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Investigation of lubricant oil consumption and its contribution to particulate matter emissions

Sam George
West Virginia University

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**Investigation of Lubricant Oil Consumption and its Contribution to Particulate Matter
Emissions**

Sam George

**Dissertation submitted to the College of Engineering and Mineral Resources
at West Virginia University in partial fulfillment of the requirements
for the degree of**

**Doctor of Philosophy
in
Mechanical Engineering**

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**Morgantown, West Virginia
2008**

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Organic Carbon**

ABSTRACT

Investigation of Lubricant Oil Consumption and its Contribution to Particulate Matter Emissions

Sam George

The global objective of this study was to determine lubricant oil consumption as a function of engine operating conditions, and determine its contribution to particulate matter (PM) emissions in a hydrogen-fueled engine. Hydrogen offers a promising alternative for internal combustion engines owing to its clean burning properties. The success of gaseous-fueled engines lies in the development and use of specially formulated and well researched lubricating oils as these oils are the only source of carbon emissions in hydrogen-fueled engines. The lubricant oil consumption can be determined in a hydrogen-fueled engine by measuring the carbonaceous emissions. This study determined lubricant oil consumption as a function of engine speed, equivalence ratio, and boost for hydrogen-fueled engine operation. The oil consumption data was fitted using multiple linear regression analysis. Elemental Carbon/Organic Carbon analysis, trace metals analysis, ions analysis, and particle size distributions at various steady state operating conditions were also performed to have an understanding of lubricant contribution to particulate emissions. The lubricant oil consumption was also measured using trace metal markers such as Ca and Zn. Oil consumption models would help in calculating ash accumulation in exhaust after-treatment devices like diesel particulate filters (DPF). The oil consumption was found to be well correlated to engine operating conditions. The particulate matter was found to be almost completely organic carbon, and the synthetic oil derived organic fraction was found to be lower in spite of its higher volatility for the conditions tested. It was found that the trace metal marker method for oil consumption determination was not a suitable method as a result of the different rates of consumption of base stocks versus additives. The particle size distributions in the case of hydrogen-fueled operation were found to be in the same order of magnitude as a diesel engine. The particle size distributions and number concentrations were found to be more influenced by the engine operating conditions and amount of oil consumed, and was not influenced by the difference in the oil volatility or the nature of the base stock (synthetic versus mineral) for the conditions tested in this study.

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NOMENCLATURE

bhp	Brake-horsepower
bhp-hr	Brake-horsepower-hour
BMEP	Brake Mean Effective Pressure
BTDC	Before Top Dead Center
Ca	Calcium
CA	Crank Angle
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CH ₄	Methane
CMD	Count Median Diameter
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
COV	Coefficient of Variance
DC	Direct Current
DPF	Diesel Particulate Filter
DRI	Desert Research Institute
EC/OC	Elemental Carbon/Organic Carbon
EPA	Environmental Protection Agency
ESC	European Stationary Cycle
EUDC	Extra Urban Driving Cycle
GC-FID	Gas Chromatography – Flame Ionization Detector
GSD	Geometric Standard Deviation
H ₂	Hydrogen
HC	Hydrocarbon
HFID	Heated Flame Ionization Detector
IC	Ion Chromatography
IDI	Indirect-injection
IMEP	Indicated Mean Effective Pressure
Mg	Magnesium
NDIR	Non-dispersive Infrared
NETL	National Energy Technology Laboratory
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
NO _x	Oxides of Nitrogen
O ₂	Oxygen

OC	Oxidation Catalyst
OH	Hydroxyl radical
P	Phosphorus
PAH	Polycyclic Aromatic Hydrocarbon
PM	Particulate Matter
ROHR	Rate of Heat Release
SAE	Society of Automotive Engineers
SMPS	Scanning Particle Mobility Sizer
SO ₂	Sulfur Dioxide
SOF	Soluble Organic Fraction
TAN	Total Acid Number
TBN	Total Base Number
THC	Total Hydrocarbons
ULEV	Ultra Low Emissions Vehicle
US	United States
VOC	Volatile Organic Compound
XRF	X-ray Fluorescence
ZDDP	Zinc Dialkyl- Dithio- Phosphate
Zn	Zinc

1. OBJECTIVES AND BACKGROUND

1.1. Objectives

The global objective of this study was to determine the lubricant oil consumption as a function of engine operating conditions, and its contribution to particulate matter emissions in a hydrogen fueled engine; hence, contribute to the understanding of lubricant oil consumption characteristics in general.

The activities performed towards the objective are listed below:

- i) Lubricant oil consumption was analyzed as a function of engine operating conditions, such as speed, load (equivalence ratio), and boost for hydrogen-fueled operation. The lubricant oil consumption was measured using the carbonaceous emissions measurements, details of which are provided later. The gaseous and particulate emissions were monitored as function of engine operating parameters, such as speed, equivalence ratio, and boost in the case of premixed hydrogen-air fueled operation. The in-cylinder pressure characteristics were also recorded to understand the influence of combustion parameters such as, combustion duration, maximum cylinder pressure, and start of combustion on oil consumption.
- ii) Elemental carbon/organic carbon (EC/OC) analysis, ions analysis, and trace metals analysis of engine particulate matter (PM), were performed along with the lubricant oil analysis in order to understand the composition of lubricant derived PM emissions. Simultaneous measurement of particle size distributions at the various steady state engine operating conditions were also performed to help understand the nanoparticle forming precursors in lubricant oils.
- iii) The lubricant oil consumption measured using trace metal markers was compared with that obtained using the carbon balance method. This was an attempt to check the feasibility of using trace metal markers for lubricant consumption measurement in the case of engines operating on carbon-based fuels such as diesel, gasoline, and CNG.
- iv) Particle number concentrations, size distributions, and particle surface area distributions were calculated for the various steady-state conditions tested. This helped to understand the contribution of lubricant oil consumption to nanoparticle formation. Soluble organic fraction (SOF) extracted from PM samples were analyzed for mutagenic activity in a

separate study performed simultaneously with this study. The dependence of mutagenicity effects on particle surface area distributions obtained was correlated to the findings of the mutagenicity study to determine whether any relation existed between particle size and surface distribution characteristics, and degree of mutagenicity.

- v) The effect of lubricant oil ageing on oil properties was determined by oil analyses of the test oil samples which were taken at regular intervals during the course of testing.

1.2. Background

The need for lower exhaust emissions to comply with stringent emissions regulations for heavy-duty diesel engines has led to research in alternative, non-petroleum based fuels. Engine exhaust PM is a complex mixture consisting of several compounds of which many are carcinogenic, and have been classified as toxics [1]. PM emissions have long been a major concern, and especially in light of the 2007 US Environmental Protection Agency (EPA) standard of 0.01 g/bhp-hr [2]. The soot or PM and eventually its inhalation have been reported to be mainly responsible for the carcinogenic effect.

Hydrogen is being considered as a promising alternative fuel for internal combustion engines owing to its clean burning properties resulting in reduced regulated emissions and global warming potential. The success of gaseous fueled engines lies in the development and use of specially formulated and well researched lubricating oils. The pyrolyzed oil can enter the combustion chamber through blow-by from the crankcase, through seepage past the valve guide seals, and/or from the positive crankcase ventilation system (that is, through the intake manifold).

It is well established that engines operating on gaseous fuels emit high levels of lubricant-oil derived toxic pollutants [3]. Development of advanced lubricating oils for gaseous-fueled engines should include development of specially formulated additive packages that will not poison the exhaust after-treatment systems, and help prevent pre-ignition. Understanding lubricant oil consumption as a function of engine operating conditions helps in determining the expected lubricant consumption for a given engine if its typical duty cycle is known. The knowledge of lubricant contribution to particulate matter will help in developing better lubricant formulations that would reduce particulate emissions, and also increase the durability and performance of the engine and exhaust after-treatment devices.

Studies [4-7] conducted in the past on hydrogen fueled engines have reported negligible amounts of carbonaceous emissions and high levels of NO_x emissions. Hydrogen fueled engines can suffer from many of the same drawbacks that are typical of natural gas engines. Hydrogen fueled engines can have high levels of lubricant derived nanoparticle and toxics emissions similar to CNG fueled engines. Figure 1-1 shows the results from a recent study on a Cummins C8.3G+ CNG engine (ULEV standards) powering a transit bus [3]. The use of the PM trap and oxidation catalyst (depicted as “Novel After-treatment” in the figure), which were developed by West Virginia University (WVU) and Emissions Control Systems (ECS) showed that toxic pollutants were reduced to levels comparable to those in the background. Figure 1-2 shows that the lubricant oil derived nanoparticle emissions were also reduced to background levels. However, the long term effects of lubricant oil derived products of combustion on the exhaust after-treatment systems is not very encouraging [3]. Hence, attempts have to be made to minimize the deleterious impact of lubricant oil derived products by reducing oil consumption. EC/OC analysis, trace metals analysis, and particle size distribution measurements along with lubricant oil consumption measurement with hydrogen fueled operation gives a good understanding of the lubricant derived nanoparticle and toxics emissions. Findings related to lubricant oil consumption in a hydrogen fueled engine can to a certain extent, be extended to natural gas and diesel engines as well. However, it should be noted that the composition of the manufacturer- recommended oils may be different for different engines, especially diesel fueled engines when compared to gaseous-fueled engines.

Lubricant oil consumption measurement is commonly performed using radioactive tracer techniques, sulfur tracer method, gravimetric method or using chemical kinetics based models which incorporate ring dynamics and piston design parameters. The lubricant oil consumption can be determined from the measurement of carbon (measured as CO₂, CO, and THC) bearing exhaust emissions from a hydrogen-fueled engine as these would be produced solely due to the oxidation of lubrication oil. This method of lubricant oil consumption measurement has been found to yield accurate results compared to other conventional methods, such as tracer techniques [4-7].

Figure 1-1 Comparison of Toxic Air Contaminants from a CNG Engine [3]

Figure 1-2 Transit Bus Steady State Operation at 35 mph (Vehicle with a WVU-ECS PM Filter and Oxidation Catalyst) [3]

Mutagenicity studies have been used as an indicator of potential health risks associated with particulate emissions [8-20]. The classification of diesel exhaust as a toxic air contaminant by California Air Resources Board (CARB) [21] and USEPA's note regarding the mutagenic potential of the soluble organic fraction (SOF) of diesel PM [8,22] have promoted the use of natural gas among other alternative fuels. But, there have been a limited number of studies [8-12] on the mutagenic potencies of CNG derived PM and it was found to be similar to the range observed in gasoline and diesel emission samples. Okamoto et al. [11] found higher mutagenic activity without an oxidation catalyst as compared to the configuration with an oxidation catalyst for a 2000 DDC Series 50G CNG fueled engine. As mentioned earlier, results from a recent study [3] found that the use of a PM trap and oxidation catalyst reduced toxic pollutants to levels comparable to those in the background. The lubricant oil derived nanoparticle emissions were also reduced to background levels. Considering both these studies [3,11], the nanoparticle emissions with a greater total surface area could be considered as a potential contributor to mutagenic activity. This study recorded nanoparticle size distributions at the steady-state conditions for which mutagenic activity were determined. Mutagenicity of PM samples was determined in a separate though simultaneously conducted study, the findings of which were used to relate particle surface area and particulate matter derived mutagenicity effects [23].

2. REVIEW OF LITERATURE

This chapter comprises a review of literature related to studies performed in the past on lubricant oil consumption measurement using carbon and sulfur balance, hydrogen-fueled engines, trace metals balance method for lubricant oil consumption measurement, and lubricant break-in methods.

2.1. Sources of Oil Consumption

The possible sources of oil consumption are illustrated in Figure 2-1 [24]. The piston-ring-liner system would include the evaporation from the cylinder walls, oil throw off from the top land as a result of inertia forces due to the varying engine speeds. Reverse gas flows into the combustion chamber through the top ring gap may occur, when gas pressures between the top ring and second ring exceed the combustion chamber pressure depending on the engine cycle [25]. This reverse flow may also transport oil into the combustion chamber.

Figure 2-1 Sources of Oil Consumption [24]

Crankcase ventilation results in blowby gases carrying oil mist into the combustion chamber through the intake air system. In the case of turbocharged engines, the leakage past the

turbocharger seals also contributes to the total oil consumption depending on engine operating conditions. The leakage past valve stem guides occurs when the intake manifold pressures are significantly low. The combustion from the different sources depends on the engine operating conditions, and typically the piston-ring-liner system makes the largest contribution to the total oil consumption.

In this study the test engine did not have a turbocharger or a positive crankcase ventilation system. The piston-ring-liner system and leakage past the valve stem guides were the major oil consumption sources. The possible effect of engine operating conditions and combustion parameters on the various sources is discussed in Section 5.1.4.

2.2. Lubricant Oil Consumption Studies

Lubricant oil consumption measurement is commonly performed using radioactive tracer techniques, sulfur tracer method, gravimetric method or using chemical kinetics based models which incorporate ring dynamics and other piston design parameters. Gravimetric methods require several hours of operation to obtain oil consumption data at a single operating point, and radioactive tracer techniques are expensive and involve safety issues. Sulfur tracer technique, using high sulfur lubricant oil and an ultra-low sulfur fuel is one of the most common methods used by various researchers to study lubricant consumption in diesel engines. The lubricant oil consumption can be studied in a hydrogen fueled engine by measuring the carbonaceous emissions.

Furuham et al. [6,7] used a hydrogen fueled engine to study the effects of engine operating conditions, piston ring gap, alignment of piston pin, and top land clearance on engine oil consumption. They had an oxidation catalyst in the sampling stream so as to convert all carbon compounds to CO₂. They assumed carbon fraction in the lubricant oil as 0.86 and calculated the oil consumption rate. It was found that oil consumption increased greatly with increase in intake manifold vacuum and also increased with load. It was also found that approximately 10% of total lubricant oil consumed in the engine became hydrocarbons whereas the remaining consumed oil was burned completely.

Ariga et al. [26] used the sulfur dioxide (SO₂) tracer technique to measure real-time total oil consumption and unburned oil consumption in a diesel engine. They found that both total and unburned oil consumption increased with speed and load. Unburned oil consumption

showed some peaks at intermediate speed, high load condition. To measure the total oil consumption, the exhaust sample was completely oxidized in an external furnace, and for unburned oil consumption, the sample was first filtered so that all particulate matter including oil aerosols was removed and only the gas flowed through the sample line to the SO₂ detector. In the latter case the detector gave the burned oil consumption, which when subtracted from the total gave the unburned oil consumption.

Several lubricant oil consumption studies at the Massachusetts Institute of Technology's Sloan Automotive Laboratory [25,27-29] have used the SO₂-based diagnostic system to measure the engine oil consumption in diesel engines. Miller [27] studied the relationship between lubricant oil derived particulate emission rate and lubricant oil consumption. He found that the oil-derived soluble organic fraction (SOF) was highest at the high speed-low load condition, and found an approximately linear relationship between engine oil consumption and the amount of oil derived SOF. Lubricant oil consumption was found to increase with decrease in intake air pressure, whereas the lubricant derived SOF first increased and then decreased.

Froelund et al. [30] used a SO₂-tracer technique referred to as Real-Time Oil consumption (RTOC)-III, to measure oil consumption for transient and steady-state engine condition. The engine-to-engine variability in oil consumption and the effect of two different ring packs were studied at various operating conditions. They found low engine-to-engine and ring pack-to-ring pack variability in both steady state as well as transient oil consumption. Froelund et al. [31] used the same technique in measuring oil consumption from an EMD 16-645E locomotive diesel engine. They found that oil consumption increased with engine speed, load factor, and also found that the oil consumption relative to fuel consumption ranged from 0.20%-0.40% for that particular engine. They had a day-to-day repeatability within $\pm 10\%$ from the average and claimed the estimated overall accuracy of the RTOC technique to be approximately $\pm 10\%$.

Li et al. [32] studied oil combustion in a spark ignited hydrogen engine. The oil consumption was measured by determining the CO and CO₂ concentrations in the exhaust. Oil consumption was found to increase with increasing equivalence ratio, whereas compression ratio was found to have little effect on oil consumption. The oil consumption was found to increase suddenly and rapidly at the onset of knock and the additional lubricant oil consumed was found

to be burned completely.

2.3. Lubricant Oil Consumption Measurement Using Trace Metals Analysis

The traditional drain and weight method for lubricant consumption measurement takes several hours for satisfactory measurement, and is more practical in the case of lubricant oil consumption measurement required over several hours of operation. In the case of oil consumption measurement over standard steady-state tests or transient tests over short periods of time, the measurement would be inaccurate and one would need to rely on radio-tracer techniques for meaningful data in the case of diesel engines or other engines operating on carbonaceous fuels. Lubricant oil consumption measurement using trace metals balance, that is, a mass balance between the trace metals (Ca, Zn, or Mg) in the lubricating oil and particulate mass has been used in some studies [33-36]. Although these studies did report the oil consumption data, the methodology was not compared against a more accurate method for reliability of the data.

In the proposed study the lubricant oil consumption measurement using trace metal balance will be compared with the carbon balance method based measurement for different operating conditions.

