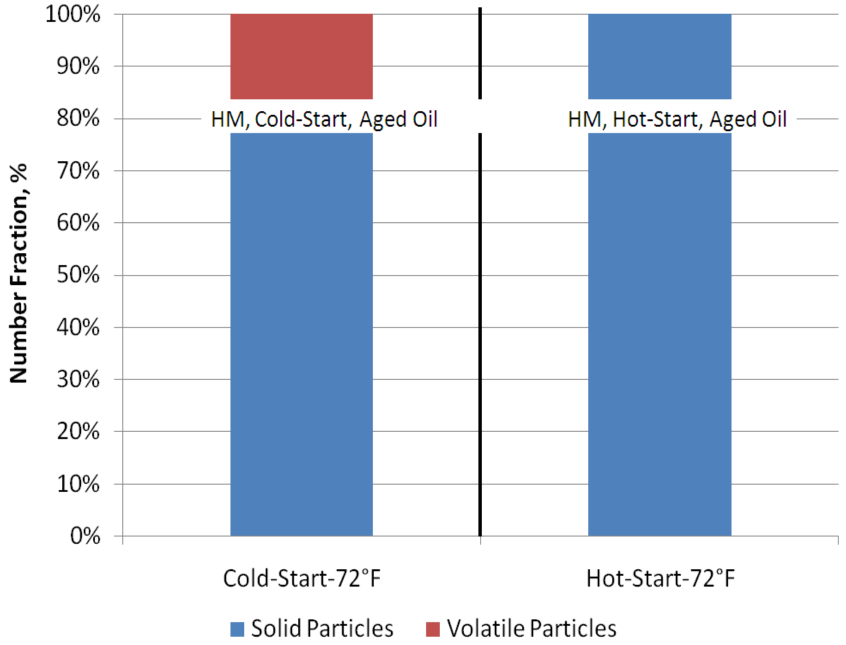

FIGURE 103. SOLID AND VOLATILE PARTICLES AS A PERCENT OF TOTAL PARTICLES (HD DIESEL, HIGH MILEAGE VEHICLE, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

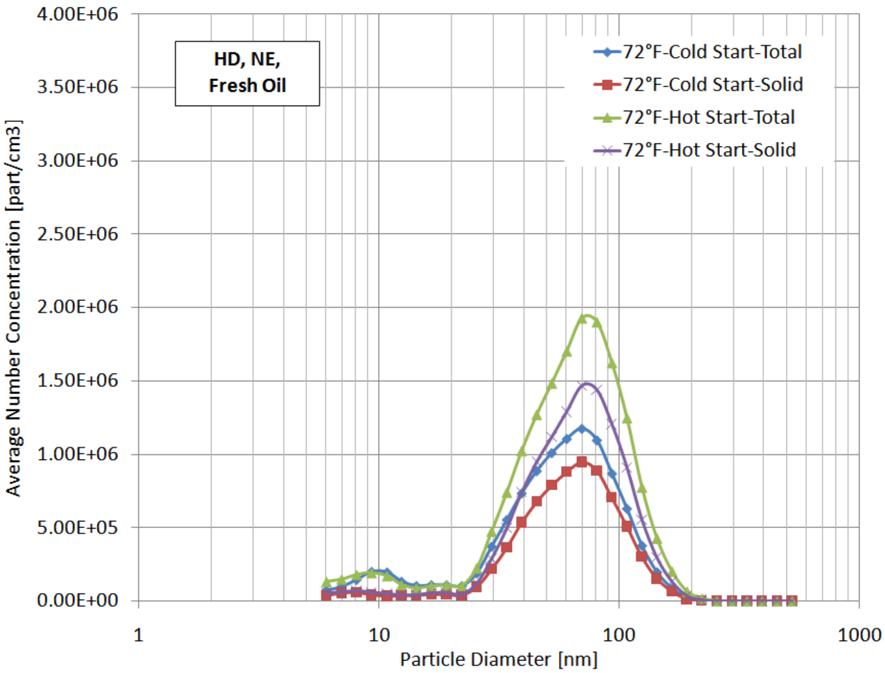

FIGURE 104. NUMBER-WEIGHTED SIZE DISTRIBUTION (HD DIESEL, NORMAL EMITTER, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

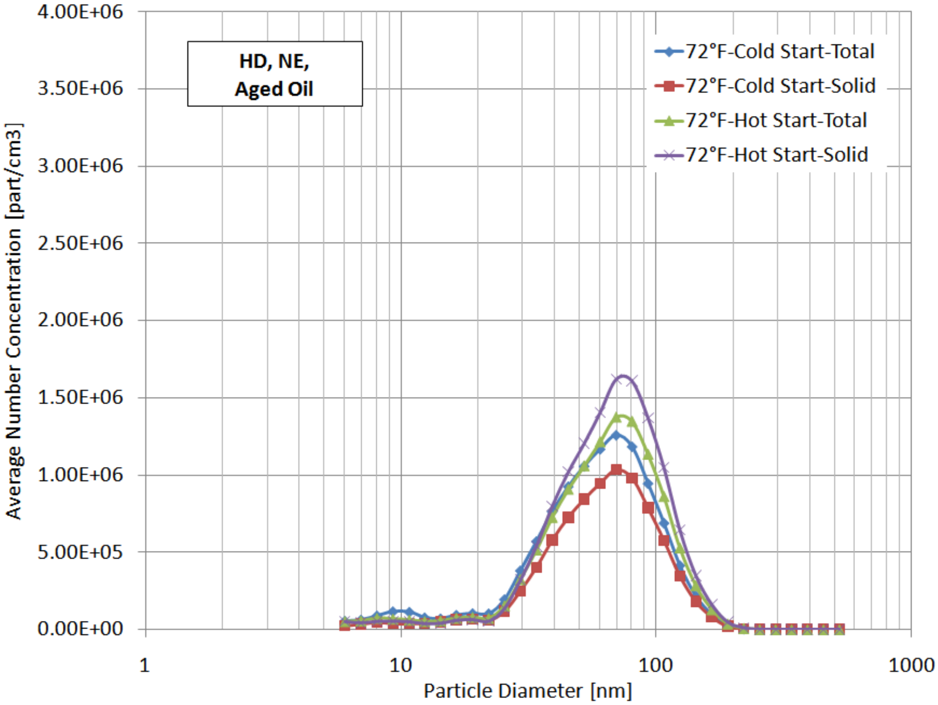

FIGURE 105. NUMBER-WEIGHTED SIZE DISTRIBUTION (HD DIESEL, NORMAL EMITTER, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

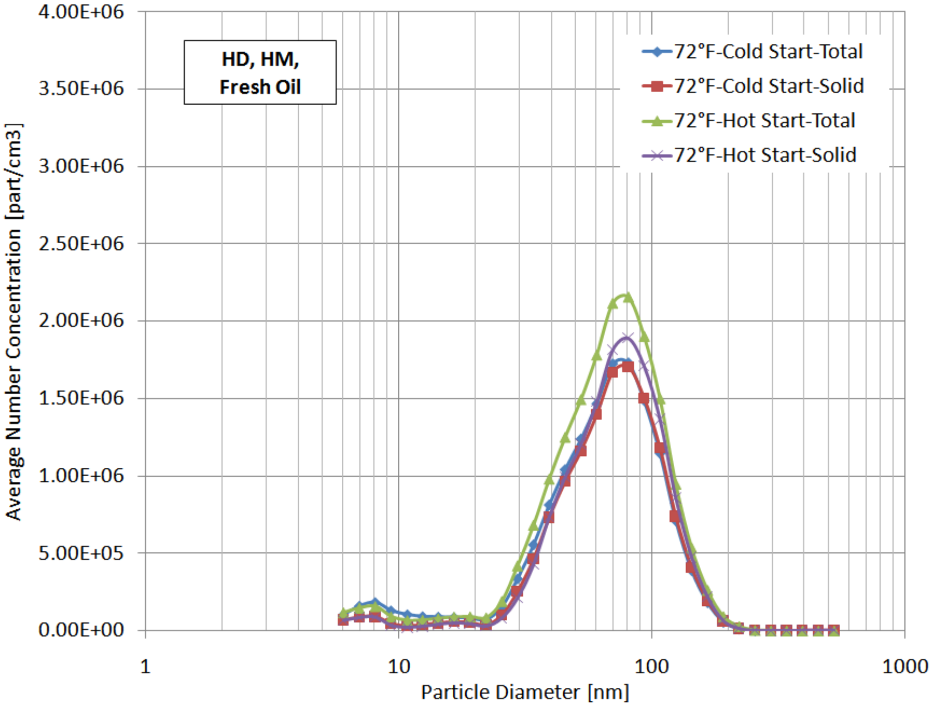

FIGURE 106. NUMBER-WEIGHTED SIZE DISTRIBUTION (HD DIESEL, HIGH MILEAGE VEHICLE, FRESH OIL)
(No Statistical Analyses Were Performed On These Data)

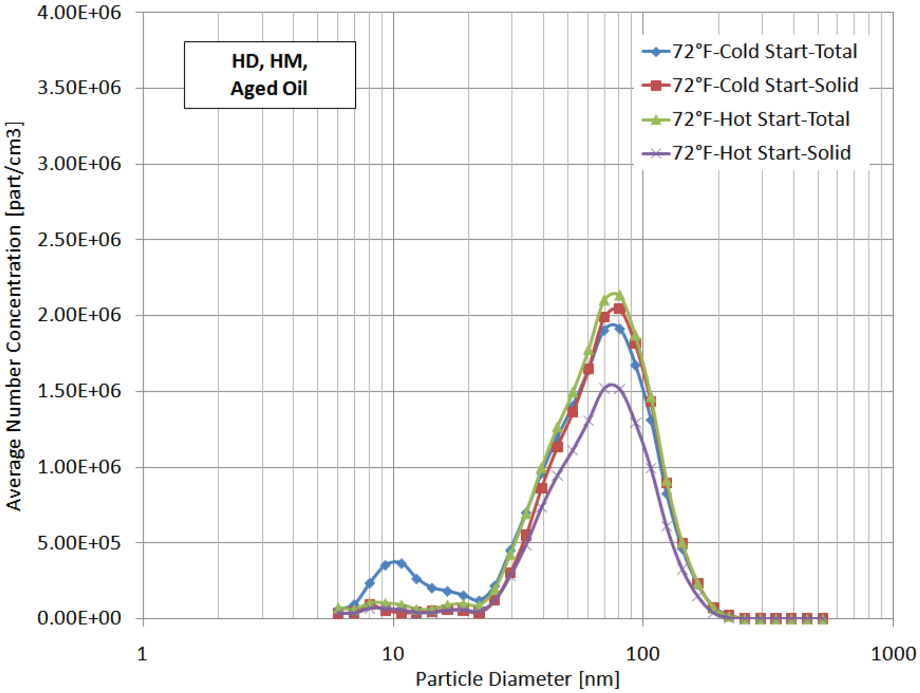

FIGURE 107. NUMBER-WEIGHTED SIZE DISTRIBUTION (HD DIESEL, HIGH MILEAGE VEHICLE, AGED OIL)
(No Statistical Analyses Were Performed On These Data)

10.6 PM Apportionment

10.6.1 Regulated Emissions and Fuel Economy

Regulated emissions and fuel economy data for each set of duplicate tests conducted on each of the two test vehicles were averaged and are presented in Table 104. The emissions and fuel usage were found to be similar for the two test vehicles with the HM having somewhat lower carbon monoxide and PM emissions than the NE. The aged oil gave higher hydrocarbon and oxides of nitrogen emissions and lower PM emissions than the fresh oil; however, there was some overlap of data in all these cases.

TABLE 104. REGULATED EMISSIONS AND FUEL ECONOMY FOR THE HEAVY-DUTY DIESEL-FUELED VEHICLES
(No Statistical Analyses Were Performed On These Data)

	NE		HM	
	Fresh Oil	**Aged Oil**	**Fresh Oil**	**Aged Oil**
HC, g/mi	0.61	0.65	0.66	0.71
CO, g/mi	6.50	6.20	5.41	5.49
NO_X, g/mi	17.65	19.97	18.20	19.07
PM, mg/mi	860	783	665	637
Fuel Usage, lb/mi	1.58	1.59	1.65	1.68

10.6.2 Estimates for Vehicle Oil Consumption Rates

As was the case for the natural gas-fueled vehicles, the XRF analyses of the HD diesel samples gave significantly higher levels of the elements in the exhaust PM than did the ICP-MS analyses. Also, although analyses of the fresh and aged oils showed similar levels of calcium, sulfur, phosphorous, and zinc, analyses of the PM by XRF gave significantly different levels of these elements for the fresh and aged oil tests. The levels of these elements in the PM for the fresh oil tests were approximately twice as high as the levels detected in the PM for the aged oil tests for both vehicles. All of these variations in the elements data made it difficult to calculate oil consumption rates with any confidence. Table 105 presents the variation in the results when the calcium emissions are used to calculate oil consumption rates for the two test vehicles. As can be seen in Table 105, XRF results give nearly equivalent oil consumption rates for the two test vehicles with fresh oil and lower, but similar, rates for the aged oil. The ICP-MS results also give oil consumption rates that are similar for the two vehicles with aged oil, but the fresh oils show a large difference for the two vehicles. These two vehicles were in-use buses and service data was available for both. The NE was reported as requiring one quart of oil per 971 miles (858 mg/mi) and the HM as having high blowby and requiring one quart of oil per 145 miles (5745 mg/mi). The records for the NE indicate that its calculated oil consumption rates may be high by a factor of nearly two except for the aged oil case by ICP-MS. Because of its high blowby rate, the service data for oil addition for HM does not provide any additional insight for comparison to the estimated exhaust emission rate of oil. In this case, blowby is not vented to the exhaust and any losses of oil related to blowby would not be included in exhaust-based calculations for estimating oil consumption.

TABLE 105. VARIATIONS IN ESTIMATED OIL CONSUMPTION RATES FOR THE HEAVY-DUTY DIESEL-FUELED VEHICLES
(No Statistical Analyses Were Performed On These Data)

	NE		HM	
	Fresh Oil	**Aged Oil**	**Fresh Oil**	**Aged Oil**
Calcium Emissions by XRF, µg/mi	5064	2870	5045	2397
Calcium Emissions by ICP-MS, µg/mi	4361	1369	1603	1137
Calcium Oil Concentrations, XRF, µg/g	2623	2707	2623	2707
Calcium Oil Concentrations, ICP-MS, µg/g	2275	2270	2275	2270
Oil Consumption Rate by XRF, mg/mi	1931	1060	1923	885
Oil Consumption Rate by ICP-MS, mg/mi	1917	603	705	501
*An oil consumption rate of 833 mg/mi equals one quart per 1000 miles				

10.6.3 Wear Elements

While analyses of the oils (both as supplied and from the crankcase before testing) showed much higher levels of selected wear elements in the aged oil (Al, Cr, Mn, Fe, Ni, Cu, Mo, Pb) than in the fresh oil, analyses of the PM, with the exception of lead, did not reflect these differences. In fact the fresh oil tests on average produced nearly twice the amount of total wear metals in the PM as did the aged oil (3400 µg/mi vs. 1900 µg/mi). The high mileage did show higher PM sulfur levels, possibly due to a more active conversion of sulfur to sulfate in the vehicle's catalyst.

10.6.4 Carbon Analyses for Elemental and Organic Content of PM

Elemental, organic, and total carbon content results from TOR analyses of the PM filters from the diesel-fueled heavy-duty vehicle tests are presented in Table 106. The total measured PM values for each vehicle are also shown for comparison. Because of the disparity of the calculated oil consumption rates with the fresh and aged oils, separate results for each oil are presented in the table. The total carbon emission rate by TOR was found to be higher than the total PM emission rate. The OC fraction of the TC was found to be higher for the HM compared to the NE (18 percent vs. 14 percent) as well as higher for the aged oil tests compared to the fresh oil tests (17 percent vs. 15 percent). Overall, the data for the two vehicles were relatively similar. Table 107 combines the total carbon results with results for the oil and wear elements for a second comparison with the total measured PM results. The overall differences in the PM elements (oil and wear) between fresh and aged oils are illustrated in the table.

TABLE 106. TOTAL, ELEMENTAL, AND ORGANIC CARBON EMISSIONS
(No Statistical Analyses Were Performed On These Data)

	EMISSIONS, mg/mi			
	NE		HM	
	Fresh Oil	**Aged Oil**	**Fresh Oil**	**Aged Oil**
EC	828	712	569	584
OC	123	132	122	131
TC	952	844	691	715
PM	860	783	665	637

TABLE 107. CARBON AND OTHER ELEMENT TOTALS COMPARED TO TOTAL PM
(No Statistical Analyses Were Performed On These Data)

	EMISSIONS, mg/mi			
	NE		HM	
	Fresh Oil	Aged Oil	Fresh Oil	Aged Oil
Total Carbon	952	844	691	715
Elements *	24	12	25	11
Hydrogen Mass for OC **	15	17	15	17
Total	991	873	731	743
Measured PM	854	783	665	637

* Element mass from XRF analyses. Mass for sulfur and phosphorous assumed to be sulfate and phosphate

** Mass for 1.5 hydrogens per carbon assumed

10.6.5 Estimation of Unburned Oil Content

The oils utilized for the heavy-duty diesel-fueled vehicles were also spiked with the hexatriacontane-d74 tracer; however, in this case, the measured concentrations of the tracer in fresh oil and aged oil were different when analyzed by GC-MS, 207 µg/g oil for the fresh oil and 127 µg/g oil for the aged oil. The total hopanes and steranes were also found to be present at different levels in the two oils; 179 µg/g oil for the fresh oil and 337 µg/g for the aged oil. Because of the variation in the oils, calculations for the unburned oil content of the PM were carried out for both oils and for both vehicles using the appropriate PM and oil concentrations. Table 108 presents oil concentrations and PM emission rates for hexatriacontane-d74, total hopanes and steranes, the unresolved complex mixture (UCM) from the GC-MS alkane analyses, and the corresponding calculated unburned oil emission rates for each set of PM and oil data.

TABLE 108. ESTIMATION OF UNBURNED OIL USING VARIOUS TRACERS
(No Statistical Analyses Were Performed On These Data)

	NE		HM	
	Fresh Oil	Aged Oil	Fresh Oil	Aged Oil
Hexatriacontane-d74 in PM, µg/mi	24.7	36.0	16.8	9.4
Hexatriacontane-d74 in oil, µg/g	207	127	207	127
Unburned oil in PM, mg/mi	119	283	81	74
Total Hopanes & Steranes in PM, µg/mi	20.5*	23.8	14.6*	20.6*
Total Hopanes & Steranes in Oil, µg/g	179	337	179	337
Unburned oil in PM, mg/mi	115	71	82	61
Total UCM in PM, mg/mi	31.8	21.2	27.5	30.0
Total UCM in oil, g/g	0.247	0.247	0.247	0.247
Unburned oil in PM, mg/mi	129	86	111	121

*Significant levels of hopanes and steranes also observed in gas phase (30 to 45 percent). Not noted for MD vehicle samples

All three methods of determining unburned oil gave similar emission rates for the NE using fresh oil (115 to 129 mg/mi), but varied widely for the NE using aged oil (71 to 283 mg/mi). A substantial amount of hopanes and steranes (30 to 45 percent of the total) was also found in the gas phase for three of the four sample sets. This level of hopanes and steranes was not observed in the medium-duty vehicle tests and was not expected. Also of note was the observation that the PM did contain fuel range C_{12} to C_{19} alkanes (0.6 to 0.8 mg/mi) on the same order as oil range C_{20} to C_{40} alkanes (0.9 to 1.8 mg/mi). The C_{12} to C_{19} fraction was slightly higher for the HM PM (38 percent) compared to the NE PM fraction (30 percent). PM alkanes were on average 20 percent of the total (PM plus gas phase) alkanes.