Andrews et al. [33] studied the relationship between the lubricant oil consumption and the unburned lubricant oil fraction in a Perkins 4-236 naturally aspirated, direct injection diesel engine. The lubricant oil consumption was determined from a Ca mass balance, and the unburned oil emission was determined by thermogravimetric analysis (TGA) of the particulate. The lubricant oil combustion efficiency was determined based on the measurement of the unburnt fraction and the total lubricant consumption. The assumptions used were that Ca compounds are well distributed through the distillation range of the lubricant oil, and that Ca would be found in both the burned and unburned fractions proportionate to the total lubricant oil consumed.

Cooke [34] showed that the Ca concentration in lubricant oil is independent of lubricant oil ageing, however Elamir et al. [35] have found that the Ca content decreased by approximately 20% over a 150 hour ageing test.

The proposed study intends to analyze the variation in lubricant properties including trace metal concentrations over a 50 hour period to study the effects of oil ageing on its properties.

Stetter et al. [36] measured the oil consumption in a Cummins N-14 single cylinder research engine using the trace metals in the particulate mass. They calculated oil consumption using both Ca and Zn concentrations measured in the particulate and in the oil and found good agreement between the two measurements. Their data indicated that the oil consumption for the steady-state testing done was approximately an order of magnitude below oil consumption found in the literature for transient test operation. Whether or not the lower magnitude of oil consumption observed in the study was a result of the steady-state conditions or a result of the inaccuracies in oil consumption measured using trace metals balance is not clear.

2.4. Hydrogen Combustion Studies

There have been several studies conducted in the past on hydrogen fueled engines to determine the engine combustion parameters [4-7, 37-52]. Most of the studies reported negligible amounts of carbonaceous emissions and high levels of NO_x emissions. Pre-ignition or backfire is considered to be one of the greatest issues in a spark-ignited hydrogen-fueled engine [4,37,38]. This is a result of the low minimum ignition energy required for hydrogen as compared to gasoline. Intake manifold backfire at higher equivalence ratios limits the power output from an external mixture formation hydrogen engine; hence, it is an obstacle for the use of hydrogen as an automotive fuel. The backfire limiting equivalence ratio at a boost pressure of 60 kPa for the test engine used in this study was 0.45. Therefore, the highest equivalence ratio (Φ) chosen for the test matrix was 0.38. The low minimum ignition energy (0.02 mJ at $\Phi=1$), the wide flammability limits ($0.21 < \Phi < 7.34$), and small surface quenching distance of the hydrogen-air mixture all contribute to backfire [39]. There are several published studies [39-46] related to the backfire mechanisms and methods to avoid backfire, but none of them succeeded in completely avoiding the backfire in an external mixture formation hydrogen engine. Some of the reasons for backfire found in the literature are:

- surfaces of the exhaust valve as an ignition source [39]
- combustion chamber hot spots due to their high local temperatures [39]
- spark plug electrode as a source of ignition [40,41]
- the electrical energy remaining in the ignition system (spark plug cable) after the ignition, which gets discharged during the intake stroke resulting in backfire [40]
- the moderately burning flame at the piston top land as a source of ignition, according to

measurement of OH radicals [42]

- catalytic effects of some materials coming in contact with the fuel-air charge in the combustion chamber by which ignition can occur at decreased temperatures [47]
- presence of deposits caused by pyrolysis of lubricating oil which act as ignition sources [48,49]
- near stoichiometric fuel-air equivalence or advanced spark timing, which results in increased wall temperature of the combustion chamber, hence, becomes a source of ignition [50]

Studies have also shown that pre-ignition or knock tend to increase the oil consumption. Li et al. [4] have observed that knock in an engine can cause significantly higher oil consumption than encountered during normal combustion. The smaller quenching distance of hydrogen, which varies with air/fuel ratio, implies that flames may enter crevices, more closely approach cylinder walls, and contribute to the observed oil consumption [4].

Further, accelerated hydrogenation of lubricant oils in the presence of a wide variety of metals, which are available in the oil, has recently emerged [51]. There is detailed, empirical, understanding of the interaction of higher hydrocarbons with hydrogen within the refining industries. A decrease in kinematic viscosity at 100°C and breakdown of lubricating and wear-resisting additives after limited, but unspecified, testing times was reported.

The onset of knock may be avoided under any set of operating conditions by reducing the equivalence ratio for lean mixture operation, lowering compression ratio and retarding the spark timing [37]. The oil consumption also would be reduced as a result of decreased equivalence ratios, but the decreased equivalence ratio would also mean reduced power output. The broad flammability limit helps in running the hydrogen fueled engine very lean, but it was found that unburned hydrogen in the exhaust increased rapidly for equivalence ratios less than 0.25. The NO_x emissions were found to be a function of equivalence ratio. The broad flammability and burn rate range helps in controlling the H₂ engine similar to a gasoline engine where the fuel/air ratio is constant and desired torque is a function of both fuel and air flow, and also similar to a diesel engine where air is unthrottled and desired torque is a function of fuel flow [38].

Miller et al. [52] investigated the formation of combustion generated particles derived from lubricating oil in the absence of soot by examining emissions from a hydrogen-fueled

Caterpillar 3304 diesel engine modified for operation with hydrogen. They also studied the dependence of number concentration and size distribution of lubricant derived particles on engine operating conditions. For the study, a portion of the raw exhaust was cooled and diluted using an ejector-type dilutor to approximately 10:1 dilution ratio. EC/OC concentrations and particle morphology were also studied apart from the particle number and size distributions. They found that the particle mean diameter and mass were very low compared to most internal combustion engines, but the number and the resulting surface area were substantial. The elemental carbon emissions were found to be extremely low whereas the organic carbon was found to be comparable to a diesel engine of similar size. It was also found that the metal-to-carbon ratio for most particles were higher compared to diesel engines.

2.5. Lubricant Oil Break-in

The effect of lubricating oil age on emissions has been reported in several studies [53-59]. Dowling [53] reported that emissions from the same engine running on the same oil varied as it aged which he attributed to the evaporation of the volatile basestock fraction, shearing of the polymer and viscosity increase as a result of soot loading and oxidation. Emissions were found to stabilize after a certain period (1000-2000 km depending on oil). Tests conducted on a Volkswagen Passat passenger car fitted with a 1.6L turbocharged IDI diesel engine with a prototype oil, resulted in CO rising from its initial value and NO_x declining until both stabilized after around 2000 km. The vehicle was driven on a test track and was tested on the chassis dynamometer at specified intervals. HC and PM emissions followed similar patterns, both declining from their initial values quickly reaching a minimum and then increased until it stabilized around 2000 km. Tests conducted using a different oil resulted in the emissions stabilizing after around 1000 km. Based on these findings, subsequent tests were conducted after ageing the oil for 20 hours at 50% of full load in the case of heavy duty oils and onroad driving of 1600 miles for passenger cars.

Andrews et al. [54] found similar variations in HC and PM from tests conducted on a small 0.220 liter Petter IDI single cylinder diesel engine over 120 hours of operation with emissions monitored every 20 hours. Fuel dilution of the lubricant oil was found to increase uniformly with time and reached about 10% after 120 hours. CO and NO_x were not influenced by the ageing of the oil. The HC emissions were high from the fresh oil which declined to a

minimum after 50 hours and then rose again. The authors attributed this to the lubricant oil volatility effects. The lubricating oil has a lower volatile fraction which is vaporized but not burnt and results in the initial high HC emissions. This fraction of the lubricant oil is lost after about 50 hours and the subsequent rise is attributed to fuel dilution resulting in a new volatile fraction of the lubricant oil. The particulate emissions also showed a similar trend. The PM emissions reduced initially by about 25% after 50 hours of operation and then rose steadily, which is again due to the fuel dilution of the lubricant oil. The higher volatility of the aged oil with fuel dilution results in more lubricant oil burning and a greater fraction of lubricant oil generated carbon.

Laurence et al. [55] and Froelund et al. [56] suggest a 5 hour lubricant oil break-in corresponding to 200-300 miles of field test using a high temperature steady state engine operation, based on studies [57-59] which suggest that most volatility reduction in fresh oil occurs during the first 10-20 hours of operation.

Andersson et al. [60,61] followed a detailed oil change and conditioning procedure throughout their test matrix to ensure repeatability and consistency of test procedures. After each oil change, the heavy-duty engine was operated continuously at ESC Mode 10 for 60 minutes, and the light-duty vehicle was subjected to three EUDC cycles. This ensured high temperature operation and enabled removal of any volatile hydrocarbon and sulfate compounds in the catalyst and exhaust systems, and also served to precondition the dilution system.

A similar lubricant oil break-in procedure was followed in the Advanced Petroleum-Based Fuels- Diesel Emissions Control (APBF-DEC) study done by the National Renewable Energy Laboratory (NREL) [62]. The current study followed the APBF study's procedure for lubricant oil break-in and is discussed in further detail in Section 4.6.

3. EXPERIMENTAL EQUIPMENT AND PROCEDURES

The study was done at the Reciprocating Engines Laboratory at the US Department of Energy's National Energy Technology Laboratory (NETL) facility in Morgantown, West Virginia. The laboratory had a single cylinder engine test bed which was used to implement the test matrix for this study.

3.1. Test Engine

The test engine was a single cylinder Ricardo Proteus research engine. The engine specifications are given in Table 3.1.

Table 3-1 Test Engine Specifications

Engine Manufacturer	Ricardo
Displacement	1.997 liters (122.4 in ³)
Bore x Stroke	0.13 m x 0.15 m
Engine Strokes per Cycle	Four
Compression Ratio	13.3:1
Ignition	Spark Ignited
Number of Valves	Two
Piston Bowl Configuration	Toroidal Combustion Bowl
Fuel Induction	Premixed Fuel-Air

The engine was previously used for diesel fuel research and was modified for spark ignited hydrogen and natural gas fueled operation, prior to the start of the current study. Engine start-up and load were controlled by a 420-V, 100 hp (75 kW), DC dynamometer. Figure 3.1 shows the schematic of the engine test facility. The intake air source for the engine and dilution air source for the mini-dilution tunnel was filtered, dried, preheated and pressurized site air. The boost pressure was varied by regulating the site air and hence turbocharger conditions were simulated.

3.2. Test Oils

Two different lubricant oils were tested in the current study. Table 3.2 gives the properties of the synthetic and mineral oil formulations that were used for this study. The oil properties were analyzed at the Valvoline Product Development Laboratory. The synthetic oil was a commercially available Amsoil SAE (20W-40) Synthetic Natural Gas Engine Oil. The

mineral oil was supplied by Valvoline.

Table 3-2 Properties of Test Oils

Oil Type	Mineral	Synthetic
Kinematic Viscosity @ 100°C, cSt (ASTM D-445)	15.01	13.97
Kinematic Viscosity @ 40°C, cSt (ASTM D-445)	140	103
Viscosity Index (ASTM D-2270)	106	133
Noack Volatility, % weight loss (g/100g) (DIN 51581)	2.68	4.17
Ash Content (ASTM D-874), %	0.37	0.43
Pour Point °C (°F) (ASTM D 97)	-27 (-17)	-48 (-54)
Carbon, wt.% (ASTM D 5291)	85.56	85.41
Hydrogen, wt.% (ASTM D 5291)	13.86	14.22
Calcium, wt.% (D 5185)	0.112	0.118
Phosphorus, wt.% (D 5185)	0.022	0.019
Zinc, wt.% (D 5185)	0.03	0.03
Sulfur, wt.% (D 5185)	0.079	0.075

3.3. Mini-dilution Tunnel

A partial flow or mini-dilution tunnel designed and previously used by McMillian [16] was used for exhaust conditioning and subsequent total particulate sample collection and particle size distribution measurements. The mini-tunnel system was reconfigured for dilution ratio measurement for hydrogen fueled operation. The mini-tunnel was constructed using a 3.25 inch (82.6 mm) ID schedule 10 type 316 stainless steel. As mentioned earlier, filtered, dried, temperature controlled and pressurized site air was used for dilution. Dilution air entered the inlet end of the tunnel circumferentially at four equidistant points. This configuration helped in obtaining efficient mixing and a uniform flow prior to reaching the particulate sample filter. The tunnel had electric heat tracing and was well insulated for maintaining constant wall temperature and minimizing thermophoretic losses. The particulate sample filter face temperature was maintained below 125°F (51.7°C). The maximum and minimum filter temperatures were recorded during each sampling period.

A 0.75 inch (19 mm) stainless steel tube inserted into the engine exhaust flow sampled the engine exhaust which was transferred into the mini-tunnel via a 0.25 inch (6.3 mm) stainless steel flexible transfer pipe. The length of the transfer line was maintained as short as possible

and walls were well insulated to minimize any sample losses, particularly diffusion and thermophoretic deposition to the tube walls. Two micromotion Coriolis flow meters, Model CMF010 and Model CMF025, were used for recording dilution air flow and the total tunnel flow, respectively. Coriolis flow meters provide direct mass flow measurements and had a gas flow measurement accuracy of $\pm 0.35\%$ of the flow for the mass flow used in this study (approximately 3 g/s). Exhaust sample was drawn through the dilution tunnel by a KNF Neuberger twin head diaphragm pump rated at 300 liters per minute free flow. The pump was placed upstream of the flow meter because of the pressure drop that results across the Coriolis meter. The leak rate for the KNF Neuberger pump was certified by the manufacturer at less than 0.005 Torr-liter/sec. The dilution ratio in the tunnel was calculated based on the dilution air flow and the total tunnel flow. Emissions based dilution ratio measurement and control was not feasible for hydrogen fueled operation because of the low raw emissions and undetectable levels of diluted emissions. The accuracy of the Coriolis flow meters helped in determining and controlling dilution ratios at desired levels. The sampling lines downstream of the particulate filters had electric heat tracing till the Coriolis meter measuring the total flow so as to prevent any condensation prior to flow measurement.

Figure 3-1 Schematic of Engine Test Facility

Figure 3-2 Schematic of Mini-tunnel Layout

3.4. Gaseous Emissions Measurement

A gas analysis bench was used to measure the concentration of raw gaseous components in the exhaust gas stream of the engine. The gas analysis bench consisted of the following major components: THC analyzer, CO₂ analyzer, CO analyzer, and a NO_x analyzer. Three heated stainless steel probes inserted into the raw engine exhaust obtained the samples for THC, CO/CO₂, and NO_x analysis. Each probe was inserted to a depth of 1.5" (38 mm) in the 4" (101 mm) exhaust line. These probes were connected to heated lines, which transferred the gaseous samples to their respective analyzers. The hydrocarbon line and probe were maintained at a wall temperature of $191^{\circ}\text{C} \pm 5.5^{\circ}\text{C}$ ($375^{\circ}\text{F} \pm 10^{\circ}\text{F}$) to prevent the higher molecular weight hydrocarbons from condensing out on the walls and other surfaces in the sampling stream. The other system probes and lines were kept at $79^{\circ}\text{C} \pm 5.5^{\circ}\text{C}$ ($175^{\circ}\text{F} \pm 10^{\circ}\text{F}$) at the wall, in order to prevent water condensation, which would have affected the measurements by the analyzers.

3.4.1. Hydrocarbon Analyzer

The hydrocarbon analyzer was a Horiba FIA-236 heated flame ionization detector (HFID), which operates on the following principle. The sensor is a burner where a regulated flow of sample gas flows through a flame produced by regulated flows of air and a pre-mixed hydrogen/helium fuel gas. Polarized electrodes then collect the ions that are produced causing current to flow through the associated electronic measuring circuitry. The current flow is proportional to the rate at which carbon atoms enter the burner. It had a repeatability of $\pm 1\%$ of full scale, zero and span drift of $\pm 1\%$ of full scale per 8 hours [63].

3.4.2. CO/CO₂ Analyzer

The sample for CO, and CO₂, analysis passed through a Baldwin Environmental Model 20410 thermoelectric sample gas conditioner from the heated sample line. The sample conditioner lowered the sample dew point to $+5^{\circ}\text{C}$ (41°F). The reported soluble gas removal rates as percent of inlet gas concentration were NO: 0% loss, NO₂: <2% loss, CO: 0% loss, and CO₂: <1% loss. The CO and CO₂ analyzers were Horiba Model VIA-510 Non-Dispersive Infrared (NDIR) analyzers. NDIR analyzers use the exhaust gas species being measured to detect itself by the principle of selective absorption, in which the infrared energy of a particular wavelength, specific to a certain gas, will be absorbed by that gas. Infrared energy of other

wavelengths will be transmitted by that gas, just as the absorbed wavelength will be transmitted by other gases. The Horiba VIA-510 has a reproducibility of $\pm 0.5\%$ of full scale reading ($\pm 1\%$ of full scale when CO, CO₂ are <100 ppm), a zero and span drift of $\pm 1.0\%$ of full-scale per 24 hours [64].

The CO₂ in the inlet air was monitored using a California Analytical Model 601 NDIR analyzer. A sample line was run directly from the site air line into the analyzer inlet through a flow meter. It was important to measure the background CO₂, since the CO₂ emissions resulting from the hydrogen fueled operation are close to background levels. The Model 601 had a repeatability of $\pm 1\%$ of full scale, linearity of 0.5% of full scale, zero and span drift of $<1\%$ of full scale per 24 hours [65].