Table 109 presents a comparison of the calculated unburned oil estimates to the organic carbon (OC) component of the PM. All three methods give unburned oil emission rates that are in good agreement with the OC for the NE fresh oil tests, but only the UCM estimates appear to track the OC for the HM test. None of the three methods produced calculated rates that were similar to the NE aged oil results. All three methods also gave calculated unburned oil emissions rates for the HM that were lower than the measured OC rate and indicate the possibility of fuel derived components or partially burned oil components at higher levels in the HM than in the NE. The higher fraction of the C_{12} to C_{19} alkanes to the total alkanes in the HM PM (38 percent) compared to the NE (30 percent) could support this supposition. If the unburned oil estimates are averaged for the three methods with the associated mass of the hydrogen removed, the results indicate that 89 percent of the NE OC is unburned oil while only 60 percent of the HM OC is unburned oil.

TABLE 109. COMPARISON OF UNBURNED OIL ESTIMATES TO OC
(No Statistical Analyses Were Performed On These Data)

	NE		HM	
	Fresh Oil	**Aged Oil**	**Fresh Oil**	**Aged Oil**
Hexatriacontane-d74, mg/mi	119	283	81	74
Hopanes & Steranes, mg/mi	115	71	82	61
UCM, mg/mi	129	86	111	121
OC, mg/mi	123	132	122	131

10.6.6 PAH PM Emissions

A total of 55 different PAH were detected in the PM from the heavy-duty diesel-fueled vehicles tested in this study. Total PAH emission rates ranged from 0.36 mg/mi for the NE aged oil tests to 0.74 mg/mi for the HM aged oil tests. While the aged oil contained approximately four times the concentration of these 55 PAH compounds as did the fresh oil (147µg/g oil compared to 35 µg/g oil), the fresh and aged oil tests on average over the two vehicles gave nearly equivalent emissions results (0.55 mg/mi). These equivalent results indicate that the PAH compounds in PM primarily originate from the fuel and not the oil. On average the HM had higher PM PAH emission rates than the NE (0.69 mg/mi for the HM and 0.40 mg/mi for the NE). When only the higher molecular weight PAH compounds were considered (benz(a)anthracene and heavier), the difference was even greater (29 µg/mi for the HM and 6 μg/mi for the NE). These PAH results also support the suggestion of a larger fraction of fuel derived material in the HM PM compared to the NE PM.

10.6.7 Summary

A number of observations regarding the make-up of the heavy-duty vehicle PM follow:

- Calculations for oil consumption rates for the heavy-duty diesel fueled vehicles varied considerably due to variations in measured levels of oil derived elements in the PM. Variations occurred between the two analysis techniques (XRF or ICP-MS) and between samples from the two oils tested with each of the two vehicles. Calculated oil consumption rates were more consistent for a single oil tested in both test vehicles than for both oils tested in a single vehicle.
- Despite higher concentrations of wear elements in the aged oil, the PM from the fresh oil tests had higher emission rates of the wear elements than did the aged oil.
- TOR analyses showed a higher fraction of the HM PM to be OC (18 percent) compared to the NE PM (14 percent). These percentages were generally lower than those obtained for the medium-duty vehicles (22 and 29 percent).
- Total PM carbon was observed to be higher than the measured PM emission rate for both vehicles.
- Three methods were utilized to calculate unburned oil in the PM. All three methods gave unburned oil rates similar to the OC rates for the NE tests with fresh oil, but none gave similar results for the NE with aged oil. All three methods gave oil consumption rates lower than the OC rates for both fresh and aged oil tests with the HM, indicating the possibility of fuel derived compounds in the PM at more significant levels than previous medium-duty or natural gas-fueled heavy-duty tests.
- The unburned oil is estimated to be 89 percent of the OC for the NE, but only 62 percent of the HM.
- The HM had higher PM PAH emission rates than the NE (0.69 mg/mi vs 0.40 mg/mi) also indicating more fuel derived combustion products in the HM PM. Also, alkanes in the fuel range size (C_{12} to C_{19}) made up a larger fraction of the total PM alkanes in the case of the HM (38 percent) compared to the NE (30 percent).

10.7 Heavy-Duty Diesel Vehicles Major Technical Findings

Fresh and Aged oil

Both vehicles produced nominally lower PM emissions with aged oil compared to fresh oil.

Fuel

Only TxLED diesel fuel was used.

Normal and High Particulate Matter (High Mileage) Emitter

The normal PM emitter produced higher PM than the high mileage vehicle; approximately 0.82g/mi for the NE compared to about 0.65g/mi for the high mileage bus.

Normal (72°F) and Low (20°F) Temperature

No low temperature tests were performed with the HD diesel vehicles.

Particle Number and Size Distributions

Particle Number

- For the HD D NE, the exhaust PN concentration ranged from about $12x10^6$ part./cm³ to $18x10^6$ part./cm³. This is comparable to the MD NE and the HD NG NE. The PN composition and size distribution are different from those emitted from the HD NG NE and similar to those emitted from the MD NE.
- No notable differences were observed between cold-start and hot-start and between fresh and aged oils.
- Seventy to ninety percent of the number of particles emitted from the HD D NE were solid in nature. This is much different from the HD NG NE that was dominated by volatile particles. It is also slightly different from the MD NE that had more volatile PN than that observed with the HD D NE. While total PN emission is similar between HD D NE and HD NG NE, the solid or soot PN emission from the HD D NE is much higher than that observed with HD NG NE. This suggests that fuel is the major contributor of PN in HD D, while lube oil is the major contributor of PN in HD NG. Even if the oil consumption is similar between the two vehicle types, the absence of soot or solid particle surface area in the HD NG vehicles promotes sulfuric acid and hydrocarbon particle nucleation and growth. The soot present in diesel exhaust dominates PN emission, and changes in lube oil volatility or properties have a lesser influence on PN.
- For the HD D high mileage (HM) vehicle, the exhaust PN concentration ranged from $10x10^6$ part./cm³ to $16x10^6$ part./cm³. This concentration range is similar to that of the HD D NE and the MD NE and MD HE, but much lower than that of the LD HE and the HD NG HM. This further demonstrates that when soot dominates PN emission, lube oil contribution to PN is minimized.
- It is interesting to note that among the vehicles tested, the LD HE and HD NG HM vehicles had the highest PN emission.
- Over 70 percent of the PN emitted from the HD D HM was solid. This is similar to the HD D NE vehicle but drastically different from the LD HE and the HD NG HM vehicle, where over 70 percent of PN was volatile. Furthermore, this is slightly different from the MD HE vehicle, where more volatile fraction of the PN was observed.
- In general, the volatile PN fraction for the HD and MD diesel vehicles were comparable, suggesting little influence of lube oil aging and oil consumption on PN emissions.

Particle Size Distribution

- For both fresh and aged oils in the HD D NE, the total and solid distributions exhibit a similar monomodal lognormal size distribution structure that consists of an accumulation mode. The accumulation mode peaks between 50 nm and 70 nm, similar to what was observed with the MD NE.
- For the HD D HM, the total and solid particle size distributions were very similar to that for the HD D NE.
- No notable differences in the size distributions were observed between the fresh oil and aged oil, the cold-start and hot-start, or the NE and HM.

HD Diesel PM Apportionment

- Calculations for oil consumption rates for the heavy-duty diesel fueled vehicles varied considerably due to variations in measured levels of oil derived elements in the PM. Variations occurred between the two analysis techniques (XRF or ICP-MS) and between samples from the two oils tested with each of the two vehicles. Calculated oil consumption rates were more consistent for a single oil tested in both vehicles than for both oils tested in a single vehicle.
- Despite higher concentrations of wear elements in the aged oil, the PM from the fresh oil tests had higher emission rates of the wear elements than from tests with the aged oil.
- TOR analyses showed a higher fraction of the HM PM to be OC (18 percent) compared to the NE PM (14 percent). These percentages were generally lower than those obtained for the medium-duty diesel vehicles (22 and 29 percent).
- Total PM carbon determined by TOR analysis was observed to be higher than the measured PM emission rate for both vehicles.
- Three methods were utilized to calculate unburned oil in the PM. All three methods gave unburned oil rates similar to the OC rates for the NE tests with fresh oil, but none gave similar results for the NE with aged oil. All three methods gave oil consumption rates lower than the OC rates for both fresh and aged oil tests with the HM, indicating the possibility of fuel derived compounds in the PM at more significant levels than in previous medium-duty or natural gas-fueled heavy-duty vehicle tests.
- The unburned oil is estimated to be 89 percent of the OC for the NE, but only 62 percent for the HM.
- The HM had higher PM PAH emission rates than the NE (0.69 mg/mi vs 0.40 mg/mi), also indicating more fuel derived combustion products in the HM PM. Also, alkanes in the fuel range size (C_{12} to C_{19}) made up a larger fraction of the total PM alkanes in the case of the HM (38 percent) compared to the NE (30 percent).

11.0 FUTURE WORK

Follow-up studies should assess the methods of PM allocations used in this study on vehicles representing the diverse spectrum between normal emitters and high emitters, and estimate the precision of the allocations obtained by running multiple analyses. Vehicles should be tested with fuels without a UCM of alkanes, or without hopanes and steranes, in order to help clarify the potential confounding (or lack thereof) when markers are parented by both fuel and lubricant. Studies should be conducted to understand the relative frequency of various types and intensities of 'high emitters' to facilitate modeling of the on-road vehicle fleet.

Future work could consider testing emissions from diesel vehicles equipped with normally-functioning particle filters to determine if this type of aftertreatment system produces similar results. Also, it would be informative to utilize the latest engine and emissions system hardware for all the vehicles to determine if the considerable efforts by regulators and OEMs have impacted PM levels. Noting that aged lubricants sometimes produces less PM than fresh oil, it would be interesting to investigate the effects of base oil volatility and type (i.e., mineral-based verses synthetic) on PM and SVOC formation.

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APPENDIX A

HEXATRIACONTANE TRACER BLENDING PROTOCOL

Protocol For Deuterated N-Alkane Handling, Storage, and Mixing

5/14/07 Rev0 MED/DH

Readme:

I followed the SOP below and I have the following notes to make. I found that heating the oil on the hotplate did a very good job of dissolving the n-alkane. I would consider it an essential, not optional step. A stir bar was used but I found that a large stir bar (18" long) worked even better since the oil is so viscous, especially when cool. Use both stir methods if you have them. Also, I was able to transfer the relatively hot beaker of oil to a large container by myself, but I think it's a job best suited for two people (one to hold the funnel, one to pour).

- Dave Hardie

Objective:

Completely dissolve 100 g of deuterated n-alkane tracer in 20 quarts of motor oil, contained in a 6 gallon fuel/oil container with no contamination of the container, laboratory facilities, clothing, or skin with the tracer.

Equipment:

- 6 gallon or larger plastic fuel/oil container with sealing pour spout
- Two 5-liter Pyrex beakers
- Large glass or plastic funnel with a large bore neck for transferring oil from beaker to 6 gallon container
- 20 quarts of lube oil (Mobil/Exxon 15W40 for diesel engines, classification CH4 or better, meeting EGR engine requirements)
- Magnetic stirrer/hotplate
- Large magnetic stirring bar (~2-3")
- Magnetic stir bar retrieval rod (long enough to retrieve stirrer from 5L beaker)
- Tyvek coveralls
- Latex gloves
- Plastic garbage bags for (1) discarded Kimwipes, Tyvek coveralls, tracer vials, and gloves, and (2) 20 empty quart containers of oil.
- 2 vials (50 g each) of deuterated hexatriacontane powder delivered from DRI

Overview:

The deuterated tracer (n-hexatriacontane, 100g) is to be dissolved in a total of 20 quarts of oil. This tracer was delivered in two separate vials, each containing 50 g of compound as a white powder. The dissolving of this material will be done in 4 batches of 4 quarts each, with the remaining oil used to rinse down the equipment used to dissolve and transfer each batch to the 6 gallon container. A second beaker is used to hold the stir bar and retrieval rod between batches. Latex gloves and Tyvek coveralls will be worn while conducting these steps. Bottles in which the oil was delivered, as well as the tracer vials, coveralls, and gloves will be discarded in a sealed plastic bag to prevent subsequent accidental contamination of lab facilities, hands, and clothing.

Other than ordinary laboratory procedures to prevent spillage, the only special care required is avoiding any traces of the deuterated alkane or alkane-containing oil on the outside of the 6 gallon container, clothing, hands, or lab equipment. Glassware should be clean and dry, but no special cleaning procedures are needed.

Note: This protocol assumes that the new motor oil being used is obtained in 1-quart plastic bottles. If delivered in larger packages (e.g. 1-gallon), then one additional 1-liter or 1.5-liter beaker can be used to measure and transfer the desired amounts of oil from the large container to the 5-liter beakers. It is not necessary that the tracer be uniformly dissolved through the entire 20 quarts in the 6 gallon container, as it will be thoroughly mixed when added to the engine.

Procedure:

1. N- hexatriacontane-d74 is packed in two separate vials; each contains 50 g of this compound. They should be kept in a safe and clean place, no need to refrigerate.
2. Before handling the tracer, assemble all needed equipment. Label the 6 gallon container using an indelible marker and/or tied-on tag "*15W40 diesel lube oil with alkane tracer,*" and put on Tyvek coveralls and gloves.
3. Open the 6 gallon container and insert the funnel, being sure that it is sufficiently vertical to allow oil to be poured into the container without the funnel overflowing.
4. Place the 5 L beaker on the hotplate and place the stir bar in it.

<u>Batch 1</u>

5. Add 2 quarts of oil to the beaker.
6. Carefully add approximately half of one vial of tracer to the beaker, being careful not to allow the light powder to become airborne.
7. Add another 2 quarts of oil to the beaker, and turn on the stirrer to dissolve the tracer. The tracer should dissolve fairly readily. The oil may be heated slightly to accelerate this process.
8. When dissolved, turn off the stirrer (and hotplate if used) and use the rod to retrieve the stirrer. Transfer the stirrer and rod to the other 5 L beaker, avoiding dripping oil on any surfaces.
9. Check gloves to be sure they do not have oil on the palms or fingertips making them slippery. If so, remove and discard them in the plastic bag, turning them inside out, and put on fresh gloves. Pour the oil from the beaker into the 6 gallon container, carefully avoiding overflowing the funnel and any drips. After pouring, if necessary, Kimwipes can be used to remove small amounts of oil on the beaker pour spout to prevent drips. These should be immediately discarded in the plastic bag, and not placed on laboratory surfaces.

Batch 2

10. Repeat steps 5 through 9 using the second half of the tracer in the first vial and another 4 quarts of oil (quarts 5 to 8).

Batch 3

11. Repeat steps 5 through 9 using the first half of the second vial of tracer and another 4 quarts of oil (quarts 9 to 12).

Batch 4

12. Repeat steps 5 through 9 using the remainder of the tracer and another 4 quarts of oil (quarts 13 to 16).

Rinsing Equipment to Capture Remaining Tracer

13. Set aside the hotplate/stirrer.
14. Add ½ quart of oil to the beaker used for mixing, pouring oil down the sides of the beaker to rinse down the tracer-containing oil (quart 17).
15. Pour the rinse oil from the beaker into the 6 gallon container.
16. Repeat steps 14 and 15 three times, using ½ quart of oil each time (quarts 17 and 18).
17. Use 1 quart of oil to rinse the tracer containing oil off of the stir bar and retrieval rod by holding the retrieval rod with stir bar attached over the second beaker so the stir bar is approximately 3 inches above the bottom of the beaker. Slowly pour the oil down the side of the rod so that it coats and rinses the rod and stir bar. Do not let the stir bar come in contact with the rinse oil in the bottom of the beaker. (quart 19)
18. Transfer the stir bar and retrieval rod to the beaker used for mixing tracer.
19. Pour the rinse oil from the rod and stirrer into the 6 gallon container.
20. Rinse the beaker with ½ quart of oil, pouring down the sides to wash down tracer containing oil, and pour into the 6 gallon container (quart 20).
21. Repeat step 20 with the last ½ quart of oil (quart 20).
22. Remove the funnel from the container and place in one of the beakers.
23. If any tracer-containing oil is on the gloves, remove the gloves (turning inside out, and discarding in the garbage bag), and put on fresh gloves.
24. Replace the filler cap on the 6 gallon container.
25. Discard tracer vials in the plastic garbage bag.
26. Discard the empty oil bottles in the other plastic garbage bag(s) and seal with a twist tie.
27. Clean the funnel, stir bar, retrieval rod and beakers using your standard laboratory procedures for organics.
28. Remove the gloves, turning them inside-out, and discard in the plastic bag.
29. Remove the Tyvek coveralls, turning them inside-out, discard in the plastic bag, and seal the plastic bag.
30. If not immediately being taken to the field, store the 6 gallon container in a secure area.

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End

APPENDIX B

TWO COLD CO FUELS ANALYSES RESULTS

TABLE B1. HYDROCARBON SPECIATION RESULTS OF TWO COLD CO FUELS

		Original COLD CO Fuel	New Cold CO Fuel		
		EM-5574-F	EM-6802-F	Original - New	Original / New
Group	Component	%Vol	%Vol	Difference, %	Ratio
Paraffin	Propane	0.014	0.004	0.01	3.5
Paraffin	n-Butane	0.528	2.422	-1.89	0.2
Paraffin	n-Pentane	5.841	5.173	0.67	1.1
Paraffin	n-Hexane	2.338	2.113	0.23	1.1
Paraffin	n-Heptane	0.918	0.875	0.04	1.0
Paraffin	n-Octane	0.287	0.314	-0.03	0.9
Paraffin	n-Nonane	0.834	0.787	0.05	1.1
Paraffin	n-Decane	1.218	1.093	0.13	1.1
Paraffin	n-Undecane	0.269	0.093	0.18	2.9
Paraffin	n-Dodecane	0.006	0.008	0.00	0.8
Paraffin	n-Tridecane	0	0.003	0.00	0.0
I-Paraffins	i-Butane	2.959	4.022	-1.06	0.7
I-Paraffins	2,2-Dimethylpropane	0.13	0.081	0.05	1.6
I-Paraffins	i-Pentane	20.161	17.194	2.97	1.2
I-Paraffins	2,2-Dimethylbutane	0.486	0.401	0.09	1.2
I-Paraffins	2,3-Dimethylbutane	0.58	0.475	0.11	1.2
I-Paraffins	2-Methylpentane	2.379	1.994	0.39	1.2
I-Paraffins	3-Methylpentane	1.317	1.119	0.20	1.2
I-Paraffins	2,4-Dimethylpentane	0.178	0.137	0.04	1.3
I-Paraffins	2,2,3-Trimethylbutane	0.041	0.037	0.00	1.1
I-Paraffins	3,3-Dimethylpentane	0.062	0.055	0.01	1.1
I-Paraffins	2-Methylhexane	1.096	1.01	0.09	1.1
I-Paraffins	3-Methylhexane	0.575	0.516	0.06	1.1
I-Paraffins	2,2,4-Trimethylpentane	3.741	4.542	-0.80	0.8
I-Paraffins	2,2-Dimethylhexane	0.028	0.035	-0.01	0.8
I-Paraffins	2,2,3-Trimethylpentane	0.072	0.069	0.00	1.0
I-Paraffins	2,5-Dimethylhexane	0.228	0.246	-0.02	0.9
I-Paraffins	2,4-Dimethylhexane	0.188	0.189	0.00	1.0
I-Paraffins	3,3-Dimethylhexane	0.019	0.018	0.00	1.1
I-Paraffins	2,3,4-Trimethylpentane	0.249	0.207	0.04	1.2
I-Paraffins	2,3-Dimethylhexane	0.064	0.055	0.01	1.2
I-Paraffins	2-Methylheptane	0.177	0.187	-0.01	0.9
I-Paraffins	4-Methylheptane	0.069	0.068	0.00	1.0
I-Paraffins	3-Methylheptane	0.145	0.151	-0.01	1.0
I-Paraffins	3-Ethylhexane	0.103	0.113	-0.01	0.9
I-Paraffins	2,2,5-Trimethylhexane	0.023	0.016	0.01	1.4
I-Paraffins	2,4-Dimethylheptane	0.023	0.015	0.01	1.5
I-Paraffins	2,6-Dimethylheptane	0.036	0.028	0.01	1.3
I-Paraffins	2,5-Dimethylheptane	0.062	0.042	0.02	1.5
I-Paraffins	3,5-Dimethylheptane	0.018	0.011	0.01	1.6
I-Paraffins	2,3-Dimethylheptane	0.042	0.022	0.02	1.9
I-Paraffins	3,5-Dimethylheptane	0.023	0	0.02	NA