3.4.3. NO_x Analyzer

The NO_x analyzer used was a Thermo Environmental Model 42C High Level chemiluminescent analyzer. The analyzer was capable of determining the concentration of either NO or NO + NO₂ (NO_x). The NO_x mode was used in this study. The sample from the heated line passed through a Horiba Model COM11, NO₂ to NO converter. The sample then passed through a Baldwin Model 8210 sample conditioner which removed water from the sample stream before it entered the analyzer. The sample NO was quantitatively converted into NO₂ by gas-phase oxidation with molecular ozone, which was generated inside the analyzer by an ozone generator that was supplied with room air routed through a desiccant. When this reaction takes place, approximately 10% of the NO₂ molecules are elevated to an electronically excited state followed by immediate reversion to the non-excited state accompanied by a photon emission. The instrument response is proportional to the total NO in the original sample plus the NO produced by the dissociation of NO₂. The response time (T_{90}) of the instrument was 5 seconds. Both, repeatability and linearity were less than $\pm 1\%$ of full scale reading. The zero drift was less than 0.05 ppm in 24 hours, and span drift is less than $\pm 1\%$ of full scale reading in 24 hours [66].

3.5. Scanning Mobility Particle Sizer (SMPS)

A SMPS system was used for recording the particle size distributions at the various steady state operating conditions. Figure 3.3 shows the Model 3936 SMPS used in this study.

Figure 3-3 Model 3936 SMPS [67]

The SMPS uses an electrical mobility detection technique. The major components of the system are: the impactor and differential mobility analyzer (DMA) which together constitutes the Model 3080 electrostatic classifier (EC), the Model 3025 condensation particle counter (CPC), and the data acquisition system. The EC classifies the particles according to their electrical mobility and the CPC counts the particle numbers in each size bin. The detailed theory of operation of the SMPS can be found in the instrument manual [67]. The diluted sample was transferred via a heated line from the mini-tunnel to the classifier inlet. For the configuration used in this study, the particle size range measured was 15nm to 660nm.

3.6. Elemental Carbon/Organic Carbon (EC/OC), Ions, Trace Metals Analyses

EC/OC analysis, ions analysis, and trace metals analysis were performed by Desert Research Institute (DRI). The EC/OC analysis was performed using the thermal/optical reflectance (TOR) method. Particulate samples were collected on 90 mm pre-fired quartz filters for EC/OC analysis. The particulate phase inorganic ions (water soluble nitrate, sulfate, chloride, etc.) analyses were performed by extracting the quartz filters and subsequent Ion Chromatographic analysis of the extracts. Filter face velocities during particulate sampling were kept within the range of 35–45 cm/s. The filter face temperature was held at approximately 47°C, and dilution ratios were held approximately at a constant ratio of 12:1 for this study.

The trace metals analysis was performed using X-Ray Fluorescence (XRF) method. Particulate samples for this was collected on 90 mm Teflon-membrane filters. A brief description of the DRI procedures for the above analyses is included in Appendix D.

3.7. High Speed Data Acquisition System

An AVL GU21D uncooled Gallium orthophosphate (GaPO_4) rapid response piezoelectric pressure transducer was used to obtain pressure signals. GaPO_4 is highly stable at high temperatures. An AVL 3066 piezo amplifier conditions the output from the transducer. The amplifier gain error (accuracy) was $< \pm 0.1\%$ and had a linearity of $< \pm 0.01\%$ of full scale output. The piezoelectric transducer was ranged at 200 bar with a linearity of $< \pm 0.3\%$ of full scale reading. The cyclic temperature drift and indicated mean effective pressure (IMEP) stability of the transducer over a 10 hour test period was less than ± 0.4 bar and 2%, respectively. AVL's "Indicom" software was used for data acquisition purpose. Engine speed and crank angle ($^\circ\text{CA}$) position were measured using an AVL 364C high precision optical encoder mounted on the crankshaft end. AVL's "Concerto" combustion analysis software package was used for post processing of the data. The parameters that were analyzed were IMEP, IMEP COV, start of combustion, combustion duration, and maximum pressure.

3.8. Low Speed Data Acquisition System

A Paragon TNT system was used for all low speed data acquisition. The Paragon system acquired signals from the various instruments (analyzers, flow meters, pressure transmitters, temperature indicators) and converted them to engineering units. Paragon TNT provides open links to third party software such as Excel spreadsheets, statistical analysis packages, etc. through dynamic data exchange (DDE). Microsoft Excel was used to communicate with the DDE subsystem in Paragon and obtain data in real time. The time averaged test data was recorded and saved in Excel files for later analysis.

3.9. Nexum Ignition System

A Nexum programmable ignition system was used to control the spark ignition in this study. This system allows the operator to manually adjust the spark characteristics (peak current, sustaining current, current decay rate, duration, etc.) from the dynamometer control console. The major advantage of this approach is the ability to rapidly reconfigure the spark while the engine is running, which makes it possible to conduct back-to-back comparisons between candidate spark configurations under virtually identical operating conditions. Figure 3.4 shows a typical setup of the ignition system.

Figure 3-4 Typical Setup of Nexum Ignition System [68]

4. EXPERIMENTAL AND ANALYSIS PROCEDURES

4.1. Introduction

The global objective of this study was to determine the lubricant oil consumption and its contribution to particulate emissions as a function of engine operating conditions in a hydrogen fueled engine. The study determined the effects of engine operating conditions such as, engine speed, equivalence ratio, boost, combustion duration, and lubricant oil volatility, on oil consumption; hence, its contribution to particulate matter emissions.

4.2. Specific Tasks

The specific tasks that were performed are listed below:

- i) Measured the gaseous, and particulate emissions as a function of engine operating parameters like equivalence ratio (load), engine speed, and boost, in the case of premixed hydrogen-air fueled operation.
- ii) Performed EC/OC analysis, and trace metals analysis for selected operating points in the test matrix for hydrogen fueled operation.
- iii) Analyzed lubricant consumption as a function of engine operating conditions, and lubricant oil volatility. The lubricant oil consumption was measured using the carbonaceous emissions measurements.
- iv) Determined contribution of lubricant oil towards organic fraction of particulate matter.
- v) Determined lubricant oil consumption using trace metal markers such as Ca, and Zn, so as to determine the viability of using trace metal markers for lubricant oil consumption measurement for engines using carbon based fuels.
- vi) Measured in-cylinder pressure signals; hence, determined lubricant oil consumption dependence on combustion duration, maximum cylinder pressure, and start of combustion.
- vii) Determined particle number concentrations, size distributions, and particle surface area distributions for the various steady-state conditions so as to determine the variation of particle size distributions with variations in lubricant oil consumption.
- viii) Determined if any relation exists between particle surface distribution characteristics and degree of mutagenicity for the test conditions considered for this study.

- ix) Determined the effect of lubricant oil ageing on lubricant oil consumption, and lubricant properties.

4.3. Test Matrix for Lubricant Oil Consumption Measurement (Pre-mixed Hydrogen/Air Operation)

“Equivalence Ratio” will be referred to as “Phi” throughout the remainder of the document. The lubricant oil consumption for the pre-mixed hydrogen/air operation was measured at three levels of engine speed, phi, and boost. The backfire limiting phi at a boost pressure of 60 kPa for the test engine was 0.45. Therefore, the highest equivalence ratio chosen for the test matrix was 0.38. Table 4-1 shows the test matrix that was used for the premixed hydrogen/air operation. The tests were performed for two lubricant oil formulations. It was necessary to keep the number of tests to a minimum possible, but at the same time adequate enough for statistical analysis. Central composite designs are response surface designs that aid in fitting full quadratic models [69,70]. Figure 4-1 shows the faced central composite design that was used and Table 4-1 shows the actual test matrix. The black solid dots represent the complete test matrix. The nine points represented by both a dot and a square were the conditions at which particulate matter samples were collected for EC/OC, and trace metals analyses.

Figure 4-1 Faced Central Composite Design for Premixed Hydrogen/Air Operation

Table 4-1 Test Matrix for Premixed Hydrogen/Air Operation

Speed (rpm) Phi	900	1350	1800
0.28	20 kPa 60 kPa	40 kPa	20 kPa 60 kPa
0.33	40 kPa	20 kPa 40 kPa 60 kPa	40 kPa
0.38	20 kPa 60 kPa	40 kPa	20 kPa 60 kPa

The boost levels of 20 kPa, 40 kPa, and 60 kPa were the values at which the site air regulator was set. The actual intake manifold pressure corresponding to these set values were approximately 14 kPa, 34 kPa, and 54 kPa, respectively. The actual values measured for speed, and phi for the test conditions were within $\pm 3\%$ of the set values. The actual measured data for speed, phi, and boost were used for the oil consumption analysis. In-cylinder pressure signals were recorded at all operating points which helped in determining combustion duration, and peak pressures. The gaseous emissions and particle size distributions were also recorded at all the points. Particulate matter emissions and potential mutagenicity in the case of pre-mixed hydrogen operation were investigated as part of a complementary study, which was simultaneously performed by Solano [23].

4.4. Test Matrix for EC/OC, Ions, and Trace Metals Analyses

The test matrix for obtaining samples for EC/OC analysis, and trace metals analysis was a subset of the matrix shown in Table 4-1, and is also represented in Figure 4-1. Table 4-2 shows the actual EC/OC analysis test matrix.

Table 4-2 Test Matrix for EC/OC, and Trace Metals Analysis

Speed (rpm) Phi	900	1350	1800
0.28	20 kPa 60 kPa		20 kPa 60 kPa
0.33		40 kPa	
0.38	20 kPa 60 kPa		20 kPa 60 kPa

4.5. Maximum Thermal Efficiency Timing Test

The steady-state tests for all the above mentioned matrices were conducted at maximum thermal efficiency (MTE) spark timing. MTE was determined at each operating point, by varying spark timing around an expected optimum, and recording thermal efficiency once the engine emissions had stabilized. The stabilization time was kept constant for all tests using a stop watch. The oil and coolant temperatures were also maintained constant during all tests. Thermal efficiency was then plotted as a function of spark timing and a second-order curve was fitted. This curve was used to determine the spark timing for MTE. The MTE spark timing used for the various steady-state conditions tested is shown in Table 4-3.

Table 4-3 Maximum Thermal Efficiency (MTE) Spark Timing Used for the Test Points

Speed (rps)/Coded Speed	Phi/Coded Phi	Boost (kPa)/Coded Boost	MTE Timing (°BTDC)
15/-1	0.28/-1	20/-1	27
15/-1	0.28/-1	60/+1	24
15/-1	0.33/0	40/0	20
15/-1	0.38/+1	20/-1	16
15/-1	0.38/+1	60/+1	13
22.5/0	0.28/-1	40/0	25
22.5/0	0.33/0	20/-1	21
22.5/0	0.33/0	40/0	20
22.5/0	0.33/0	60/+1	19
22.5/0	0.38/+1	40/0	15
30/+1	0.28/-1	20/-1	27
30/+1	0.28/-1	60/+1	24
30/+1	0.33/0	40/0	20
30/+1	0.38/+1	20/-1	16
30/+1	0.38/+1	60/+1	13

4.6. Lubricant Oil Break-in

The need to break-in fresh lubricant oil has already been discussed in Section 2.4. The lubricant oil used for this study was subjected to a break-in following the procedure adopted by a previous study [62]. Multiple oil flushes, followed by a 3 hour break-in at maximum speed, phi, and boost condition was performed. The procedure [62] was as follows:

1. Drained previous test oil.
2. Removed oil filter and replaced.
3. Engine was filled with fresh test oil.
4. Started engine and brought to operating temperature.
5. Stopped engine and allowed to cool down.
6. Drained oil (1st Flush).
7. Removed oil filter and replaced.
8. Refilled engine with fresh oil.
9. Started engine and brought to operating temperature.
10. Stopped engine and allowed to cool down.
11. Drained oil (2nd Flush).
12. Removed oil filter and replaced.
13. Refilled engine with fresh test oil.
14. Started engine and brought to operating temperature.
15. Ran engine at maximum speed, phi, and boost condition for 3 hours.
16. Brought engine to idle and prepared for steady-state tests.

4.7. Carbon Balance Oil Consumption Calculation (g/bhp-hr)

The brake-specific oil consumption (g/bhp-hr) based on carbon balance was calculated using the following equation,

$$\dot{m}_{oil} = \frac{3600}{m_c * W} \left[Kw \left\{ \left(\frac{[CO_2]}{10^6} V_{exh} \rho_{CO_2} \frac{MW_c}{MW_{CO_2}} \right) + \left(\frac{[CO]}{10^6} V_{exh} \rho_{CO} \frac{MW_c}{MW_{CO}} \right) \right\} + \left(\frac{[THC]}{10^6} V_{exh} \rho_{THC} \frac{MW_c}{MW_{THC}} \right) \right]$$

Equation 4-1

m_c = Carbon mass fraction of the oil,

W = Power, bhp

$[CO_2]$, $[CO]$, $[THC]$ = Concentrations of CO_2 , CO , THC in the exhaust, ppm

V_{exh} = Exhaust volumetric flow (m^3/sec) at $20^\circ C$ and $101.3kPa$ pressure, and is given by,

$$V_{exh} = \frac{\dot{m}_a + \dot{m}_f}{\rho_{air}}$$

Equation 4-2

where, $\dot{m}_a$ = Intake air flow rate, g/s

$\dot{m}_f$ = Fuel (hydrogen) mass flow rate, g/s

ρ_{air} = Density of air at $20^\circ C$ and $101.3kPa = 1204 g/m^3$

ρ_i = Density of exhaust components, $i = CO_2, CO, THC$

MW_i = Molecular weight, $i = C, CO_2, CO$

MW_{THC} = Relative molecular weight (that is, ratio of total molecular weight of all elements to $12 * MW_C$)

The molecular weights and densities were obtained from the NIST website [71], and the Code of Federal Regulations [72] respectively.

$$MW_C = 12.0107, MW_{CO_2} = 44.0095, MW_{CO} = 28.0101, MW_{THC} = 13.0186, \rho_{CO_2} = 1830 \text{ g/m}^3, \\ \rho_{CO} = 1164 \text{ g/m}^3, \rho_{THC} = 574.6 \text{ g/m}^3$$

m_c , the mass fraction of carbon for the oil samples collected were analyzed by Southwest Research Institute using the ASTM D5291 analysis procedure. The results of the analysis are included in Table 5-6. The uncertainty analysis for Equation 4-1 is presented in Appendix A.

The power output (bhp) for a given test was calculated as,

$$W = \frac{2\pi NT}{60000} * 1.34,$$

where, N =Speed, rpm

T = Torque, Nm

1.34 = Conversion factor for conversion of kW to hp

K_w in Equation 4.1 is the dry to wet correction factor, and was calculated as

$$K_w = 1 - M_{H_2O},$$

where, M_{H_2O} = Mole fraction of H_2O , and is given by,

$$M_{H_2O} = \frac{2\phi}{\phi + 4.76}$$

The above expression can be obtained from a hydrogen combustion equation involving “ a ” moles of H_2 and $\phi < 1$.

4.8. Overview of Statistical Tools Used for Analysis

This section comprises a brief review of the statistical tools and terms used for the presentation of results in Chapter 5.

4.8.1. Regression Analysis

Regression analysis is a statistical tool to determine a relationship between a set of variables or factors and a response. It aids in finding the statistical significance of each factor on the response, and the effects of interaction of variables. The dependent variables (or response) are modeled as a function of the independent variables (or factors).

4.8.1.1. Simple Linear Regression

In a simple linear regression model, the relation between one factor and a single response is estimated. For example, if x_i represents “n” factor data points, and y_i represents the corresponding response data, then y_i can be expressed as,

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i ; i=1, \dots, n,$$

where, β_0 and β_1 are called the parameters which need to be estimated in order to model the above relation and ε_i is the random error term. The estimated model can be represented as,

$$\hat{y}_i = \hat{\beta}_0 + \hat{\beta}_1 x_i + e_i$$

where “^” denotes that the terms are estimates. e_i is the residual associated with the model and is given by, $e_i = y_i - \hat{y}_i$.

The most common method of estimation of parameters is by minimizing the sum of squares of the residuals (SSE), where, $SSE = \sum_{i=1}^n e_i^2$.

The mathematical equations associated with the calculation can be found in any advanced statistical text book. References [70,73] also provide further details and references.

4.8.1.2. Multiple Linear Regression

Multiple linear regression is an extension of simple linear regression. In this case, the relation between multiple independent variables (factors) and a dependent variable (response) is modeled. In the current study, multiple linear regression was employed to estimate the oil consumption model.

The multiple linear regression, in particular for the current study can be represented as,

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \beta_3 x_{3i} + \beta_{12} x_{1i} x_{2i} + \beta_{13} x_{1i} x_{3i} + \beta_{23} x_{2i} x_{3i} + \beta_{11} x_{1i}^2 + \beta_{22} x_{2i}^2 + \beta_{33} x_{3i}^2 + \varepsilon_i.$$

With respect to the current study, y_i is the oil consumption data, x_1 , x_2 , and x_3 are speed, phi, and boost respectively. β_{12} , β_{13} and β_{23} are interaction parameters, and β_{11} , β_{22} and β_{33} are the parameters for the quadratic effects.

The parameters are estimated in a similar fashion as in simple linear regression, the only difference being that the number of equations to solve increase depending on the number of factors; hence, involves matrix computation.