		Original COLD CO Fuel	New Cold CO Fuel		
		EM-5574-F	EM-6802-F	Original - New	Original / New
Group	**Component**	**%Vol**	**%Vol**	**Difference, %**	**Ratio**
I-Paraffins	4-Ethylheptane	0.014	0.008	0.01	1.8
I-Paraffins	4-Methyloctane	0.101	0.052	0.05	1.9
I-Paraffins	2-Methyloctane	0.146	0.076	0.07	1.9
I-Paraffins	Heptane, 3-ethyl-	0.026	0	0.03	NA
I-Paraffins	3-Methyloctane	0.172	0.116	0.06	1.5
I-Paraffins	C10 - IsoParaffin - 1	0.013	0.006	0.01	2.2
I-Paraffins	2,2,4-trimethylheptane	0.073	0.092	-0.02	0.8
I-Paraffins	C10-isoparaffin-x	0	0	0.00	NA
I-Paraffins	2,3-Dimethyloctane	0.058	0.087	-0.03	0.7
I-Paraffins	2,2-Dimethyloctane	0.097	0.094	0.00	1.0
I-Paraffins	2,5-Dimethyloctane	0.142	0.15	-0.01	0.9
I-Paraffins	2,7-Dimethyloctane	0.057	0.053	0.00	1.1
I-Paraffins	2,4-Dimethyloctane	0.046	0.069	-0.02	0.7
I-Paraffins	2,6-Dimethyloctane	0.179	0.215	-0.04	0.8
I-Paraffins	C10 Isoparaffin -1	0.047	0.054	-0.01	0.9
I-Paraffins	3-Methyl-5-ethylheptane	0.067	0.123	-0.06	0.5
I-Paraffins	5-Methylnonane	0.148	0.177	-0.03	0.8
I-Paraffins	4-Methylnonane	0.25	0.245	0.01	1.0
I-Paraffins	2-Methylnonane	0.283	0.24	0.04	1.2
I-Paraffins	3-Ethyloctane	0.049	0.061	-0.01	0.8
I-Paraffins	3-Methylnonane	0.286	0.273	0.01	1.0
I-Paraffins	Heptane, 2,2,3,5-tetramethyl-	0.03	0.053	-0.02	0.6
I-Paraffins	C11-Isoparaffin-2	0.039	0.043	0.00	0.9
I-Paraffins	C10 - IsoParaffin - 5	0.045	0.075	-0.03	0.6
I-Paraffins	2,3,3-trimethyloctane	0.026	0.046	-0.02	0.6
I-Paraffins	C11-Isoparaffin-3	0.022	0.033	-0.01	0.7
I-Paraffins	C11 Isoparaffin-4	0.075	0.079	0.00	0.9
I-Paraffins	C11-Isoparaffin-5	0.184	0.209	-0.03	0.9
I-Paraffins	3-Ethylnonane	0.095	0.059	0.04	1.6
I-Paraffins	C11-Isoparaffin-6	0	0.035	-0.04	0.0
I-Paraffins	C11-Isoparaffin-7	0.099	0.113	-0.01	0.9
I-Paraffins	C11-Isoparaffin-8	0.045	0.039	0.01	1.2
I-Paraffins	C11-Isoparaffin-9	0.032	0.036	0.00	0.9
I-Paraffins	C11- Isoparaffin-11	0.11	0.063	0.05	1.7
I-Paraffins	C11- IsoParaffin - 13	0.13	0.057	0.07	2.3
	C12 - IsoParaffin - 1	0.009	0	0.01	NA
Mono-Aromatics	C12 - IsoParaffin - 2	0	0.004	0.00	0.0
Mono-Aromatics	C12 - IsoParaffin - 4	0	0.006	-0.01	0.0
Mono-Aromatics	Benzene	0.491	0.611	-0.12	0.8
Mono-Aromatics	Toluene	11.942	16.076	-4.13	0.7
Mono-Aromatics	Ethylbenzene	0.058	0.035	0.02	1.7
Mono-Aromatics	m-Xylene	0.171	0.186	-0.02	0.9
Mono-Aromatics	p-Xylene	0.06	0.06	0.00	1.0
Mono-Aromatics	o-Xylene	0.178	0.05	0.13	3.6

		Original COLD CO Fuel	New Cold CO Fuel		
		EM-5574-F	EM-6802-F	Original - New	Original / New
Group	**Component**	**%Vol**	**%Vol**	**Difference, %**	**Ratio**
Mono-Aromatics	i-Propylbenzene	0.103	0.021	0.08	4.9
Mono-Aromatics	n-Propylbenzene	0.744	0.695	0.05	1.1
Mono-Aromatics	1-Methyl-3-ethylbenzene	2.598	2.385	0.21	1.1
Mono-Aromatics	1-Methyl-4-ethylbenzene	1.198	1.112	0.09	1.1
Mono-Aromatics	1,3,5-Trimethylbenzene	1.411	1.438	-0.03	1.0
Mono-Aromatics	1-Methyl-2-ethylbenzene	1.066	0.735	0.33	1.5
Mono-Aromatics	1,2,4-Trimethylbenzene	4.311	3.419	0.89	1.3
Mono-Aromatics	i-Butylbenzene	0.09	0.093	0.00	1.0
Mono-Aromatics	1,2,3-Trimethylbenzene	0.984	0.531	0.45	1.9
Mono-Aromatics	1-Methyl-3-i-propylbenzene	0.038	0.024	0.01	1.6
Mono-Aromatics	1-Methyl-4-i-propylbenzene	0.019	0.018	0.00	1.1
Mono-Aromatics	1,3-Diethylbenzene	0.159	0.087	0.07	1.8
Mono-Aromatics	1-Methyl-3-n-propylbenzene	0.402	0.254	0.15	1.6
Mono-Aromatics	1-Methyl-4-n-propylbenzene	0.265	0.126	0.14	2.1
Mono-Aromatics	n-Butylbenzene	0.047	0.044	0.00	1.1
Mono-Aromatics	1,3-Dimethyl-5-ethylbenzene	0.475	0.187	0.29	2.5
Mono-Aromatics	1,2-Diethylbenzene	0.045	0.026	0.02	1.7
Mono-Aromatics	1-Methyl-2-n-propylbenzene	0.173	0.098	0.08	1.8
Mono-Aromatics	C9 - Aromatic - 1	0.086	0.051	0.04	1.7
Mono-Aromatics	1,4,Dimethyl-2-ethylbenzene	0.442	0.171	0.27	2.6
Mono-Aromatics	1,3-Dimethyl-4-ethylbenzene	0.448	0.205	0.24	2.2
Mono-Aromatics	1,2-Dimethyl-4-ethylbenzene	1.085	0.436	0.65	2.5
Mono-Aromatics	1,3-Dimethyl-2-ethylbenzene	0.06	0.033	0.03	1.8
Mono-Aromatics	1-Methyl-4-t-butylbenzene	0.013	0.035	-0.02	0.4
	1-Ethyl-3-i-propylbenzene	0.008	0	0.01	NA
Mono-Aromatics	1,2-Dimethyl-3-ethylbenzene	0.127	0.141	-0.01	0.9
Mono-Aromatics	1-Ethyl-4-i-propylbenzene	0.015	0.014	0.00	1.1
Mono-Aromatics	C11 - Aromatic - 1	0.009	0.014	-0.01	0.6
Mono-Aromatics	1,2,4,5-Tetramethylbenzene	0.41	0.425	-0.02	1.0
Mono-Aromatics	1,2,3,5-Tetramethylbenzene	0.781	0.606	0.18	1.3
Mono-Aromatics	C11 - Aromatic - 2	0	0.002	0.00	0.0
Mono-Aromatics	C11 - Aromatic - 3	0.015	0.066	-0.05	0.2
Mono-Aromatics	1,2-Di-i-propylbenzene	0.021	0.074	-0.05	0.3
Mono-Aromatics	1-methyl-4-(1-methylpropyl)be	0.039	0.109	-0.07	0.4
Mono-Aromatics	C11 - Aromatic - 4	0	0.051	-0.05	0.0
Mono-Aromatics	n-Pentylbenzene	0.006	0.023	-0.02	0.3
Mono-Aromatics	tert-Pentylbenzene	0.034	0.11	-0.08	0.3
Mono-Aromatics	1-Methyl-2-n-butylbenzene	0.014	0.051	-0.04	0.3
Mono-Aromatics	C11 - Aromatic - 7	0.017	0.064	-0.05	0.3
Mono-Aromatics	1,4-Di-i-propylbenzene	0.027	0.095	-0.07	0.3
Mono-Aromatics	C11 - Aromatic - 9	0.294	0.131	0.16	2.2
Mono-Aromatics	C11 - Aromatic - 10	0	0.011	-0.01	0.0
Mono-Aromatics	1,3-Di-n-propylbenzene	0.027	0.067	-0.04	0.4
Mono-Aromatics	C11 - Aromatic - 11	0.016	0.038	-0.02	0.4