4.8.1.3. Stepwise Multiple Regression

Stepwise regression can be based on a forward elimination procedure or a backward elimination procedure. In the case of forward elimination procedure, the model starts with only the intercept term. In the succeeding steps, each factor is added one at a time, and the significance of each of the variables in the model is determined. The variables with p-value above a certain threshold are eliminated and the model is refitted without the eliminated variables. In the case of backward elimination procedure, the model starts with all the variables, and eliminates variables with p-values higher than the threshold and refits the model at each step. The forward elimination procedure was used in the current study as it was the default procedure in the JMP® software [73].

4.8.1.4. Robust Regression

Robust regression models are less sensitive to outliers. The method involves weighting of data points. The initial iteration weights all data points equally and fits a model. In subsequent

iterations, data points resulting in large residuals or potential outliers are given less weight compared to the rest of the data points and the model is re-fitted. This method is particularly useful in data sets where some outliers skew the fitted model significantly.

4.8.2. Design of Experiments (DoE)

Design of experiments is a systematic method of analyzing a process. The tests are designed in a way that most of the information pertaining to the process can be determined with minimum test time and resources. The effects of factors, their interaction, and quadratic effects can be determined based on the number of factors, test points and design chosen.

Central Composite Designs (CCDs) are among the most popular models in DoE. Figures 5-50 through 5-52 [69] show the three types of CCDs, face-centered, circumscribed, and inscribed designs. All three designs are efficient in determining full quadratic models.

The inscribed and circumscribed methods use five levels of each factor for the experiments. In the current study, the operating window considered was not wide enough for five factor levels due to the backfire limiting equivalence ratio of the engine. The face centered design which uses three levels for each factor was appropriate for the objective of the study.

Figure 4-2 Face-centered Central Composite Design

Figure 4-3 Circumscribed Central Composite Design

Figure 4-4 Inscribed Central Composite Design

4.8.3. JMP[®] Statistical Summary Report

The JMP[®] statistical analysis software from SAS (Statistical Analysis Institute) was used for the regression analysis in this study. Figure 4-5 shows an example of a typical JMP[®] statistical analysis report for a multiple linear regression analysis.

Figure 4-5 Typical JMP Statistical Summary Report

Whole Model Actual by Predicted Plot

1

Summary of Fit

RSquare 0.964542
RSquare Adj 0.961515
Root Mean Square Error 0.317621
Mean of Response 4.531778
Observations (or Sum Wgts) 90

2

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	225.03113	32.1473	318.6599
Error	82	8.27239	0.1009	
C. Total	89	233.30352		

Prob > F <.0001

3

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	43	3.8381236	0.089259	0.7850
Pure Error	39	4.4342667	0.113699	
Total Error	82	8.2723902		

Prob > F 0.7808
Max RSq 0.9810

4

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	4.568629	0.065044	70.24	<.0001
Speed(15,30)	1.7662661	0.040905	43.18	<.0001
Phi(0.28,0.38)	0.2453224	0.041687	5.88	<.0001
Boost(14,54)	0.7114114	0.041818	17.01	<.0001
Speed*Phi	0.2976576	0.045332	6.57	<.0001
Speed*Boost	0.3041245	0.046663	6.52	<.0001
Speed*Speed	-0.268263	0.081116	-3.31	0.0014
Phi*Phi	0.1921544	0.07978	2.41	0.0183

5

Residual by Predicted Plot

6

**Speed(15,30)
Leverage Plot**

7

The numbers in the following text refer to the corresponding boxed numbers in Figure 4.5.

- 1) Scatter plot of whole model predicted values versus the actual experimental data.
- 2) The summary of the fit consists of the following.
 - Rsquare: The number shows that the model accounts for or explains approximately 96% of the variation around the mean (for the example shown). It is the ratio of the Model Sum of Squares to the Total Sum of Squares from (3).
 - Rsquare Adj: The adjusted Rsquare accounts for the number of parameters that define the model.
 - Root Mean Square Error: Standard deviation of the residual error. It is the square root of the Mean Square of Error from (3).
 - Mean of Response: The mean of all the observations.
 - Observations: Number of data points.

3) Analysis of Variance Table

- DF (Degrees of Freedom): The number of degrees of freedom for the model is the number of parameters excluding the intercept that define the model. The total degree of freedom is one less than the number of observations. The difference of the two gives the DF of error.
- Sum of Squares: The total sum of squares is the sum of squares of the residuals if all regression effects were removed except for the intercept. The Error Sum of Squares is sum of squares of residuals. The model sum of squares is the difference between the two or the sum of squares of residuals considering all the regression effects.
- Mean Square: The ratio of Sum of Squares to DF
- F Ratio: Ratio of Model Mean Square to Error Mean Square.
- Prob>F: Indicates whether the model fits better than simply fitting the mean if $p < 0.05$ (for 95% confidence). In the example $p < 0.0001$ indicates that the F Ratio is highly significant or that the model fits much better than just considering the mean.

4) Lack of Fit Table

The Lack of Fit Total Error is same as the model error in (3). The total error is split into two : Lack of Fit Error and Pure Error.

- Pure Error is the error associated with the experiments as a result of random effects and can be determined for tests where replicates are performed.
- The Lack of Fit Error is obtained by subtracting the Pure Error from the total error.
- The number of degrees of freedom (DF) for the pure error depends on the number of exact replicates. For the current study, 3 runs were performed at each of the 15 operating states for the two oils. Therefore, the DF of pure error should be, $30 * (3-1) = 60$. Since, the actual data for speed, phi, and boost were used for the analysis rather than the set points, the number of exact replicates will be less, and hence the DF of pure error is seen to be less than 60 in the example shown.
- The DF of Lack of Fit is, Total Error DF – Pure Error DF.
- The Sum of Squares (SS) of pure error is obtained from the replicate data points, and the Lack of Fit SS = Total SS – Pure Error SS.
- The Mean Square is the ratio of Sum of Squares to DF as in (3).
- F Ratio as in (3) is the ratio of Lack of Fit Mean Square to Pure Error Mean Square. In the example, the p-value denotes that the lack of fit is not significant, or which indicates that the model is adequate.
- Max RSq indicates the maximum Rsquare value that can be obtained by adding more parameters to the existing model.

5) The parameter estimates table lists the estimates of the model parameters, the standard error associated with the estimates, t-ratios, and the p-values.

- Parameter estimates are obtained such that their values minimize the residual Sum of Squares, and involve matrix computation for multiple regressions.
- Standard error is the estimate of the standard deviation of the parameter estimate.
- t-Ratio is the ratio of the estimate to its standard error. Higher the t-Ratio, more the significance of the parameter.

- Prob > (t): significance probability (p-value).

6) Plot of residuals versus the model predicted values. Residual plots help to visualize the adequacy of the models

7) Effects Leverage Plots: The Leverage plots illustrate how each effect contributes to the fit. The leverage plots have the following included.

- The sloped line enclosed by the confidence curves (red lines). The distance from each point to the sloped line is the residual for the full model, the sum of squares of which is the SSE (Error Sum of Squares).
- The horizontal line (blue line) is the restricted model without the effect (the mean of the response). The distance from each point to this line is the residual for restricted model without the effect.

The effect is significant if the points support the sloped line significantly away from the horizontal line, that is, if the difference in sums of squares of the two residuals defined above is large, the effect is significant. Also, the confidence curves will not enclose the horizontal line, if the effect is significant.

4.8.4. Normal Probability Plots

Normal probability plots can be used for checking distributional normality for large samples of data, and also to point out suspect data values. The vertical axis scale is adjusted so that the probability versus data displayed is approximately a straight line for data from a normal distribution.

Normal Probability Plots are used in this study to compare the data from the two test oils so as to check the effect of oil type (in this case effect of volatility) on oil consumption. Normal probability plots can also give estimates of the mean and standard deviations of the data set.

4.8.5. Box Plots

Box Plots provide a graphical summary of the data and is a common visual analysis tool to compare multiple data sets. Box Plots are used along with probability plots in the current study to compare data between the test oils. Figure 4-6 shows the box plot convention used in this study.

Figure 4-6 Typical Box Plot

5. RESULTS AND DISCUSSION

The results discussed in this chapter are in the following order:

- i. Oil consumption based on gaseous carbon emissions (CO_2 , CO, THC)
 - Brake-specific (g/bhp-hr) oil consumption model as a function of speed, ϕ , and boost
 - Absolute or time-specific (g/hr) oil consumption model as a function of speed, ϕ , and boost
 - The influence of combustion parameters, such as combustion duration, peak cylinder pressures, start of combustion, and exhaust temperatures on lubricant oil consumption and possible contribution of the different sources of oil consumption
- ii. EC/OC, trace metals analyses results
 - Oil consumption determined based on organic carbon in the exhaust
 - Oil consumption determined based on Ca and Zn concentrations in the exhaust
 - Comparison of the different methods for an understanding of total oil consumption
- iii. Particle number, size, and surface area distributions
 - Particle number concentration dependence on lubricant oil consumption, and engine operating conditions
 - Particle size distributions during motoring (fuel shut-off) conditions
 - Particle surface area and impact of lubricant derived PM on mutagenicity
- iv. Effect of ageing on lubricant oil properties

5.1. Oil Consumption Analysis (Carbon Balance Method)

The oil consumption was studied using the faced central composite design as shown in Figure 4-1. The fifteen operating conditions, shown in Table 5-1 were employed with the two oils, Valvoline (will be referred as “Mineral Oil” in the rest of the document), and Amsoil (will be referred as “Synthetic Oil” in the rest of the document). The values -1, 0, and 1 denote the three levels of speed, phi, and boost already shown in Table 4-1. The operating conditions will be referred by their corresponding state numbers (given in Table 5-1) in the rest of the document.

Table 5-1 Steady-state Test Points Denoted by State Numbers

State No.	Speed (rps)/Coded Speed	Phi/Coded Phi	Boost (kPa)/Coded Boost
1	15/-1	0.28/-1	20/-1
2	15/-1	0.28/-1	60/+1
3	15/-1	0.33/0	40/0
4	15/-1	0.38/+1	20/-1
5	15/-1	0.38/+1	60/+1
6	22.5/0	0.28/-1	40/0
7	22.5/0	0.33/0	20/-1
8	22.5/0	0.33/0	40/0
9	22.5/0	0.33/0	60/+1
10	22.5/0	0.38/+1	40/0
11	30/+1	0.28/-1	20/-1
12	30/+1	0.28/-1	60/+1
13	30/+1	0.33/0	40/0
14	30/+1	0.38/+1	20/-1
15	30/+1	0.38/+1	60/+1

The oil consumption model based on three factors, namely, speed, phi, and boost was determined by stepwise multiple linear regression analysis. The above tests were replicated twice for a total of three runs with each test oil. Tests were conducted in a random order. Table B1 in Appendix B shows the coded data matrix of factors and the response based on the actual data obtained in the order the tests were done. Table 5-2 shows the average oil consumption results for the two oils for the various operating states.

Table 5-2 Brake-specific Oil Consumption (g/bhp-hr) Results for the Test Oils

State No.	Brake-specific Oil Consumption(g/bhp-hr)					
	Mineral Oil			Synthetic Oil		
	Avg	S.D.	COV	Avg	S.D.	COV
1	0.40	0.01	0.03	0.43	0.02	0.05
2	0.36	0.00	0.01	0.36	0.01	0.04
3	0.30	0.01	0.04	0.31	0.00	0.01
4	0.28	0.02	0.07	0.31	0.01	0.03
5	0.24	0.02	0.08	0.25	0.02	0.08
6	0.43	0.03	0.06	0.42	0.01	0.02
7	0.41	0.04	0.10	0.37	0.01	0.04
8	0.34	0.02	0.06	0.35	0.01	0.03
9	0.31	0.01	0.02	0.31	0.03	0.10
10	0.31	0.02	0.06	0.31	0.01	0.02
11	0.54	0.06	0.12	0.53	0.02	0.03
12	0.41	0.01	0.03	0.39	0.02	0.04
13	0.35	0.01	0.01	0.33	0.03	0.08
14	0.42	0.01	0.03	0.37	0.01	0.02
15	0.33	0.03	0.09	0.35	0.00	0.01

Avg = Average, S.D. = Standard Deviation, COV = Coefficient of Variance

Stepwise regression was used to determine the significant factors, their quadratic effects, and two way interaction effects. The accuracy of the regression analysis was checked using ANOVA (analysis of variance), and the analysis of residuals. JMP[®] statistical analysis software was used for the regression analysis. The statistics toolbox of MATLAB[®] was also used for the analysis of results.

Quadratic models for both brake-specific (g/bhp-hr), and absolute (g/hr) oil consumption were developed using stepwise multiple linear regression. The absolute oil consumption model was found to fit better with experimental data; hence, it may be a better method to determine oil consumption as a function of engine operating conditions. Details for both analyses are provided in the following sections.

The gaseous emissions results of CO₂, CO, and THC which were used to calculate the oil consumption, and the NO_x emissions results are given in Appendix C. CO₂ was the major contributor among the carbonaceous emissions. The NO_x emissions were low as expected due to the low equivalence ratios.

5.1.1. Brake-specific Oil Consumption Analysis (Carbon Balance Method)

A simple multiple linear regression showed no effect in the oil consumption as a result of the oil types used in the study. This was further reinforced by a normal probability plot and a box plot of the actual brake-specific oil consumption data obtained for the test oils. The normal probability plot and the box plots of brake-specific oil consumption for the mineral oil and synthetic oil are shown in Figures 5-1 and 5-2, respectively. The normal plot shows that the two data sets are part of similar normal distributions, and the box plot shows that the data have similar medians, as well. The normal plots and box plots are two of the most common techniques and basic analytical methods for this purpose.

Figure 5-1 Normal Probability Plot of Brake-specific Oil Consumption Data for the Test Oils

Figure 5-2 Box Plot of Brake-specific Oil Consumption Data for the Test Oils

Based on the finding that the two oil types had similar oil consumption behavior for the entire design, it was decided to analyze the data together. This also provided several more data points for the model determination. The model parameters, ANOVA table, and residual plots are shown in Report 5-1 below for the stepwise multiple linear regression analysis. Brake-specific oil consumption is denoted as “OC” in the statistical report. Speed data used for the analysis was in rps (revolutions per second).

Report 5-1 Statistical Analysis Report of the Stepwise Multiple Linear Regression of Brake-specific Oil Consumption Data

Whole Model Actual by Predicted Plot

Summary of Fit

RSquare	0.876796
RSquare Adj	0.866279
Root Mean Square Error	0.026655
Mean of Response	0.361111
Observations (or Sum Wgts)	90

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	0.41462710	0.059232	83.3661
Error	82	0.05826179	0.000711	Prob > F
C. Total	89	0.47288889		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	43	0.03481179	0.000810	1.3464
Pure Error	39	0.02345000	0.000601	Prob > F
Total Error	82	0.05826179		0.1746
			Max RSq	0.9504

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	0.3388579	0.005914	57.29	<.0001
Speed(15,30)	0.037392	0.003438	10.88	<.0001
Phi(0.28,0.38)	-0.054989	0.003492	-15.75	<.0001
Boost(14,54)	-0.038662	0.003507	-11.02	<.0001
Phi*Boost	0.0103953	0.003971	2.62	0.0105
Speed*Speed	-0.014358	0.007089	-2.03	0.0461
Phi*Phi	0.0271126	0.006912	3.92	0.0002
Boost*Boost	0.0183959	0.007281	2.53	0.0134

Residual by Predicted Plot

**Speed(15,30)
Leverage Plot**

**Phi(0.28,0.38)
Leverage Plot**

**Boost(14,54)
Leverage Plot**

**Phi*Boost
Leverage Plot**

**Speed*Speed
Leverage Plot**

**Phi*Phi
Leverage Plot**

**Boost*Boost
Leverage Plot**

Speed, equivalence ratio, boost, and the quadratic effect of all three parameters were found to be significant at the 95% confidence level. The only interaction term found to be significant was the interaction effect of equivalence ratio and boost.

Robust regression allows removing any skewness in the model associated with outliers. A robust fit of the data was also performed using the coefficient estimates of the significant factors and factor interactions determined by the stepwise regression. The MATLAB[®] statistics toolbox was used for this purpose. The oil consumption predicted by robust regression analysis was similar to results from the stepwise regression analysis showing the absence of any potential outliers in the data set. Figure 5-3 shows parity plots of brake-specific oil consumption predicted by the stepwise regression model and robust regression model versus the actual data. The robust

regression model provided a better fit for the model based on least squares and residual analysis. Figure 5-4 shows comparison of residuals based on step wise regression analysis model versus the robust regression analysis.

Figure 5-3 Comparison of Step-wise Regression Model vs. Robust Regression Model

Figure 5-4 Residual Comparison

The robust linear fit was used to derive a quadratic response surface. The quadratic brake-specific oil consumption (m_{oil} , g/bhp-hr) model based on the robust regression is given in Equation 5-1.

$$m_{oil} = 0.34 + 0.036 * Speed - 0.055 * Phi - 0.035 * Boost + 0.011 * (Phi * Boost) - 0.013 * (Speed)^2 + 0.027 * (Phi)^2 + 0.016 * (Boost)^2$$

Equation 5-1

The variables Speed, Phi, and Boost in the above equation are the coded speed, coded phi, and coded boost, respectively. The above equation was used to obtain brake-specific oil consumption behavior over the entire design envelope. The quadratic response surface is shown in Figure 5-5. The trend can be better visualized by analyzing slices of constant speed, phi, and boost as shown in Figures 5-6 through 5-8, respectively.