		Original COLD CO Fuel	**New Cold CO Fuel**		
		EM-5574-F	**EM-6802-F**	**Original - New**	**Original / New**
Group	**Component**	**%Vol**	**%Vol**	**Difference, %**	**Ratio**
Naphthalenes	1-ethyl-2,4,5-trimethylbenzen	0.014	0.02	-0.01	0.7
Naphthalenes	C11 - Aromatic - 13	0	0.003	0.00	0.0
Naphtheno/Olefino-Benzs	2-Methylnaphthalene	0	0.006	-0.01	0.0
Naphtheno/Olefino-Benzs	1-Methylnaphthalene	0	0.003	0.00	0.0
	C12 - Aromatic - 1	0.003	0	0.00	NA
Indenes	5-Methylindan	0.134	0.209	-0.08	0.6
Indenes	2-Methylindan	0.269	0.267	0.00	1.0
Indenes	Indan	0.262	0.235	0.03	1.1
Indenes	2-Methylindan	0.088	0.034	0.05	2.6
Indenes	1H-Indene, 2,3-dihydro-1,2-dim	0.012	0.007	0.01	1.7
Indenes	4-Methylindan	0.12	0.273	-0.15	0.4
Indenes	4,7-Dimethyl Indane	0.005	0.004	0.00	1.3
Mono-Naphthenes	1,1-Dimethyl Indane	0.005	0.021	-0.02	0.2
Mono-Naphthenes	Dimethyl Indane - 1	0	0.005	-0.01	0.0
Mono-Naphthenes	Cyclopentane	0.449	0.452	0.00	1.0
Mono-Naphthenes	Methylcyclopentane	1.562	1.585	-0.02	1.0
Mono-Naphthenes	Cyclohexane	1.536	1.638	-0.10	0.9
Mono-Naphthenes	1t,3-Dimethylcyclopentane	0.168	0.171	0.00	1.0
Mono-Naphthenes	1c,3-Dimethylcyclopentane	0.152	0.157	-0.01	1.0
Mono-Naphthenes	1t,2-Dimethylcyclopentane	0.268	0.271	0.00	1.0
Mono-Naphthenes	Methylcyclohexane	1.657	1.87	-0.21	0.9
Mono-Naphthenes	1,1,3-Trimethylcyclopentane	0.04	0.04	0.00	1.0
Mono-Naphthenes	Ethylcyclopentane	0.055	0.06	-0.01	0.9
Mono-Naphthenes	1c,2t,4-Trimethylcyclopentane	0.038	0.038	0.00	1.0
Mono-Naphthenes	1t,2c,3-Trimethylcyclopentane	0.03	0.029	0.00	1.0
Mono-Naphthenes	1,3-dimethyl-t-cyclohexane	0.164	0.183	-0.02	0.9
Mono-Naphthenes	1,1-Dimethylcyclohexane	0.042	0.038	0.00	1.1
Mono-Naphthenes	3c-Ethylmethylcyclopentane	0.01	0.008	0.00	1.3
Mono-Naphthenes	3t-Ethylmethylcyclopentane	0.014	0.011	0.00	1.3
Mono-Naphthenes	1c,4-Dimethylcyclohexane	0.045	0.044	0.00	1.0
Mono-Naphthenes	1c,2-Dimethylcyclohexane	0.02	0.012	0.01	1.7
Mono-Naphthenes	Ethylcyclohexane	0.121	0.096	0.03	1.3
Mono-Naphthenes	1c,2t,4t-Trimethylcyclohexane	0.062	0.032	0.03	1.9
Mono-Naphthenes	C9 - MonoNaph - 4	0.016	0.007	0.01	2.3
Mono-Naphthenes	1c,2t,4c-Trimethylcyclohexane	0.014	0.012	0.00	1.2
Mono-Naphthenes	Cyclohexane, 1,2,4-trimethyl-,	0.02	0.02	0.00	1.0
Mono-Naphthenes	Cyclopentane, 1-methyl-2-propyl-	0.017	0.032	-0.02	0.5
Mono-Naphthenes	trans-1,3-Diethylcyclopentane	0.1	0.119	-0.02	0.8
Mono-Naphthenes	C10 - MonoNaph - 1	0	0.005	-0.01	0.0
Mono-Naphthenes	1,1-Methylethylcyclohexane	0.078	0.136	-0.06	0.6
Mono-Naphthenes	1-Methyl-2-propyl-cyclopentan	0.005	0.008	0.00	0.6

		Original COLD CO Fuel	New Cold CO Fuel		
		EM-5574-F	EM-6802-F	Original - New	Original / New
Group	**Component**	**%Vol**	**%Vol**	**Difference, %**	**Ratio**
Mono-Naphthenes	1,2,3,5-t-Tetramethylcyclohex	0.141	0.198	-0.06	0.7
Mono-Naphthenes	1,2,3,5-c-Tetramethylcyclohex	0	0.025	-0.03	0.0
Mono-Naphthenes	i-Butylcyclohexane	0.075	0.107	-0.03	0.7
Mono-Naphthenes	C10 - MonoNaph - 2	0.024	0.034	-0.01	0.7
Mono-Naphthenes	1t-Methyl-2-n-propylcyclohexan	0	0.017	-0.02	0.0
n-Olefins	n-ButylCyclohexane	0.076	0.1	-0.02	0.8
n-Olefins	C11-MonoNaphthene-2	0.021	0.008	0.01	2.6
	t-Butene-2	0.003	0	0.00	NA
	c-Butene-2	0.004	0	0.00	NA
	Pentene-1	0.004	0	0.00	NA
	t-Pentene-2	0.012	0	0.01	NA
	c-Pentene-2	0.006	0	0.01	NA
n-Olefins	Hexene-1	2.812	4.587	-1.78	0.6
n-Olefins	t-Nonene-3	0	0.013	-0.01	0.0
Iso-Olefins	C10-n-Olefin	0.02	0.031	-0.01	0.6
Iso-Olefins	3-Decene	0.009	0.018	-0.01	0.5
	5-Undecene	0.007	0	0.01	NA
Iso-Olefins	3-Methyl-c-pentene-2	0	0.008	-0.01	0.0
	2-Methylbutene-1	0.008	0	0.01	NA
	2-Methylbutene-2	0.017	0	0.02	NA
Iso-Olefins	3-Methyl-t-hexene-2	5.403	4.294	1.11	1.3
Iso-Olefins	C8 - Diolefin - 1	0.012	0.011	0.00	1.1
Iso-Olefins	3-Heptene, 4-methyl-	0.069	0.073	0.00	0.9
Iso-Olefins	C9 - IsoOlefin - 1	0.012	0.009	0.00	1.3
Iso-Olefins	2,3-Dimethylheptene-2	0.016	0.023	-0.01	0.7
Iso-Olefins	C10 - IsoOlefin - 2	0.039	0.054	-0.02	0.7
Iso-Olefins	C10-IsoOlefin-4	0.006	0.009	0.00	0.7
Iso-Olefins	C10 Iso-olefin - 5	0.023	0.062	-0.04	0.4
Iso-Olefins	C10 Iso-olefin - 6	0.017	0.025	-0.01	0.7
Iso-Olefins	C10-IsoOlefin-7	0.053	0.076	-0.02	0.7
Iso-Olefins	C10 - IsoOlefin - 8	0	0.021	-0.02	0.0
Iso-Olefins	2,3-Dimethyl-2-octene	0.013	0.03	-0.02	0.4
Iso-Olefins	C10-IsoOlefin-12	0.043	0.08	-0.04	0.5
Naphtheno-Olefins	C10-IsoOlefin -15	0.101	0.128	-0.03	0.8
Naphtheno-Olefins	3-Nonene, 3-methyl-, (E)-	0.014	0.03	-0.02	0.5
Naphtheno-Olefins	C8 - Naph-Olefin - 1	1.368	1.047	0.32	1.3
	1-Ethyl-2-Methylcyclopentene	0.036	0.02	0.02	1.8
	C9-NaphthenoOlefin-6	0	0	0.00	NA

APPENDIX C

LUBRIZOL LETTER REPORT
LIGHT-DUTY HIGH PM EMISSIONS VEHICLE

June 9, 2008

Mr. Lew Williams
The Lubrizol Corporation
29400 Lakeland Blvd.
Wickliffe, OH 44092-2298
lewis.williams@lubrizol.com

Ref: Letter Report, "Selecting the High Smoke Emissions Vehicles,"
SwRI Project No. 03-11309.

Dear Mr. Williams:

The location, selection process for the candidate vehicles, and final decision to pick the ‘high-emitting’ gasoline vehicle were performed by SwRI and approved in consultation with the members of the CLOSE and AVFL-14 projects. SwRI’s criteria for high-emitting vehicle was not based on make, model, type of owner, mileage, or any other a priori assumptions regarding the likelihood of any specific type of vehicle being a good candidate. With decades of emission regulations in place, and manufacturers producing extremely durable engine and exhaust control systems, SwRI recognizes that ‘smoking’ vehicles are not the norm in the existing fleet of operational vehicles; therefore, any vehicle selected is atypical.

1.0 BACKGROUND

According to the proposed scope of work the high-emitting gasoline vehicle was defined as “a gasoline-fueled vehicle with visible smoke related to lubrication oil. The RFP requests a PM emission rate greater than 200 mg/mi over the Unified Driving Cycle (UDC). In SwRI’s experience, vehicles that continually and consistently emit “white” smoke related to lubricating oil typically have PM emission rates well above this value (Whitney 2000, 1998). This vehicle will likely be solicited from SwRI employees, families, and friends. Candidate vehicles will be screened for visual indication of consistent “white” smoke emissions during a variety of driving conditions. Although the RFP states that there is no restriction on vehicle age or mileage, consideration will be given to the representativeness of the vehicle, as well as its ability to be safely and repeatably tested on a chassis dynamometer.”

2.0 SOLICITATION

The following notice was sent by email to all SwRI employees:

WANTED: Smoking Car

A project in the Office of Automotive Engineering requires a test car that emits visible smoke during all running conditions and needs frequent oil fills. Cars, half-ton pickups, and SUVs could be utilized. The vehicle should be in otherwise sound mechanical condition and driven regularly. We will pay the owner $500 plus provide an intermediate-size rental car for approximately 10 weeks. If you know of such a car and we choose to use it, a finder's fee of $100 is available. Contact Jim Carroll at 522-5015 or (mailto:jcarroll@swri.org).