Figure 5-5 Quadratic Brake-specific Oil Consumption (g/bhp-hr) Model

The data clearly indicates increasing brake-specific oil consumption with increasing speed and decreasing equivalence ratio and boost. The diagonal joining the points represented by $[(\text{Speed}, \text{Phi}, \text{Boost}) = (-1, 1, 1)]$ and $[(\text{Speed}, \text{Phi}, \text{Boost}) = (1, -1, -1)]$ can be considered as the line of steepest ascent of brake-specific oil consumption for the model under consideration. The discussion of these results is presented in the next section following the absolute oil consumption analysis.

Figure 5-6 Quadratic Brake -specific Oil Consumption Model : Constant Speed Steps

Figure 5-7 Quadratic Brake-specific Oil Consumption Model : Constant Phi Steps

Figure 5-8 Quadratic Brake-specific Oil Consumption Model : Constant Boost Steps

5.1.2. Time-specific Oil Consumption Analysis (Carbon Balance Method)

Absolute oil consumption (g/hr) or time-specific oil consumption was also analyzed as a function of speed, equivalence ratio, and boost as performed in the previous section. The analysis was done for the combined (mineral oil and synthetic oil) data as before.

The statistical analysis results are shown below in Report 5-2. Time-specific oil consumption is denoted as “OC” in the statistical report. Speed data used for the analysis was in rps (revolutions per second).

Report 5-2 Statistical Analysis Report of the Stepwise Multiple Linear Regression of Time-specific Oil Consumption Data

Whole Model Actual by Predicted Plot

Summary of Fit

RSquare	0.964542
RSquare Adj	0.961515
Root Mean Square Error	0.317621
Mean of Response	4.531778
Observations (or Sum Wgts)	90

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	225.03113	32.1473	318.6599
Error	82	8.27239	0.1009	Prob > F
C. Total	89	233.30352		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	43	3.8381236	0.089259	0.7850
Pure Error	39	4.4342667	0.113699	Prob > F
Total Error	82	8.2723902		0.7808
				Max RSq
				0.9810

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	4.568629	0.065044	70.24	<.0001
Speed(15,30)	1.7662661	0.040905	43.18	<.0001
Phi(0.28,0.38)	0.2453224	0.041687	5.88	<.0001
Boost(14,54)	0.7114114	0.041818	17.01	<.0001
Speed*Phi	0.2976576	0.045332	6.57	<.0001
Speed*Boost	0.3041245	0.046663	6.52	<.0001
Speed*Speed	-0.268263	0.081116	-3.31	0.0014
Phi*Phi	0.1921544	0.07978	2.41	0.0183

Residual by Predicted Plot

Speed(15,30) Leverage Plot

Phi(0.28,0.38) Leverage Plot

**Boost(14,54)
Leverage Plot**

**Speed*Phi
Leverage Plot**

**Speed*Boost
Leverage Plot**

**Speed*Speed
Leverage Plot**

**Phi*Phi
Leverage Plot**

Speed was found to be the largest factor influencing the absolute oil consumption. This can be seen from the t-ratio of the parameter estimates table as well as the speed leverage plot.

Equivalence ratio, boost, quadratic effects of speed, and equivalence ratio were also significant at the 95% confidence level. The quadratic time-specific oil consumption (m_{oil} , g/hr) model based on the stepwise multiple linear regression analysis is given in Equation 5-2.

$$m_{oil} = 4.57 + 1.77 * Speed + 0.245 * Phi + 0.711 * Boost + 0.298 * (Speed * Phi) + 0.304 * (Speed * Boost) - 0.268 * (Speed)^2 + 0.192 * (Phi)^2$$

Equation 5-2

The variables Speed, Phi, and Boost in the above equation are the coded speed, coded phi, and coded boost, respectively. The above equation was used to obtain time-specific oil consumption behavior over the entire design envelope. The quadratic response is shown in Figure 5-9 below, and the constant speed, phi, and boost slices are also shown in Figures 5-10 through 5-12.

Figure 5-9 Quadratic Time-specific Oil Consumption (g/hr) Model

Figure 5-10 Quadratic Time -specific Oil Consumption (g/hr) Model: Constant Speed Steps

Figure 5-11 Quadratic Time -specific Oil Consumption (g/hr) Model: Constant Phi Steps

Figure 5-12 Quadratic Time -specific Oil Consumption (g/hr) Model: Constant Boost Steps

The data clearly indicates increasing absolute oil consumption with increasing speed, equivalence ratio and boost. The diagonal joining the points represented by [(Speed, Phi, Boost) = (-1,-1,-1)] and [(Speed, Phi, Boost) = (1,1,1)] in Figure 5-9 can be considered as the line of steepest ascent of absolute oil consumption for the model under consideration. The trend can be better visualized by analyzing slices of constant speed, phi, and boost shown in Figures 5-10 through 5-12.

The results show that time-specific oil consumption determination provides a better fit compared to brake-specific oil consumption. The absolute oil consumption increases with increased speed, equivalence ratio, and boost.

The increase in speed results in increased revolutions and as a result an increase in the amount of oil transported to the combustion chamber may be expected. The effects of speed, phi, and boost can be better explained along with the combustion parameters data given in Table 5-3 and the statistical analysis that follows.

5.1.3. Influence of Combustion Parameters on Oil Consumption

The combustion parameters, namely, combustion duration, maximum cylinder pressure and start of combustion were also analyzed as a function of engine speed, phi, and boost using stepwise multiple linear regression. The combustion parameters data is shown in Table 5-3, and was used for the statistical analysis. The exhaust temperature was used as an indicator of the combustion temperature and was also analyzed as a function of engine operating conditions. The exhaust temperature data is shown in Table 5-4.

All of the four above mentioned parameters were found to be well correlated with the engine operating conditions. Reports 5-3 through 5-6 report the statistical analyses.

Table 5-3 Combustion Parameters Data for the Operating States Tested for the Test Oils

State No.	Combustion Duration (°Crank Angle)						Maximum Cyclinder Pressure (bar)						Start of Combustion (°BTDC)					
	Mineral Oil			Synthetic Oil			Mineral Oil			Synthetic Oil			Mineral Oil			Synthetic Oil		
	Avg	S.D.	COV	Avg	S.D.	COV	Avg	S.D.	COV	Avg	S.D.	COV	Avg	S.D.	COV	Avg	S.D.	COV
1	42.4	1.68	0.02	47.4	11.07	0.12	50.0	0.54	0.01	50.0	0.77	0.01	-8.3	0.23	0.01	-8.3	0.38	0.02
2	32.8	4.20	0.064	33.4	2.414	0.04	64.1	2.54	0.02	64.4	1.24	0.01	-6.3	0.79	0.06	-6.7	0.05	0.00
3	38.4	2.03	0.026	38.4	4.721	0.06	60.7	3.70	0.03	60.0	0.88	0.01	-5.3	2.26	0.21	-5.0	0.38	0.04
4	42.8	4.04	0.047	44.8	6.761	0.08	55.2	2.75	0.02	54.7	4.60	0.04	-2.9	1.19	0.20	-3.0	1.29	0.21
5	30.7	1.73	0.028	30.8	7.732	0.13	68.3	0.62	0.00	68.2	5.11	0.04	-0.8	0.25	0.16	-0.8	0.82	0.50
6	35.7	5.07	0.071	34.7	1.724	0.02	59.3	1.23	0.01	59.3	1.38	0.01	-7.5	0.77	0.05	-8.0	0.27	0.02
7	44.7	1.42	0.016	48.4	6.483	0.07	54.5	1.97	0.02	54.0	0.52	0.00	-5.7	0.64	0.06	-5.5	1.22	0.11
8	37.9	2.39	0.032	42.7	2.97	0.03	60.7	1.32	0.01	61.8	1.52	0.01	-4.7	0.65	0.07	-4.9	0.83	0.08
9	32.8	1.09	0.017	35.6	4.647	0.07	68.2	1.72	0.01	68.1	1.76	0.01	-4.1	0.78	0.09	-4.0	0.54	0.07
10	35.3	2.56	0.036	36.7	0.266	0.00	61.8	0.99	0.01	62.8	0.70	0.01	-1.7	0.37	0.11	-2.1	0.43	0.10
11	44.0	6.03	0.068	45.0	4.422	0.05	50.1	1.24	0.01	51.4	5.74	0.06	-9.2	0.60	0.03	-8.8	1.06	0.06
12	33.1	2.17	0.033	31.9	3.565	0.06	65.0	2.20	0.02	64.4	0.61	0.00	-6.9	0.41	0.03	-6.9	0.45	0.03
13	38.0	5.10	0.067	37.3	1.143	0.02	59.5	1.97	0.02	59.6	0.14	0.00	-5.1	0.25	0.02	-5.1	0.47	0.05
14	41.7	4.46	0.054	43.7	2.032	0.02	52.4	1.57	0.02	51.6	3.05	0.03	-2.5	0.42	0.08	-2.3	1.08	0.23
15	29.8	1.57	0.026	29.4	0.389	0.01	61.7	1.18	0.01	62.5	0.31	0.00	0.7	0.37	0.26	0.5	0.54	0.58

Table 5-4 Exhaust Temperature Data for the Operating States Tested for the Test Oils

State No.	Exhaust Temperature (°C)					
	Mineral Oil			Synthetic Oil		
	Avg	S.D.	COV	Avg	S.D.	COV
1	232.9	2.8	0.01	234.8	6.8	0.01
2	234.1	7.6	0.02	236.1	4.5	0.01
3	269.3	5.0	0.01	270.1	2.5	0.00
4	300.1	3.2	0.01	298.4	9.2	0.02
5	305.4	0.2	0.00	304.4	13.0	0.02
6	254.6	2.8	0.01	256.6	1.3	0.00
7	300.3	2.0	0.00	300.9	5.6	0.01
8	293.7	4.3	0.01	299.6	7.8	0.01
9	297	0.6	0.00	298.7	6.1	0.01
10	332.8	1.4	0.00	334.6	1.0	0.00
11	274.1	2.2	0.00	275.4	7.4	0.01
12	268.3	5.3	0.01	270.1	3.0	0.01
13	316.1	12.4	0.02	320	3.7	0.01
14	358.3	4.2	0.01	357.7	4.8	0.01
15	359	2.6	0.00	365.4	12.6	0.02

Report 5-3 Statistical Analysis Report of the Stepwise Multiple Linear Regression of Combustion Duration (CD) Data

Whole Model Actual by Predicted Plot

Summary of Fit

RSquare	0.936759
RSquare Adj	0.923584
Root Mean Square Error	1.538134
Mean of Response	38.01
Observations (or Sum Wgts)	30

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	841.06648	168.213	71.1004
Error	24	56.78052	2.366	Prob > F
C. Total	29	897.84700		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	18	19.995516	1.11086	0.1812
Pure Error	6	36.785000	6.13083	Prob > F
Total Error	24	56.780516		0.9979
			Max RSq	0.9590

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	38.840021	0.548988	70.75	<.0001
Speed(15,30)	-0.778015	0.345851	-2.25	0.0339
Phi(0.28,0.38)	-0.729377	0.347358	-2.10	0.0464
Boost(14,54)	-6.457245	0.357646	-18.05	<.0001
Phi*Phi	-2.966923	0.64844	-4.58	0.0001
Boost*Boost	1.9227156	0.672454	2.86	0.0086

Residual by Predicted Plot

Speed(15,30) Leverage Plot

Phi(0.28,0.38) Leverage Plot

**Boost(14,54)
Leverage Plot**

**Phi*Phi
Leverage Plot**

**Boost*Boost
Leverage Plot**

Report 5-4 Statistical Analysis Report of the Stepwise Multiple Linear Regression of Maximum Cylinder Pressure (Pmax) Data

Whole Model Actual by Predicted Plot

Summary of Fit

RSquare	0.988715
RSquare Adj	0.985124
Root Mean Square Error	0.710756
Mean of Response	59.47667
Observations (or Sum Wgts)	30

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	973.67982	139.097	275.3446
Error	22	11.11384	0.505	Prob > F
C. Total	29	984.79367		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	16	9.813843	0.613365	2.8309
Pure Error	6	1.300000	0.216667	Prob > F
Total Error	22	11.113843		0.1024
				Max RSq
				0.9987

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	61.323131	0.254974	240.51	<.0001
Speed(15,30)	-0.381407	0.159716	-2.39	0.0260
Phi(0.28,0.38)	1.0242259	0.160666	6.37	<.0001
Boost(14,54)	6.7962999	0.165179	41.15	<.0001
Speed*Phi	-1.381211	0.180932	-7.63	<.0001
Phi*Boost	-0.623102	0.187447	-3.32	0.0031
Speed*Speed	-1.978252	0.299328	-6.61	<.0001
Phi*Phi	-0.912087	0.302097	-3.02	0.0063

Residual by Predicted Plot

**Speed(15,30)
Leverage Plot**

**Phi(0.28,0.38)
Leverage Plot**

**Boost(14,54)
Leverage Plot**

**Speed*Phi
Leverage Plot**

**Phi*Boost
Leverage Plot**

**Speed*Speed
Leverage Plot**

**Phi*Phi
Leverage Plot**

Report 5-5 Statistical Analysis Report of the Stepwise Multiple Linear Regression of Start of Combustion (SOC) Data

Whole Model Actual by Predicted Plot

Summary of Fit

RSquare	0.991664
RSquare Adj	0.989012
Root Mean Square Error	0.288954
Mean of Response	-4.70667
Observations (or Sum Wgts)	30

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	7	218.52179	31.2174	373.8854
Error	22	1.83688	0.0835	Prob > F
C. Total	29	220.35867		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	16	1.7268806	0.107930	5.8871
Pure Error	6	0.1100000	0.018333	Prob > F
Total Error	22	1.8368806		0.0187
			Max RSq	0.9995

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	-5.055055	0.103876	-48.66	<.0001
Speed(15,30)	0.1361531	0.064981	2.10	0.0479
Phi(0.28,0.38)	3.1192207	0.065282	47.78	<.0001
Boost(14,54)	1.0592752	0.067191	15.77	<.0001
Speed*Phi	0.3371114	0.073235	4.60	0.0001
Speed*Boost	0.2437026	0.077627	3.14	0.0048
Phi*Phi	0.280601	0.121998	2.30	0.0313
Boost*Boost	0.2899599	0.130053	2.23	0.0363

Residual by Predicted Plot

Speed(15,30)
Leverage Plot

Phi(0.28,0.38)
Leverage Plot

Boost(14,54)
Leverage Plot

Speed*Phi
Leverage Plot

Speed*Boost
Leverage Plot

Phi*Phi
Leverage Plot

Boost*Boost Leverage Plot

Report 5-6 Statistical Analysis Report of the Stepwise Multiple Linear Regression of Exhaust Temperature (Exhaust T) Data

Whole Model Actual by Predicted Plot

Summary of Fit

RSquare	0.996672
RSquare Adj	0.995979
Root Mean Square Error	2.427951
Mean of Response	293.9333
Observations (or Sum Wgts)	30

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	5	42376.388	8475.28	1437.719
Error	24	141.479	5.89	Prob > F
C. Total	29	42517.867		<.0001

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	10	29.64537	2.96454	0.3711
Pure Error	14	111.83333	7.98810	Prob > F
Total Error	24	141.47871		0.9398
				Max RSq
				0.9974

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	298.07553	0.870835	342.29	<.0001
Speed(15,30)	23.704624	0.544038	43.57	<.0001
Phi(0.28,0.38)	39.159636	0.548382	71.41	<.0001
Speed*Phi	4.9243973	0.615128	8.01	<.0001
Speed*Speed	-3.511783	1.022442	-3.43	0.0022
Phi*Phi	-2.492186	1.030644	-2.42	0.0236

Residual by Predicted Plot

Speed(15,30) Leverage Plot

Phi(0.28,0.38) Leverage Plot

**Speed*Phi
Leverage Plot**

**Speed*Speed
Leverage Plot**

**Phi*Phi
Leverage Plot**

The combustion parameters, namely, combustion duration (CD, crank angle degrees), maximum cylinder pressure (Pmax, bar), start of combustion (SOC, °BTDC), and exhaust temperature (Exhaust T, °C) models based on the stepwise multiple linear regression analyses are given in Equations 5-3 through 5-6.

$$CD = 38.8 - 0.778 * Speed - 0.729 * Phi - 6.46 * Boost - 2.97 * (Phi)^2 + 1.92 * (Boost)^2$$

Equation 5-3

$$P_{max} = 61.3 - 0.381 * Speed + 1.02 * Phi + 6.80 * Boost - 1.38 * (Speed * Phi) - 0.623 * (Phi * Boost) - 1.98 * (Speed)^2 - 0.912 * (Phi)^2$$

Equation 5-4

$$SOC = -5.1 + 0.14 * Speed + 3.1 * Phi + 1.1 * Boost + 0.34 * (Speed * Phi) + 0.24 * (Speed * Boost) + 0.28 * (Phi)^2 + 0.29 * (Boost)^2$$

Equation 5-5

$$ExhaustT = 298 + 23.7 * Speed + 39.2 * Phi + 4.92 * (Speed * Phi) - 3.51 * (Speed)^2 - 2.49 * (Phi)^2$$

Equation 5-6

The variables Speed, Phi, and Boost in the above equations are the coded speed, coded phi, and coded boost, respectively. The influence of the engine operating conditions on the combustion parameters, namely, combustion duration (CD), maximum cylinder pressure (Pmax), start of combustion (SOC) and the exhaust temperature (Exhaust T), and the resulting influence on oil consumption is summarized in Table 5-5. The influences of only the main effects, namely, speed, equivalence ratio (phi), and boost are shown in Table 5-5. Some of the interaction effects and quadratic effects were also significant as can be seen in Reports 5-3 through 5-6.