3.0 RESPONSES AND SELECTION PROCESS

SwRI received 22 responses to the email solicitation. SwRI used the following selection criteria in generally descending order of importance to pick the high emitting test vehicle:

1. Visible smoke upon hot start, at idle, during acceleration, and at steady speed.
2. Relatively modern emission control system, i.e. equipped with exhaust catalyst, closed-loop control, fuel injection.
3. Automatic transmission.
4. Stock engine, exhaust system, and drivetrain.
5. Driven regularly.
6. Fully operational drivetrain and brake system.
7. No external engine oil leaks.
8. None or easily repairable engine codes.
9. Owner had good knowledge of vehicle history.
10. Known high oil consumption.

List of responses received and reasons for rejection of candidates:

1998 Saturn SE2 Coupe – could not connect an ECM reader to the wiring harness without the horn on the vehicle blowing, symptom of wiring harness degradation or ECM problem.

1988 Chevrolet Caprice – owned for just two weeks, not driven, fouled plugs within two weeks.

1988 Chevrolet Camaro IROC – owner unresponsive.

1995 Mitsubishi Eagle Talon – standard transmission.

1963 Ford Fairlane – too old, produced prior to emissions controls.

1993 Toyota Tercel – standard transmission.

1995 Acura Integra – engine rebuilt once to high output configuration, then put back to original configuration. Not ‘stock.’

1986 Chevrolet truck – no catalyst.

1994 Jeep Grand Cherokee – no catalyst.

1995 Mitsubishi Eclipse – standard transmission.

1995 Mitsubishi Eagle Talon – aftermarket performance exhaust and intake system, standard transmission.

1995 Nissan 240SX – smoke visible upon acceleration only, no smoke at idle, startup, or at steady speed. Some oil seepage around head cover gasket.

1994 Mercury Cougar – owner unresponsive.

1998 Pontiac Gran Prix – some smoke at start, but not enough during steady-state operation.

1993 Mazda Protégé – standard transmission.

1998 Mitsubishi Montero – standard transmission

1999 Dodge Neon – initially thought to be a good candidate, but found oil leaks at head cover gasket and crankshaft main seal; also the engine had a mechanical knock.

1991 Acura – coolant leak, brakes unsafe, transmission shifted poorly, the engine shuddered. Best candidate for recycling.

1990 Honda Accord – no smoke at idle, not enough smoke during acceleration.

1999 Dodge Durango – smoke visible at idle only.

1990 Honda Accord – smoked if engine was revved, otherwise there was no smoke visible.

4.0 RECOMMENDED VEHICLE

1993 Mercury Grand Marquis

- Visible smoke upon hot and cold starts, at idle, during acceleration, and at steady speeds.
- Relatively modern emission control system.
- Automatic transmission.
- Stock engine, exhaust system, and drivetrain.
- Driven weekly.
- Fully operational drivetrain and brake system.
- No external engine oil leaks.
- Engine code set was traced to EGR system. EGR lines were cleaned and controls were replaced. Codes were cleared and have not re-set since.
- Owner had knowledge of complete vehicle history.

The owners indicated that at approximately 30,000 miles they took it to the dealer due to what they believed was excessive oil consumption. The dealer conducted an oil consumption test and determined it to be approximately 1 quart every 1,200 miles. The dealer assured the owners that this was within normal specifications and that there was no problem with the vehicle. The owners noticed visible smoke at approximately 50,000 miles, and it has gotten progressively worse over the years.

The vehicle has approximately 125,000 miles on the odometer and emits visible "blue" smoke during both cold and warm conditions. A set of preliminary four-phase Unified Cycle tests were conducted to evaluate the repeatability of this vehicle. Composite and phase-level particulate emission results are given in Table 1. Composite gaseous emission results are given in Table 2. These results indicate the test vehicle has relatively repeatable emissions and should meet the needs of this project.

TABLE 1. FOUR-PHASE UNIFIED CYCLE PM EMISSION RATE, MG/MI

	Phase 1	Phase 2	Phase 3	Phase 4	Composite
Test 1	31.2	77.3	133.6	130.3	101.1
Test 2	41.4	79.5	133.9	142.9	108.3
Test 3	35.8	61.7	156.7	118.8	91.0

TABLE 2. COMPOSITE UNIFIED CYCLE PM EMISSION RATE, G/MI

	THC	CO	NO_X
Test 1	0.55	6.6	1.7
Test 2	0.70	8.1	1.7
Test 3	0.66	7.3	1.7

Due to concern regarding the failure mode of the this high PM emitter that SwRI recommended for testing, an effort was undertaken to evaluate and document the mechanical status of the vehicle as regards oil consumption. Evaluations included the following:

- Spark plugs were removed, inspected, and photographed.
- Each cylinder piston top, cylinder wall, and cylinder head was inspected and rated by borescope.
- A compression and leak down check was performed on each cylinder.
- Oil consumption was determined gravimetrically over 300 miles of highway operation.
- The vehicle owner was contacted in an effort to get more detailed information regarding observed oil consumption for this vehicle.

Figures 1 through 8 are photographs of the spark plugs pulled from the vehicle's engine. The numbering convention is cylinders/plugs 1-4 are front-to-back from the right cylinder bank if viewed from the driver, and plugs 5-8 are the left cylinder bank. The plugs did not appear to be fouled; they are dry, and some show electrode loss and unidentified white deposits.

Figure 1. Spark Plug 1

Figure 2. Spark Plug 2

Figure 3. Spark Plug 3

Figure 4. Spark Plug 4

Figure 5. Spark Plug 5

Figure 6. Spark Plug 6

Figure 7. Spark Plug 7

Figure 8. Spark Plug 8

The results from the cylinder compression check, and leak down tests are shown in Tables 3, and 4, respectively. The compression test variation is good (within 10%) on the right bank but poor on the left bank. Cylinder leak down results are poor to bad (5-10% is good). The cylinders showed no sign of bore polishing or scuffing during the borescope inspection.

TABLE 3. CYLINDER COMPRESSION TEST

Right Cylinder Bank		Left Cylinder Bank	
Cyl 1	130 psi	Cyl 5	110 psi
Cyl 2	140 psi	Cyl 6	140 psi
Cyl 3	130 psi	Cyl 7	150 psi
Cyl 4	130 psi	Cyl 8	130 psi

TABLE 4. CYLINDER LEAK DOWN TEST

Right Cylinder Bank		Left Cylinder Bank	
Cyl 1	14%	Cyl 5	28%
Cyl 2	24%	Cyl 6	28%
Cyl 3	18%	Cyl 7	14%
Cyl 4	36% (Checked 2 times)	Cyl 8	38% (Checked 2 times)

SwRI completed the 300 mile oil consumption test. On 3/3/08, the vehicle was filled with the a preweighed amount of test oil and a new preweighed oil filter. The vehicle was operated for 457 miles. This included the 150 miles of highway driving at 65 to 70 mph, plus the chassis dyno testing presented in Tables 1 and 2. The oil consumption for the 457 miles was 2.37 lbs of oil. On 4/21/08, the oil and used oil filter were drained and the weights recorded. The used oil and the used filter were reinstalled and the vehicle underwent another accumulation interval of 300 miles on the highway at 65 to 70 mph. On 4/24/08 the used oil and used filter were drained and the weights recorded. The oil consumption for the 300 miles was 1.85 lbs of oil.

Using a density of 1.8 lb per quart of oil, the average oil consumption on the candidate smoking vehicle equates to 319 miles per quart. This is consistent with what was reported by the owner who stated that he has been adding 1 quart about every 300 miles.

5.0 CLOSURE

Following the completion of the smoking vehicle evaluation, all data was presented to the CLOSE/AVFL-14 team. The team recommended the use of the high emitting vehicle for the project. It is clear that this particular vehicle is atypical and not representative of this or any other make or model of on-highway high-mileage vehicle.

Submitted by:	Reviewed by:
James N. Carroll Principal Engineer Department of Emissions R&D	Kevin A. Whitney Manager Department of Emissions R&D

Approved by:

Jeff J. White
Director
Department of Emissions R&D

/sat

APPENDIX D

DESERT RESEARCH INSTITUTE REPORT ON RENO FUELS

TABLE D1. HOPANES AND STERANES IN FUELS FROM RENO NEVADA

	Hopanes and Steranes, ug/gram								
Reno Fuels	Chevron Diesel	Chevron Premium	Chevron Regular	Shell Diesel	Shell Premium	Shell Regular	Texaco Diesel	Texaco Premium	Texaco Regular
hop15	0.418	0.000	0.000	0.332	0.000	0.088	0.320	0.000	0.000
hop17	0.720	0.111	0.132	0.743	0.106	0.039	0.609	0.097	0.122
hop19	0.267	0.006	0.108	0.205	0.080	0.081	0.203	0.157	0.092
hop20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
hop21	0.081	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
hop22	0.158	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
hop23	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
hop24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
hop25	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
hop26	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
hop27	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ster42	0.161	0.000	0.000	0.223	0.000	0.000	0.158	0.000	0.000
ster43	0.372	0.000	0.018	0.364	0.000	0.000	0.348	0.000	0.000
ster44	0.225	0.000	0.000	0.191	0.000	0.000	0.206	0.000	0.000
ster45_40	0.064	0.000	0.000	0.672	0.000	0.000	0.000	0.000	0.000
ster46	0.038	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ster47	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ster48	0.000	0.000	0.000	0.000	0.000	0.000	0.221	0.000	0.000
ster49	0.023	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ster50	0.000	0.000	0.000	0.000	0.000	0.000	0.031	0.000	0.000
ster51	0.064	0.000	0.000	0.057	0.000	0.007	0.041	0.000	0.000
ster52	0.022	0.000	0.000	0.044	0.000	0.039	0.000	0.000	0.000
ster53	0.108	0.005	0.000	0.065	0.055	0.017	0.088	0.007	0.000