The significance of the corresponding factors (high to low) based on the parameter estimates are denoted by “+++”, “++”, and “+” in Table 5-5. The increase and decrease in the effect is denoted by “↑” and “↓”, respectively. The effects are shown for increase in speed, phi, and boost. The exhaust temperature was found to depend only on speed and phi.

Table 5-5 Effects of Combustion Parameters and Oil Consumption as a Result of Increasing Speed, Phi, and Boost

	C.D.	Pmax	SOC	Exhaust T	Oil Consumption (C-balance)	
					Brake-specific (g/bhp-hr)	Absolute (g/hr)
Speed (↑)	↓ (+)	↓ (+)	↑ (+)	↑ (+++)	↑ (+++)	↑ (+++)
Phi (↑)	↓ (+)	↑ (++)	↑ (+++)	↑ (+++)	↓ (+++)	↑ (++)
Boost (↑)	↓ (+++)	↑ (+++)	↑ (++)		↓ (+++)	↑ (++)

Based on parameter estimates in Report 5-2 (Section 5.1.2), boost was more significant than phi with respect to oil consumption. Boost was found to have a good correlation with combustion duration and is shown in Figure 5-13. The effect of boost on combustion duration was also seen in the statistical analysis, the results of which are summarized in Table 5-5.

Combustion duration is inversely related to flame speed or flame propagation rate in the case of spark ignition engines [4]. As a result, shorter combustion duration (higher flame propagation) results in a higher consumption of oil from the combustion chamber walls. Figure 5-13 shows that boost is inversely related to combustion duration, and as a result increased boost results in increased absolute oil consumption. Li et al. [4] found a good correlation between ϕ and combustion duration, but this was not the case in this study. However, they had a wider range for ϕ at a lower compression ratio and had only a single level of boost.

Figure 5-13 Correlation between Combustion Duration and Boost

The effect of ϕ can be explained by the relation between quenching distance and equivalence ratio. Shrestha and Karim [74] showed an inverse relation between ϕ and quenching distance. As can be seen from Table 5-5, increase in ϕ was found to decrease the combustion duration (though not as significant as the effect of boost), increase the maximum cylinder pressure, and increase combustion temperature, all of which influence the quenching distance; more specifically, decrease the quenching distance. Quenching distance is a characteristic length scale which is defined by the smallest crevice width that the flame can enter without being quenched. Increased ϕ results in smaller quenching distance and as a result the total oil consumed increases.

Speed was also not found to influence combustion duration as much as boost. Rather, speed can be considered to contribute to increased transport of oil into the combustion chamber, and it was the effect of ϕ and boost that impacted the consumption of oil entering the

combustion chamber. This can be attributed to the significance of speed-phi, speed-boost interaction in Report 5-2.

The increase in phi at constant speed and boost results in increased work done. This leads to reduced brake-specific oil consumption even though the absolute consumption increases.

Li et al. [4] employed a similar oil consumption measurement approach. However, contrary to their results, this study found that the HC emissions were more significant for oil consumption determination than CO emissions. They had neglected HC emissions and were not reported. In the current study, the gaseous products of oil consumption were primarily CO₂. HC was found to contribute around 10-25% of oil consumption depending on engine operating point consistent with studies of Furuhashi and Hiruma [6], whereas CO emissions were almost zero for most test points. Szabowski et al. [75] also reported HC emissions less than 1% of carbon oxide emissions for their test results.

It should also be noted that the previous studies [4,6,7,75] mentioned here had limited operating points tested, where oil consumption was calculated for varying levels of only a single factor.

The oil consumption trend as a function of equivalence ratio was similar to the study of Li et al. [4]. The backfire limiting equivalence ratio in the case of Li et al. [4] was also similar to the current study for a compression ratio of 8.5. The compression ratio for the test engine in this study was 13.3:1.

5.1.4. Influence of Engine Operating Conditions, and Combustion Parameters on Oil Consumption Sources

The major contributing sources to oil consumption in this study can be classified as follows:

- 1) Oil evaporation from liner (O.E.)
- 2) Oil transported into combustion chamber from piston-ring-liner system (O.T.)
- 3) Oil transported past the valve guides (O.V.)

Based on results summarized in Table 5-5, a similar table was summarized for the effects of engine operating conditions on each of the oil consumption sources, and is shown in Table 5-6. It should be noted that the oil consumption sources(O.E., O.T., O.V.) were not measured, but

the behavior of the sources are hypothesized based on the changes of combustion parameters with engine operating conditions.

Table 5-6 Effects of Engine Operating Conditions, and Combustion Parameters on Sources of Oil Consumption

	C.D.	Pmax	SOC	Exhaust T	Oil Contribution Source			Oil Consumption (C-balance)	
					O.E.	O.T.	O.V.	Brake-specific (g/bhp-hr)	Absolute (g/hr)
Speed ↑	↓	↓	↑	↑	↑	↑	↑	↑ (+++)	↑ (+++)
Phi ↑	↓	↑	↑	↑	↑	↓	↓	↓ (+++)	↑ (++)
Boost ↑	↓	↑	↑		↑	↓	↓	↓ (+++)	↑ (++)

The increase in speed results in an increase in the combustion temperature, and hence results in increased O.E. contribution. The O.T. and O.V. sources are assumed to increase with speed as a result of the increased revolutions. Hence, increase in speed can be considered to result in an increase in all the contribution sources, and this explains the high significance of speed towards the increase in both the brake-specific and absolute oil consumption.

The increase in phi and boost results in decreased combustion duration, which as discussed in Section 5.1.3 would increase the O.E. contribution. The increased cylinder pressures with increasing phi, and boost is attributed to the decreased O.T. and O.V. contributions at these conditions. The increase in phi and boost results in increase in work done; hence, decreased brake-specific oil consumption even though the absolute oil consumption increases as O.E. contribution can be considered dominant compared to O.T and O.V. for these conditions.

5.2. Elemental Carbon/ Organic Carbon (EC/OC), Trace Metals Analysis

The oil consumption discussed thus far was calculated from a carbon-balance utilizing gaseous emissions; CO₂ being the major contributor. The CO amounts were negligible, whereas the HC contributed to 10%-25% of the total oil consumption measured depending on the engine operating point. The oil consumed ending up in the gas phase can be considered as lubricant oil that is completely consumed. The partially burned and unburned lubricant oil gets converted to the particulate phase. Even though some of the gas phase hydrocarbons may also end up in the particulate phase and result in double counting, for the current study, it was assumed that the gas

phase hydrocarbons did not end up in the particulate phase.

Oil consumption studies in published literature present or define oil consumption in different ways. A few of them are cited in this section.

Li et al. [4] has defined the oil consumption in their hydrogen fueled engine study as what ends up in the exhaust as carbon oxide emission (neglecting hydrocarbons). Min et al. [5] determined oil consumption in their hydrogen engine study from CO₂ measurements alone. Furuhashi and Hiruma [6,7] in their study using hydrogen engine employed an oxidation catalyst upstream of the CO₂ analyzer so as to convert HC and CO emissions to CO₂, and calculated oil consumption from the CO₂ emissions.

Ariga et al. [25] and Froelund et al. [30,31] used SO₂ tracer technique for oil consumption measurement. In both studies, there was a furnace upstream of the SO₂ analyzer and the oil consumption calculated was represented as total oil consumption.

In studies [33-36] employing trace-metals or radio-tracer techniques, the oil consumption calculated from the tracer balance was assumed as total oil consumption.

The study by Puffel et al. [76] at the BMW liquid hydrogen test bed is of interest as they defined total oil consumption based on HC emissions. They defined measurements of single aromatic hydrocarbons made by a laser mass spectrometer as representative of unburned oil constituents, and HC measurements made by a Flame Ionization Detector (FID) and GC-FID as burned oil constituents. They assumed oil ending up as CO₂ as negligible. This was in contrast to what was observed in the current study.

Based on the discussion above, it is obvious that the selection of measurement and analysis methodologies are critical and the nature of oil consumption measured (burned, unburned, or total) needs to be clearly stated. The oil consumption calculated using Equation 4-1 is the gas phase derived oil consumption, and is representative of oil that is completely consumed.

This section involves determination of oil consumption based on the organic fraction, and trace metals contained in the particulate matter sampled from the partial flow dilution tunnel. The oil consumption determined from the organic carbon in the exhaust can be considered as representative of partially burned and unburned oil and is denoted as BSOC_{org} (g/bhp-hr).

The organic carbon based oil consumption was calculated for each steady-state test condition as follows,

$$\text{BSOC}_{\text{org}} = \frac{1}{m_c * W} * [\text{Organic Carbon in the exhaust}] * \frac{1}{10^6} \quad \text{Equation 5-7}$$

where, [Organic Carbon in the exhaust] = OC *SR,

where, OC = Background corrected Organic Carbon per test, µg/ filter, and

SR = Split Ratio,

W = Power output (bhp) as defined in Section 4.7.

The Split Ratio, SR, is given by,

$$\text{SR} = \frac{\dot{m}_a + \dot{m}_f}{\dot{m}_{\text{tun}} - \dot{m}_{\text{dil}}} \quad \text{Equation 5-8}$$

where, $\dot{m}_a$ = Intake air mass flow rate, g/s

$\dot{m}_f$ = Fuel (hydrogen) mass flow rate, g/s

$\dot{m}_{\text{tun}}$ = Diluted exhaust mass flow rate through the dilution tunnel, g/s

$\dot{m}_{\text{dil}}$ = Dilution air mass flow rate into the tunnel, g/s

The EC/OC analysis performed showed that the EC fraction was negligible and the particulate matter collected was almost all organic carbon. The analysis report from Desert Research Institute (DRI) is given in Table D1 in Appendix D.

Ca and Zn were the only two trace metal components found in the exhaust with concentrations greater than the uncertainty levels associated with their measurement. Mg is also usually found in significant levels in the case of diesel engine particulate emissions, but was not the case for either of the two oils in this study for the test conditions considered.

The brake-specific Ca and Zn balance based oil consumption (g/bhp-hr) were calculated as follows:

$$\text{BSOC}_{\text{Ca}} = \frac{1}{m_{\text{Ca}} * W} * [\text{Ca in the exhaust}] * \frac{1}{10^6} \quad \text{Equation 5-9}$$

where, [Ca in the exhaust] = [Ca] * SR,

where, [Ca] = Ca per test, µg/ filter, and

SR = Split Ratio

W = Power output (bhp) as defined in Section 4.7.

m_{Ca} = Mass fraction of Ca in the lubricant oil

Similarly,

$$\text{BSOC}_{\text{Zn}} = \frac{1}{m_{\text{Zn}} * W} * [\text{Zn in the exhaust}] * \frac{1}{10^6} \quad \text{Equation 5-10}$$

where, [Zn in the exhaust] = [Zn] * SR,

where, [Zn] = Zn per test, µg/ filter, and

SR = Split Ratio

m_{Zn} = Mass fraction of Zn in the lubricant oil

Table 5-7 shows the oil consumption calculated based on the various calculations. C-balance is the oil consumption based on gas phase emissions (completely burned oil). Organic C-balance, Ca-balance, Zn-balance, are based on the calculations in Equations 5-7 through 5-10, using the organic carbon, and trace metal concentrations contained in the PM sampled from a partial flow dilution tunnel. The % C-balance in Table 5-7 denotes the ratio of the corresponding oil consumption calculated to C-balance in percentage.

Table 5-7 Comparison of Oil Consumption (C-balance, Organic Fraction, Ca-balance, Zn-balance)

(Speed, Phi, Boost) Coded	C-balance g/bhp-hr	Organic C-balance		Ca-balance		Zn-balance	
		g/bhp-hr	% C-balance	g/bhp-hr	% C-balance	g/bhp-hr	% C-balance
Valvoline							
(-1,-1,-1)	0.40	0.18	44	0.10	24	0.03	8
(-1,-1,1)	0.36	0.15	43	0.09	25	0.10	27
(-1,1,-1)	0.28	0.21	74	0.14	50	0.16	58
(-1,1,1)	0.24	0.11	46	0.09	36	0.07	29
(0,0,0)	0.34	0.10	29	0.10	31	0.06	18
(1,-1,-1)	0.54	0.11	21	0.08	14	0.07	13
(1,-1,1)	0.41	0.04	11	0.05	11	0.03	7
(1,1,-1)	0.42	0.07	17	0.06	13	0.02	4
(1,1,1)	0.33	0.03	10	0.07	21	0.05	15
Amsoil							
(-1,-1,-1)	0.43	0.15	35	0.04	10	0.03	7
(-1,-1,1)	0.36	0.11	31	0.05	15	0.03	9
(-1,1,-1)	0.31	0.15	51	0.04	12	0.03	9
(-1,1,1)	0.25	0.09	34	0.06	23	0.04	14
(0,0,0)	0.35	0.10	29	0.06	18	0.05	14
(1,-1,-1)	0.53	0.06	11	0.02	3	0.04	8
(1,-1,1)	0.39	0.03	9	0.02	4	0.03	7
(1,1,-1)	0.37	0.04	10	0.05	13	0.01	3
(1,1,1)	0.35	0.06	17	0.01	3	0.03	9

The Ca and Zn based oil consumption may also be considered as representative of partially burned and unburned lubricant oil as it is obtained in the particulate matter.

In the previous section, it was seen that the carbon-balance derived oil consumption was similar for the two oils in spite of the synthetic oil being more volatile as indicated by the Noack volatility index. This shows that for conditions tested, the volatility does not have an impact on the completely consumed oil fraction. Figure 5-14 shows the normal probability plot and Figure 5-15 shows the box plot for the brake-specific organic fraction (mg/bhp-hr) for the two oils. Results indicate that the organic carbon in the exhaust is different for the two oils even though the carbon-balance derived oil consumption values calculated were the same for the given test conditions. This can be seen from results for organic fraction, and the Ca and Zn emissions results as well.

Figure 5-14 Normal Probability Plot (Organic Fraction Data for Mineral Oil and Synthetic Oil)

Figure 5-15 Box Plot (Organic Fraction Data for Mineral Oil and Synthetic Oil)

The results in Table 5-3 shows that the oil consumption calculated from a Ca-balance and Zn-balance have a significant difference (5-50% depending on operating state) compared to C-balance. This is similar to the findings in previous studies [36,62,77-80] where the Ca and Zn estimated from oil consumption estimates were higher than what was actually measured in the exhaust. The difference was attributed to the selective evaporation of the base-stocks compared to the additives. The two fractions evaporate at different temperatures; hence, result in the difference in calculated versus measured oil consumption. In this study, results of oil consumption based on C-balance were similar for the two oils, and the Ca and Zn mass fractions were also similar for the two oils, but the Ca and Zn that was detected in the PM samples were different. This was similar for the organic fraction as well. Figures 5-16 through 5-19 show the normal probability plots and box plots for brake-specific Ca and Zn emissions measured. The normal plots indicate that the data are normally distributed, but are different for the two oils, and the box plot also confirms the normal plot results.

Figure 5-16 Normal Probability Plot (Brake-specific Ca: Mineral Oil and Synthetic Oil)

Figure 5-17 Box Plot (Brake-specific Ca: Mineral Oil and Synthetic Oil)

Figure 5-18 Normal Probability Plot (Brake-specific Zn: Mineral Oil and Synthetic Oil)

Figure 5-19 Box Plot (Brake-specific Zn: Mineral Oil and Synthetic Oil)

It is generally considered that higher volatility results in higher oil consumption. However, results presented above show evidence to the contrary, that is, the consumption of partially burned oil calculated from the organic carbon fraction is higher for the mineral oil in spite of its lower volatility. The same is true for Ca and Zn emissions, as well. This may be attributed to differences in the base-stocks between the mineral oil and synthetic oil and the slightly lower C-mass fraction for the synthetic oil (approximately, 0.84-0.85) compared to the mineral oil (approximately, 0.85-0.86). In the case of synthetic oil base stocks, molecules are uniform in size and shape, and devoid of contaminants, which are attributed to the chemical processes adopted to produce the oils; hence, a more complete combustion of the oil that is consumed. Whereas, mineral oil base stocks are comprised of molecules of different chemical properties, shapes and sizes, which make some of its components evaporate more readily. It is very likely that mineral oils have contaminants resulting from inadequacies in the extraction and refining processes involved. This would explain the higher partially burned and unburned fraction for the mineral oil in spite of its lower volatility.

Figure 5-20 shows the comparison between C-balance, organic fraction based, and Ca/Zn based oil consumption results.

Figure 5-20 Comparison of Calculated Oil Consumption Values (Mineral Oil and Synthetic Oil)

Results clearly indicate that the trace-metal balance is not a suitable method for oil consumption determination because additives have a different rate of consumption compared to the base-stock. Also, it is seen from this study that the trace-metal concentrations measured in the exhaust are different for the two oils even though the oil consumption levels and the trace-metal concentrations in the oils are similar. Results presented in this section also indicate the importance of differentiating between the definition of oil consumption based on various methods employed for oil consumption determination.

5.3. PM Concentrations and Size Distribution Analysis

5.3.1. Brake-specific Particle Size Distribution Results

Particle size distributions were recorded using an SMPS for all the fifteen operating states for both the test oils. The SMPS recorded five samples for each test. The normalized particle size distribution data is shown in Appendix E, with error bars denoting two standard deviations

($\pm 2\sigma$) . The particle number data was more repeatable for the high speed and high equivalence ratio operating states. Brake-specific particle number distributions were calculated using the following equation,

$$BSPN = \frac{PN * DR * V_{exh} * t * 10^6}{W} \quad \text{Equation 5-11}$$

PN = Particle number concentration, $\#/cm^3$

V_{exh} = Volumetric exhaust flowrate (Equation 4-2), m^3/s

t = Test time for the operating point under consideration

W = Work done during the operating state, bhp-hr

DR = Dilution Ratio, and is given by,

$$DR = \frac{\dot{m}_{tun}}{\dot{m}_{tun} - \dot{m}_{dil}} \quad \text{Equation 5-12}$$

$\dot{m}_{tun}$ = Diluted exhaust mass flow rate through the dilution tunnel, g/s

$\dot{m}_{dil}$ = Dilution air mass flow rate into the tunnel, g/s

Figure 5-21 shows the lognormal probability plot for the average particle number data in the case of the two test oils for all the operating states. It is seen that the PM has lognormal size distributions, and that there is no significant difference with respect to the total particle numbers between the mineral oil and synthetic oil. The data for the two oils are in the same order of magnitude for corresponding operating states.

Figure 5-21 Lognormal Probability Plot of Particle Number Data

Figures 5-22 through 5-36 show the brake-specific particle number distribution, and the integrated particle number results. The integrated brake-specific number results are shown for each operating state alongside the brake-specific oil consumption (carbon-balance) and brake-specific organic fraction (from EC/OC results) data to illustrate the effects of lubricant oil consumption and organic fraction variation on particle formation. The error bars denote two standard deviations ($\pm 2\sigma$). The brake-specific organic fraction results do not have error bars since the results are based on one sample at each of the nine operating states for which PM was collected.

Figure 5-22 Brake-specific Particle Number Distribution (Mineral Oil): Speed = 15 rps

Figure 5-23 Brake-specific Oil Consumption, OC Fraction, Particle # (Mineral Oil): Speed = 15 rps

Figure 5-24 Brake-specific Particle Number Distribution (Synthetic Oil): Speed = 15 rps

Figure 5-25 Brake-specific Oil Consumption, OC Fraction, Particle # (Synthetic Oil):
Speed = 15 rps

Figure 5-26 Brake-specific Particle Number Distribution (Mineral Oil): Speed = 22.5 rps

Figure 5-27 Brake-specific Oil Consumption, OC Fraction, Particle # (Mineral Oil): Speed = 22.5 rps

Figure 5-28 Brake-specific Particle Number Distribution (Synthetic Oil): Speed = 22.5 rps

Figure 5-29 Brake-specific Oil Consumption, OC Fraction, Particle # (Synthetic Oil):
Speed = 22.5 rps

Figure 5-30 Brake-specific Particle Number Distribution (Mineral Oil): Speed = 30 rps

Figure 5-31 Brake-specific Oil Consumption, OC Fraction, Particle # (Mineral Oil): Speed = 30 rps

Figure 5-32 Brake-specific Particle Number Distribution (Synthetic Oil): Speed = 30 rps

Figure 5-33 Brake-specific Oil Consumption, OC Fraction, Particle # (Synthetic Oil):
Speed = 30 rps

The total brake-specific particle number increases for decreasing brake-specific oil consumption. Table 5-8 shows the integrated particle number data for each of the test points with the associated standard deviation and coefficient of variance (COV). The geometric mean diameter (or count median diameter, CMD, for lognormal distribution) is also listed for the operating states tested. Some of the test points have multiple CMDs because of the bimodal distributions; hence, CMD was calculated for each mode. The CMD and geometric standard deviations (GSD) were calculated using the following equations,

$$CMD = \exp \left[\frac{\sum n_i \ln d_p}{N} \right] \quad \text{Equation 5-13}$$

where, n_i = Number of particles in i^{th} bin,

d_p = Mean diameter of i^{th} bin,

N = Total number of particles

$$GSD = \exp \left[\frac{\sum n_i (\ln d_p - \ln CMD)^2}{N - 1} \right]^{1/2} \quad \text{Equation 5-14}$$

Table 5-8 Particle Number Statistics for the Operating States

State No.	Mineral Oil					Synthetic Oil				
	Integrated Particle Number			CMD	GSD	Integrated Particle Number			CMD	GSD
	Avg (#/cm3)	S.D.	COV			Avg (#/cm3)	S.D.	COV		
1	3.44E+07	1.69E+06	0.05	233	1.65	4.74E+07	2.88E+06	0.06	196	1.69
2	8.32E+07	4.09E+06	0.05	225	1.68	5.66E+07	6.64E+06	0.12	200	1.72
3	1.28E+08	1.24E+07	0.10	192	1.66	1.38E+08	2.14E+07	0.16	137	2.03
4	3.10E+08	4.59E+06	0.01	130	2.35	4.79E+08	1.64E+07	0.03	121	2.20
5	5.24E+08	1.11E+07	0.02	125	2.19	5.31E+08	2.00E+07	0.04	95	2.49
6	1.33E+08	3.66E+06	0.03	(31,209)	(1.31,1.49)	5.14E+08	1.28E+08	0.25	(35,172)	(1.39,1.55)
7	2.75E+08	2.44E+07	0.09	112	3.41	3.44E+08	1.15E+07	0.03	(32,145)	(1.42,1.65)
8	5.90E+08	4.20E+07	0.07	(34,186)	(1.33,1.51)	1.54E+09	1.68E+08	0.11	48	1.73
9	1.97E+09	1.13E+08	0.06	49	1.59	7.32E+08	5.04E+07	0.07	(43,163)	(1.54,1.43)
10	2.00E+09	4.46E+07	0.02	42	1.57	1.17E+09	5.87E+07	0.05	74	2.28
11	4.35E+08	5.03E+07	0.12	(28,189)	(1.27,1.58)	1.42E+09	1.46E+08	0.10	36	1.43
12	1.51E+09	3.36E+08	0.22	36	1.48	1.46E+09	1.03E+08	0.07	32	1.50
13	2.94E+09	2.66E+08	0.09	56	1.75	4.15E+09	2.91E+08	0.07	46	1.61
14	3.14E+09	2.18E+08	0.07	55	1.79	4.46E+09	9.19E+07	0.02	43	1.51
15	5.84E+09	1.66E+08	0.03	60	1.77	7.18E+09	4.11E+08	0.06	59	1.88

It was observed that the CMD shifted to the smaller diameters as speed increased. The lower CMDs also correspond to operating states for which the ratio of organic fraction based oil consumption to gaseous emissions based oil consumption is lower (Refer Table 5-3). This signifies that as the organic fraction (which represents unburned and partially burned oil) increases, there is a corresponding rise in the accumulation mode particles. The shift in distribution to lower particle diameters at the higher speeds may also be attributed to the lesser time for agglomeration at high speeds.

PM distributions become bimodal with increasing speed (that is, the nuclei mode appears) in the case of some of the operating states. The increase in ϕ was found to increase the total particle number, and also shifted the CMDs to the lower diameters, whereas increase in boost resulted in increase in particle numbers without making any significant change in the size distribution pattern.

The results show no significant effects of volatility on particle formation. It is evident that the PM concentrations and size distributions depend more on the amount of oil consumed and the combustion conditions. Figures 5-34 through 5-36 show the oil-specific particle number (#/g of oil) for the two oils for the operating conditions tested. The particle size distributions, the total particle numbers, and the mean diameters are very similar for the two oils tested, showing no significant advantage for either lubricant oil in terms of number of particles formed. The mean diameters were slightly lower for the synthetic oil compared to the mineral oil for the low speed operating states.

The lower organic fraction and trace-metal concentrations for the synthetic oil compared to mineral oil did not result in a corresponding decrease in particles formed for the synthetic oil (even though the mean diameters were slightly lower) leading to a possible explanation that most of the particles were formed from homogenous nucleation of the gas phase hydrocarbons. The nanoparticle formation is also driven by an absence of carbonaceous soot particles, which usually act as a “sponge” for the volatile particle forming precursors [81].

Figure 5-34 Comparison of Oil-specific Particle Number : Speed = 15 rps

Figure 5-35 Comparison of Oil-specific Particle Number : Speed = 22.5 rps

Figure 5-36 Comparison of Oil-specific Particle Number: Speed = 30 rps

The brake-specific particle number increases with speed, equivalence ratio, and boost and the increase is seen primarily in the number of nanoparticles formed. Even though the brake-specific oil consumed decreases, the increase in number is a result of the increase in the amount of oil (g/hr) consumed. In summary, as more oil consumed, higher the particles formed, and higher the combustion temperature, higher the number of nanoparticles formed.

5.3.2. Particle Size Distribution (Motoring versus Combustion)

Particle size distributions were measured at motoring (no-fuel operation) conditions for five different steady-state modes. It was assumed that the motoring operation results would shed light on how the oil is transported into the combustion chamber, and eventually gets consumed or partially consumed when combustion occurs.

Figures 5-37 and 5-39 illustrate the particle size distribution results for motoring conditions at a constant boost (40 kPa) operation (at the three levels of speed), and for constant speed (22.5 rps) operation (at the three levels of boost), respectively.

Figures 5-38 and 5-40 show the results for corresponding operating states (that is, same boost and speed) with combustion at a ϕ of 0.33.

Figure 5-37 Particle Size Distribution (Motoring): Constant Boost = 40 kPa

Figure 5-38 Particle Size Distribution: Constant Boost = 40 kPa, $\Phi = 0.33$

Figure 5-39 Particle Size Distribution (Motoring): Constant Speed = 22.5 rps

Figure 5-40 Particle Size Distribution: Constant Speed = 22.5 rps, $\Phi = 0.33$

Table 5-5 shows integrated results, exhaust temperatures and maximum cylinder pressures obtained for the different states.

The difference between the combustion mode and the motoring mode in all the cases is an increase in the accumulation mode particles as a result of combustion. The amount of oil entering the combustion chamber and hence number of particles formed will be different in the two modes because of the difference in the cylinder pressures and the combustion conditions. Nevertheless, results provide evidence of lubricant oil derived nanoparticle formation at motoring conditions. This would be observed in on-road vehicles during coasting or downhill drives.

At lower speeds, the accumulation mode was dominant. This could be attributed to the higher ratio of particulate phase to gas phase hydrocarbons as can be seen from Table 5-2 presented in Section 5-2.

**Table 5-9 Comparison of Integrated Particle Number, Exhaust Temperatures, and
Maximum Cylinder Pressures (Combustion vs Motoring)**

Motoring (Constant Boost = 40 kPa)			
Speed (rps)	Total (#/cm3)	Exhaust Temp (oC)	Pmax (bar)
15	1.54E+09	38	40
22.5	4.82E+09	43	40
30	3.65E+09	60	40

Combustion				
Speed (rps)	Phi	Total (#/cm3)	Exhaust Temp (oC)	Pmax (bar)
15	0.33	1.28E+08	270	60
22.5	0.33	5.90E+08	294	60
30	0.33	2.94E+09	316	60

Motoring (Constant Speed = 22.5 rps)			
Boost (kPa)	Total (#/cm3)	Exhaust Temp (oC)	Pmax (bar)
20	3.82E+09	51	35
40	4.82E+09	43	41
60	4.97E+09	35	47

Combustion				
Boost (kPa)	Phi	Total (#/cm3)	Exhaust Temp (oC)	Pmax (bar)
20	0.33	2.59E+08	300	55
40	0.33	5.90E+08	294	61
60	0.33	1.97E+09	297	68

5.3.3. Particle Surface Area Distribution Analysis

In recent years the relation between nanoparticles to health effects has been of concern [82-84]. The increased concentrations of nanoparticles result in a greater surface area which in turn results in higher exposure of PM-bound toxic compounds. Figures 5-41 through 5-49 show the surface area distributions for the different operating states for the two oils and also the integrated surface areas. The total geometric surface area was calculated from the particle number data based on electrical mobility diameter assuming the particles to be spherical. The surface area results trend in much the same way as the particle number results: higher the number, higher the surface area. The increase in number is always due to an increase in the concentration of nanoparticles; hence, increased surface area.

Figure 5-41 Particle Surface Area Distribution (Mineral Oil): Speed = 15 rps

Figure 5-42 Particle Surface Area Distribution (Synthetic Oil): Speed = 15 rps

Figure 5-43 Comparison of Integrated Particle Surface Area (Mineral vs. Synthetic): Speed = 15 rps

Figure 5-44 Particle Surface Area Distribution (Mineral Oil): Speed = 22.5 rps

Figure 5-45 Particle Surface Area Distribution (Synthetic Oil): Speed = 15 rps

Figure 5-46 Comparison of Integrated Particle Surface Area (Mineral vs. Synthetic): Speed = 22.5 rps

Figure 5-47 Particle Surface Area Distribution (Mineral Oil): Speed = 30 rps

Figure 5-48 Particle Surface Area Distribution (Synthetic Oil): Speed = 30 rps

Figure 5-49 Comparison of Integrated Particle Surface Area (Mineral vs. Synthetic): Speed = 30 rps

As seen for the particle number behavior, the surface area is also found to increase with increasing speed, load and boost. Mutagenicity (a measure of the toxicity associated with a substance) of the particulate matter collected for selected operating states were simultaneously performed with this study by Solano [23]. Results showed increased mutagenic activity with increasing speed and load, which relates with the increased surface area found at these conditions. It was found that even though the surface area, and the particle numbers were similar for both oils, the mineral oil was found to be more mutagenic at most of the operating states. This could be due to multiple reasons. One, the organic fraction was more for the mineral oil which could be the driving factor for mutagenicity, and second, the chemical properties of the synthetic base stock. However, considerable more experiments are needed before arriving at any firm conclusions.

5.4. Lubricant Oil Aging: Effects on Lubricant Properties

Lubricant samples were collected after the lubricant break-in and approximately at 15-20 hour intervals over the 50 hour test matrix for both test oils. A previous study [51] on a hydrogen fueled engine has reported a decrease in kinematic viscosity at 100°C and a breakdown in lubricating and wear-resisting additives after a limited but unspecified testing time. The study had also suggested crankcase ventilation as a possible remedy to avoid such a situation. The current study used a forced crankcase ventilation system which consisted of a continuous supply of site air so as to purge the crankcase of any blow-by gases into the exhaust stack. Table 5-6 shows the lubricant properties analyzed for samples collected at different intervals. The lubricant analysis was performed by the Valvoline Product Development Laboratory.

Viscosities and volatilities were fairly uniform over the entire testing period for both the test oils. The carbon, and hydrogen mass fractions, and the trace metal fractions were also the same for the different samples.

The Total Acid Number (TAN) and Total Base Number (TBN) are good indicators of oil quality. TAN is a measure of the acidity level of the lubricant oil. Increase in TAN indicates lubricant oxidation or contamination of the oil with acidic products. TBN on the other hand is a measure of the alkalinity or the alkaline additives of the lubricant oil. The alkaline additives are required to neutralize the acidic products (for example, nitric acid or sulfuric acid formed by reaction of NO_x or SO₂ with water vapor). The TAN usually increases and TBN usually decreases over period of time for in-service lubricant oil. The time of cross over of TAN and TBN is an indicator of loss of lubricant properties. In this study, both the TAN and TBN were about the same level for all the samples. In fact, the TAN and TBN were found to decrease slightly over the test duration. The same can be said for the oxidation and nitration levels also.

The water content was also found to decrease with time. The water is usually evaporated as a result of the hot operating conditions during engine operation. In the case of a hydrogen-fueled engine, the by-product of combustion is water; hence, the water content would be of concern, as water would deteriorate the lubricant properties.

Results presented in Table 5-6 show no significant variation in properties over the 50 hour testing time for both oils. The short test duration, and forced crankcase ventilation could be offered as reasons for the lack of variations in oil properties.