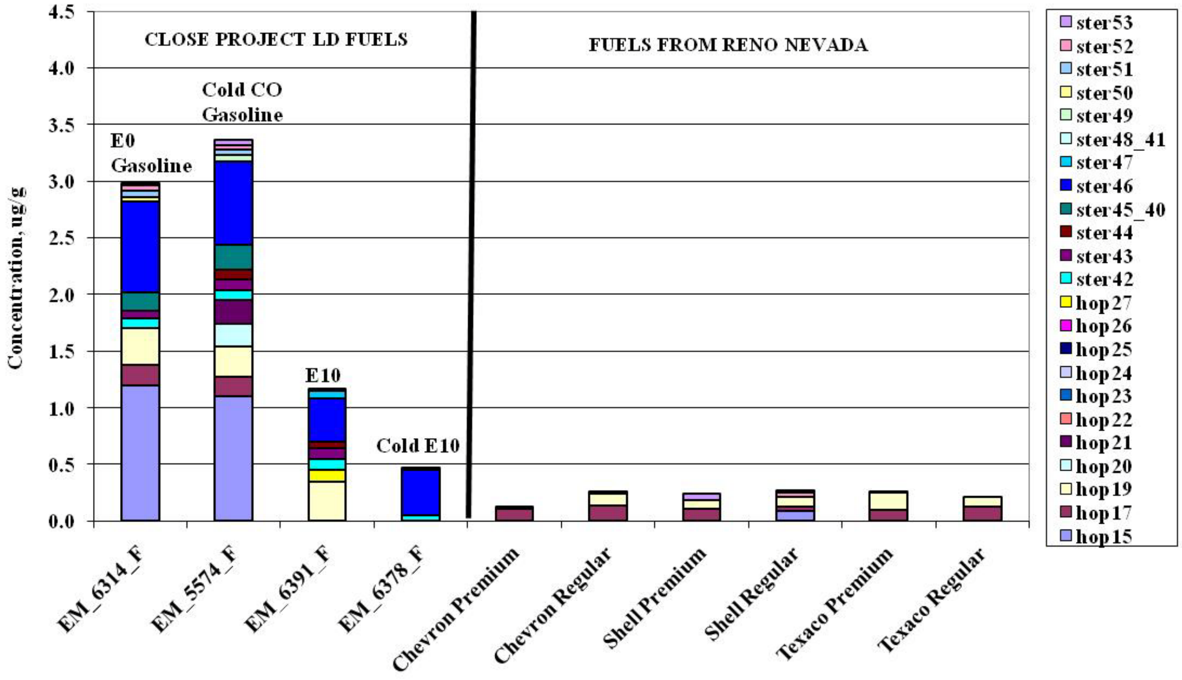

FIGURE D1. CLOSE PROJECT LIGHT-DUTY FUELS AND RENO FUELS HOPANES AND STERANES CONCENTRATIONS

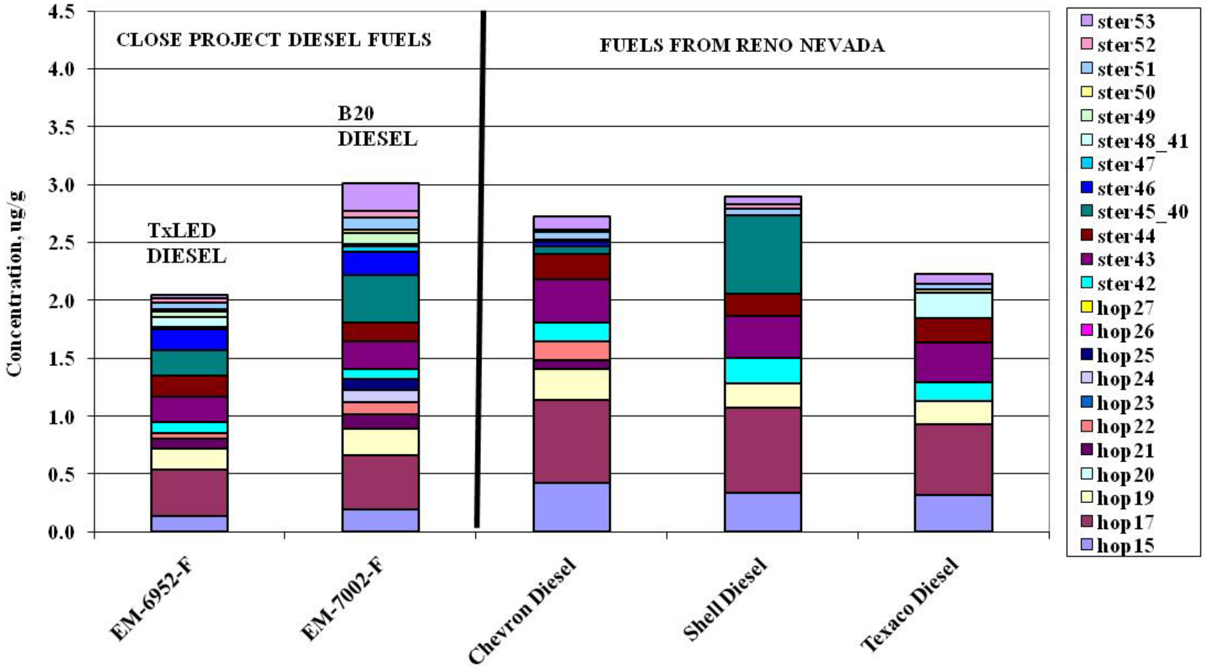

FIGURE D2. CLOSE PROJECT AND RENO DIESEL FUELS HOPANES AND STERANES CONCENTRATIONS

APPENDIX E

HEAVY-DUTY SMOKER REPORT ON CPS VEHICLES

July 16, 2009

Dr. Douglas R. Lawson
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401

Email: Doug_Lawson@nrel.gov

Subject: Heavy-Duty Diesel Candidate Vehicles for "CLOSE: Collaborative Lubricating Oil Study on Emissions"
NREL Subcontract Number AEV-7-66409-01, SwRI Project No. 03.13012

1.0 DISCUSSION

SwRI was invited to inspect heavy-duty vehicles at City Public Service (CPS) Company, which is the electrical utility in the San Antonio area. The vehicles have been released from service and can be used in the CLOSE program as heavy-duty diesel PM emission test vehicles. Table 1 contains information regarding the vehicles we inspected.

These vehicles were used as construction and repair support vehicles for CPS. All the vehicles are 1993 to 1998 models. Although many show low mileage accumulation, their engines were operated while the vehicle was at a stand still to power auxiliary systems such as lifts, winches, pumps, welders, etc. Thus the engines can have many more hours of operation than the vehicles.

During our inspection of the vehicles each one was started and allowed to come to normal operating temperature for 5 to 10 minutes but they were not driven. During warm up the engine was quickly accelerated, operated at a few steady-state no-load points, and left to idle a few times. The exhaust plume from each vehicle was watched for smoke during operation and notes are included in Table 1.

Three vehicles are candidates for use as high PM emission test vehicles. Vehicle #88153 had clean engine exhaust upon start up but as the engine warmed up smoke was released. The exhaust smelled of lubricant, rather than diesel fuel, which indicates that its fuel system is operating normally and its oil control is compromised. Vehicle #88443 smoked upon start, during accelerations, and at elevated no-load speeds while cold, but did not smoke once the engine warmed. Vehicle #52159 showed slight smoke during start up and during accelerations, but none at idle.

Table 1. Heavy-Duty Diesel Vehicle Inspections

VEHICLE NUMBER	**VEHICLE #88153 HIGH PM EMISSION TEST CANDIDATE**	**VEHICLE #88443**	**VEHICLE #52159**	**VEHICLE #88195**	**VEHICLE #98484**	**VEHICLE #52183 NORMAL PM EMISSION TEST CANDIDATE**
VEHICLE MODEL	’93 Ford F600	’98 International 4700 T444E	’94 Ford Type L90460	’96 Ford 1996 F80350	International 4700 DT 466	Ford ’94 Type L9460
VEHICLE TYPE			Tow truck			5th Wheel truck
MILEAGE	160,722 miles	39,558 miles		66,542 miles	79,843 miles	
AXLE	Single axle	Single axle	Tandem axle	Single axle	Single axle	Tandem axle
ENGINE	Ford 5.9L 403A, Model B5.9-160	Navistar Model B175F 7.3L, Family #WNVXH044FNA	8.3L Ford Model C8.3-225		Model A175 I-6 466 c.i., 175 hp	Cummins Engine
GVW, LB	23,100		45,000			45,000
VIN NUMBER	#1FDWK64C5RCA21384	#1HTSCABL5WH558209	#1FDYL90E8SVA19584	#1FDYF80E3TVA06230		#1FDYL90E3SCA19587
NOTES	Dead battery	Good puff of smoke at start.	Smoke on start, idles clean.	Clean at start, then engine died, then black on restart.	Dead battery	Clean exhaust.
	No smoke at start and low idle.	Good puff of smoke at tip in.	Slight fog at tip in.	Does not idle when cold.	Wisp of smoke at startup.	
	After warm up, there was plenty of smoke upon tip in, acceleration, and at high idle.	Slight smoke at high idle, but none at low idle.		Wisping smoke at idle “white” smoke.	Some smoke (smells of diesel fuel) on first high idle rise.	
	Smoke did not smell of diesel fuel, rather, it smelled of oil.	After extended idle, very little smoke even at tip in.		When warm, high idle exhaust was clean.	Seems to misfire on tip in.	
				Exhaust smells of fuel.	Once warm, slight smoke haze, still smells like diesel.	

Vehicles #88195 and #98484 produced exhaust with a strong diesel smell indicating a problem with their fuel systems.

2.0 TEST VEHICLE RECOMENDATIONS

Vehicle #52183 did not smoke during startup, accelerations, or at higher speed no-load operation. SwRI recommends that this vehicle be used for the normal emitter heavy-duty diesel tests.

For the high PM emitter tests, SwRI recommends that vehicle #88153 be utilized. It produced the greatest level of smoke and its exhaust did not smell of diesel fuel.

3.0 CONCLUSION

SwRI plans to test CNG fueled heavy-duty vehicles before HD diesel vehicles but has had difficulty locating them, and suspects that they may not be available by the time medium-duty vehicle testing is completed. Therefore, SwRI requests input from CLOSE project supporters regarding our recommendations for the HD diesel vehicle testing. We can then begin more detailed inspections of the vehicles in preparation for testing and move into the next phase of tests without interruption.

Sincerely:

James N. Carroll, Principal Engineer
Light-Duty Vehicle Emissions Section
Emissions Research and Development