Table 5-10 Lubricant Oil Properties at Various Testing Intervals

Oil Type	Mineral Oil (Valvoline)					Synthetic Oil (Amsoil)				
Sample Age →	Fresh	~3hr	~18hr	~33hr	~48hr	Fresh	~3hr	~18hr	~33hr	~48hr
Properties ↓										
Carbon (wt. %)	85.56	85.62	86.55	86	85.75	85.41	85.03	84.04	84.16	83.72
Hydrogen (wt. %)	13.86	13.85	14.25	13.74	13.68	14.22	14.14	13.95	14.05	14
Viscosity @ 100 C	15.01	14.997	14.94	14.95	14.96	13.97	13.99	14.02	14.03	14.06
Viscosity @ 40 C	140.76	141.36	141.21	140.97	140.64	103	103.13	103.76	103.61	103.61
Pour Point (oC)	-27	-27	-27	-27	-27	-48	-48	-48	-45	-45
Noack (% wt. loss)	2.68%	2.89%	2.97%	2.98%	2.91%	4.17%	4.43%	4.57%	4.38%	4.42%
X-Ray Metals										
Ca (wt. %)	0.112	0.111	0.115	0.114	0.113	0.118	0.121	0.12	0.117	0.118
Zn (wt. %)	0.03	0.031	0.031	0.031	0.031	0.03	0.03	0.03	0.03	0.03
P (wt. %)	0.022	0.02	0.02	0.022	0.021	0.019	0.019	0.018	0.021	0.019
S (wt. %)	0.079	0.075	0.077	0.079	0.081	0.075	0.075	0.074	0.075	0.076
Water %	0.075	0.051	0.057	0.045	0.049	0.054	0.054	0.047	0.05	0.039
Sulfated Ash %	0.371	0.427	0.39	0.347	0.438	0.43	0.366	0.45	0.442	0.421
TAN	1.04	0.89	1.01	0.9	0.78	1.23	1.22	1.1	1.09	1.16
TBN	6.18	5.22	5.25	4.88	5.21	4.26	5.68	4.49	4.74	4.46
Fuel %	0.5	0.5	0.5	0.5	1.3	0.5	0.5	0.5	0.5	0.5
Soot %	0	0	0	0	0	0	0	0	0	0
Oxidation	6	6	7	6	6	6	9	9	6	6
Nitration	8	8	11	8	8	8	9	10	8	8

6. CONCLUSIONS AND RECOMMENDATIONS

The objective of the study was to determine lubricant oil consumption as a function of engine operating conditions, and also provide an understanding of the lubricant oil consumed that ends up in the gaseous and particulate phases.

6.1. Conclusions

The relevant conclusions from this study are summarized below:

1. Lubricant oil consumption was found to be well correlated to engine operating conditions, such as engine speed, equivalence ratio, and intake air boost pressure. The brake-specific oil consumption (g/bhp-hr) was found to increase with increase in speed, decrease with increase in equivalence ratio, and decrease with increase in boost. The time-specific or absolute oil consumption (g/hr) was found to increase with increase in speed, increase in equivalence ratio, and increase in boost. (Section 5.1.1 and Section 5.1.2)
2. The oil consumption measurements based upon the carbon-balance method were found to be very repeatable at the steady-state modes tested in this study. This was in contrast to previous studies on diesel-fueled engines, where the repeatability of data based upon the sulfur-balance method was poor, and was attributed to the nature of oil consumption. (Section 5.1)
3. The oil consumption based on carbon balance was found to be similar for the two oils (mineral and synthetic). The organic fraction and trace metals which are representative of partially and unburned lubricant oil were higher for the mineral oil operation in spite of its lower volatility. (Section 5.1)
4. The combustion parameters, namely combustion duration, peak cylinder pressure, start of combustion, and exhaust temperature were well correlated to the engine operating conditions; hence, influenced the variation in oil consumption, and oil consumption sources at the various operating states. (Section 5.1.3 and Section 5.1.4)
5. Absolute or time-specific oil consumption (g/hr) was found to be better predicted compared to brake-specific oil consumption. Hence, absolute oil consumption

(g/hr) would be a better metric to represent oil consumption. (Section 5.1)

6. The need for distinguishing between the completely consumed oil fraction (gas based or gas phase measurements), and partially and unburned fraction (based on particulate phase measurement) was deemed important because of the significant differences between the two and the large variations in the ratios of the two measurements at different engine operating states. A review of published literature revealed the use of several different methods for oil consumption measurement, but in most cases the measured parameter was defined as total oil consumed, irrespective of the method employed. (Section 5.2)
7. Ca and Zn were the only elements found in detectable quantities in the particulate phase. The low levels of other elements are attributed to the low equivalence ratios used in this study, and the extremely low ash composition of the two oils (<0.45 wt.%). (Section 5.2)
8. It was found that the trace metal marker balance for oil consumption measurement was not a feasible method of oil consumption determination as a result of the variation in base stock versus additive consumption. The selective evaporation of base stock versus additives was also found to be vary with the operating conditions. (Section 5.2)
9. Carbon balance method can be considered reliable to a certain extent, since carbon is the most abundant element in lubricant oil. Other methods, such as sulfur balance, trace metal balance, or radio-tracer method require extremely accurate measurements owing to the extremely low (<1%) mass fractions of these elements compared to carbon (>80%). However, the carbon balance method would not be applicable in the case of diesel or CNG fueled engines (carbon based fueled engines). Therefore, care must be taken in interpreting results of lubricant consumption from such engines when the method is based on sulfur balance, and trace metal balance methods. (Section 5.2)
10. The particle size distributions and total particle number were found to be a function of mass of oil consumed. Lower CMDs were associated with higher speed, and loads, and lower ratios of organic fraction to oil consumed. The

particle size distributions also tended to be bimodal distributions (that is, nanoparticles appear) at certain operating conditions of higher speeds for both oils. (Section 5.3.1)

11. The PM concentrations for both oils were of the same order of magnitude, and the size distributions were also similar even though the CMD were slightly lower for the synthetic oil compared to mineral oil for the low speed operating points. This showed there were no significant effects of volatility, or synthetic versus mineral base stock on particle formation. It was evident that the particle number concentrations and size distributions depended more on the amount of oil consumed and the combustion conditions. (Section 5.3.1)
12. The particle size distributions for the motoring (no-fuel) test conditions were found to have higher concentrations, particularly in the nuclei mode, compared to the corresponding “fueled” modes. This highlights the presence of nanoparticle emissions during coasting or downhill driving conditions in the case of on-road vehicles. (Section 5.3.2)
13. The particle surface area distributions were found to have trends similar to the particle size distributions. A simultaneous study conducted to determine the mutagenicity of lubricant derived PM, found higher mutagenic activities for higher speed, and load conditions especially in the case of the mineral oil operation. This was found to correlate with the higher particle surface areas found at these conditions, and the higher organic fractions for the mineral oil compared to the synthetic oil. (Section 5.3.3)
14. Lubricant oil ageing (50 hours) showed no significant impact on oil properties. This could be attributed to the forced crankcase ventilation system used in this study which prevented blow-by gases from getting trapped in the crankcase, whereas in normal engines blow-by gases are either vented out into the exhaust or introduced back into the intake air system (positive crankcase ventilation). (Section 5.4)

6.2. Recommendations

Based on the findings from this study, the following recommendations for further improvement are suggested for future studies:

1. The operating envelope for the current study was limited by the premixed hydrogen-air fueling and the resulting backfire limiting equivalence ratios. It would help in a more complete understanding of oil consumption over the entire operating curve if a direct injection system employed engine is made available for a similar study.
2. Wider operating ranges could also help in using a circumscribed or inscribed central composite designs for the test matrix which employ five levels for each factor; hence, a better coverage of the operating envelop.
3. It is recommended to use several more oil formulations of lubricant oils with varying additive compositions, and varying lubricant properties (viscosity and volatility) so as to understand the components contributing to organic fraction and particle formation.
4. The oil temperature in this study was controlled at approximately 80°C for all the steady state operating states. It is recommended to study the effects of varying oil temperature on lubricant oil consumption and lubricant properties.
5. The lubricant oil is also recommended to be tested for 150-200 hours of operation to study variations in properties as a result of extended use, because 50 hours at the operating conditions tested in the current study found no significant effect on the oils tested.

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APPENDIX A : Uncertainty Analysis

The uncertainty associated with the carbon balance oil consumption, dilution ratio, and split ratio calculations are calculated below, using the root-sum square equation.

For any given equation,

$$F(x) = f(x_1, x_2, x_3, \dots, x_n),$$

the uncertainty associated with the measurement of F is given by,

$$\Delta F = \sqrt{\left(\frac{\partial F}{\partial x_1} \Delta x_1\right)^2 + \left(\frac{\partial F}{\partial x_2} \Delta x_2\right)^2 + \dots + \left(\frac{\partial F}{\partial x_n} \Delta x_n\right)^2},$$

where $\Delta x_1, \Delta x_2, \dots, \Delta x_n$ are the errors associated with $x_1, x_2, \dots, x_n$ respectively.

A1 C-balance Oil Consumption Calculation : Uncertainty

The carbon balance oil consumption (g/hr) was calculated as,

$$\dot{m}_{oil} = \frac{3600}{m_c} * \left[K_w \left\{ \left(\frac{[CO_2]}{10^6} V_{exh} \rho_{CO_2} \frac{MW_c}{MW_{CO_2}} \right) + \left(\frac{[CO]}{10^6} V_{exh} \rho_{CO} \frac{MW_c}{MW_{CO}} \right) \right\} + \left(\frac{[THC]}{10^6} V_{exh} \rho_{THC} \frac{MW_c}{MW_{THC}} \right) \right]$$

The uncertainty associated with $\dot{m}_{oil}$ neglecting the uncertainties in the constants used, that is, $\rho_{CO_2}, \rho_{CO}, \rho_{THC}, MW_c, MW_{CO_2}, MW_{CO}, MW_{THC}, m_c$, is given as,

$$\Delta \dot{m}_{oil} = \left[\left(\frac{\partial \dot{m}_{oil}}{\partial K_w} \Delta K_w \right)^2 + \left(\frac{\partial \dot{m}_{oil}}{\partial CO_2} \Delta CO_2 \right)^2 + \left(\frac{\partial \dot{m}_{oil}}{\partial CO} \Delta CO \right)^2 + \left(\frac{\partial \dot{m}_{oil}}{\partial THC} \Delta THC \right)^2 + \left(\frac{\partial \dot{m}_{oil}}{\partial V_{exh}} \Delta V_{exh} \right)^2 \right]^{\frac{1}{2}}$$

$$\frac{\partial \dot{m}_{oil}}{\partial K_w} = \frac{3600}{m_c} \left[\left(\frac{[CO_2]}{10^6} V_{exh} \rho_{CO_2} \frac{MW_c}{MW_{CO_2}} \right) + \left(\frac{[CO]}{10^6} V_{exh} \rho_{CO} \frac{MW_c}{MW_{CO}} \right) \right]$$

$$K_w = 1 - M_{H_2O}$$

$$\Delta K_w = \frac{\partial K_w}{\partial M_{H_2O}} \cdot \Delta M_{H_2O}$$

$$= -\Delta M_{H_2O}$$

$$\begin{aligned}
M_{H_2O} &= \frac{2\phi}{\phi + 4.76} \\
\Delta M_{H_2O} &= \frac{\partial M_{H_2O}}{\partial \phi} \cdot \Delta \phi \\
&= \frac{9.52}{(\phi + 4.76)^2} \cdot \Delta \phi \\
\phi &= 34.2 * \frac{\dot{m}_f}{\dot{m}_a},
\end{aligned}$$

where, 34.2 is the stoichiometric air-fuel ratio for hydrogen combustion in air.

$$\Delta \phi = \left[\left(\frac{\partial \phi}{\partial \dot{m}_f} \Delta \dot{m}_f \right)^2 + \left(\frac{\partial \phi}{\partial \dot{m}_a} \Delta \dot{m}_a \right)^2 \right]^{\frac{1}{2}}$$

$$\begin{aligned}
\frac{\partial \phi}{\partial \dot{m}_f} &= \frac{34.2}{\dot{m}_a} \\
\frac{\partial \phi}{\partial \dot{m}_a} &= \frac{-34.2 * \dot{m}_f}{\dot{m}_a^2}
\end{aligned}$$

$$\frac{\partial \dot{m}_{oil}}{\partial \dot{m}_{CO_2}} = \frac{3600 * K_w * V_{exh} * \rho_{CO_2}}{m_c * 10^6} \cdot \frac{MW_c}{MW_{CO_2}}$$

$$\frac{\partial \dot{m}_{oil}}{\partial \dot{m}_{CO}} = \frac{3600 * K_w * V_{exh} * \rho_{CO}}{m_c * 10^6} \cdot \frac{MW_c}{MW_{CO}}$$

$$\frac{\partial \dot{m}_{oil}}{\partial \dot{m}_{THC}} = \frac{3600 * V_{exh} * \rho_{THC}}{m_c * 10^6} \cdot \frac{MW_c}{MW_{THC}}$$

$$\frac{\partial \dot{m}_{oil}}{\partial V_{exh}} = \frac{3600}{m_c} * \left[K_w \left\{ \left(\frac{[CO_2]}{10^6} \rho_{CO_2} \frac{MW_c}{MW_{CO_2}} \right) + \left(\frac{[CO]}{10^6} \rho_{CO} \frac{MW_c}{MW_{CO}} \right) + \left(\frac{[THC]}{10^6} \rho_{THC} \frac{MW_c}{MW_{THC}} \right) \right\} \right]$$

$$V_{exh} = \frac{\dot{m}_a + \dot{m}_f}{\rho_{air}}$$

$$\Delta V_{exh} = \left[\left(\frac{\partial V_{exh}}{\partial \dot{m}_a} \Delta \dot{m}_a \right)^2 + \left(\frac{\partial V_{exh}}{\partial \dot{m}_f} \Delta \dot{m}_f \right)^2 \right]^{\frac{1}{2}}$$

$$\frac{\partial V_{exh}}{\partial \dot{m}_a} = \frac{1}{\rho_{air}}$$

$$\frac{\partial V_{exh}}{\partial \dot{m}_f} = \frac{1}{\rho_{air}}$$

Substituting for the above values, the calculated uncertainty in oil consumption measured ranged between 9-12% for the ranges of operating states considered in the study.

A2 Dilution Ratio Calculation : Uncertainty

The dilution ratio is calculated as,

$$DR = \frac{\dot{m}_{tun}}{\dot{m}_{tun} - \dot{m}_{dil}}$$

The uncertainty associated with DR is given by,

$$\Delta DR = \left[\left(\frac{\partial DR}{\partial \dot{m}_{tun}} \Delta \dot{m}_{tun} \right)^2 + \left(\frac{\partial DR}{\partial \dot{m}_{dil}} \Delta \dot{m}_{dil} \right)^2 \right]^{\frac{1}{2}}$$

$$\frac{\partial DR}{\partial \dot{m}_{tun}} = - \frac{\dot{m}_{dil}}{\left(\dot{m}_{tun} - \dot{m}_{dil} \right)^2}$$

$$\frac{\partial DR}{\partial \dot{m}_{dil}} = \frac{\dot{m}_{tun}}{\left(\dot{m}_{tun} - \dot{m}_{dil} \right)^2}$$

The uncertainty in dilution ratio for a dilution ratio of 12 used in this study was

approximately 9%.

A3 *Split Ratio Calculation : Uncertainty*

The split ratio is calculated as,

$$SR = \frac{\dot{m}_a + \dot{m}_f}{\dot{m}_{tun} - \dot{m}_{dil}}$$

The uncertainty associated with SR is given by,

$$\Delta SR = \left[\left(\frac{\partial SR}{\partial \dot{m}_a} \Delta \dot{m}_a \right)^2 + \left(\frac{\partial SR}{\partial \dot{m}_f} \Delta \dot{m}_f \right)^2 + \left(\frac{\partial SR}{\partial \dot{m}_{tun}} \Delta \dot{m}_{tun} \right)^2 + \left(\frac{\partial SR}{\partial \dot{m}_{dil}} \Delta \dot{m}_{dil} \right)^2 \right]^{\frac{1}{2}}$$

$$\frac{\partial SR}{\partial \dot{m}_a} = \frac{1}{\dot{m}_{tun} - \dot{m}_{dil}}$$

$$\frac{\partial SR}{\partial \dot{m}_f} = \frac{1}{\dot{m}_{tun} - \dot{m}_{dil}}$$

$$\frac{\partial SR}{\partial \dot{m}_{tun}} = - \frac{\dot{m}_a + \dot{m}_f}{\left(\dot{m}_{tun} - \dot{m}_{dil} \right)^2}$$

$$\frac{\partial SR}{\partial \dot{m}_{dil}} = \frac{\dot{m}_a + \dot{m}_f}{\left(\dot{m}_{tun} - \dot{m}_{dil} \right)^2}$$

The uncertainty in the split ratio ranged from approximately 3% to 13% in this study depending on the tunnel flow rate and exhaust flow rate at the various operating states.

APPENDIX B : Lubricant Oil Consumption Analysis - Experiment Matrix and Data

Test	Pattern	Speed rpm	Phi	Boost kPa	Oil	Coded Speed	Coded Phi	Coded Boost	Brake-specific Oil Consumption (g/bhp-hr)			Time-specific Oil Consumption (g/hr)		
									Actual	Stepwise	Robust	Actual	Stepwise	Robust
1	+++	30.1	0.38	52	M	1.01	1.00	0.85	0.30	0.32	0.32	6.97	7.69	7.76
2	000	22.5	0.33	34	M	0.00	0.00	-0.05	0.36	0.34	0.34	4.76	4.53	4.56
3	---	15.0	0.28	16	M	-1.00	-1.00	-0.95	0.39	0.43	0.43	2.11	2.39	2.40
4	a00	15.1	0.33	36	M	-0.99	0.00	0.05	0.29	0.29	0.29	2.56	2.59	2.61
5	A00	29.9	0.32	33	M	0.99	-0.20	-0.10	0.36	0.38	0.38	5.53	5.85	5.93
6	+++	30.1	0.28	51	M	1.01	-1.00	0.80	0.40	0.42	0.41	6.41	6.54	6.61
7	---	15.0	0.28	55	M	-1.00	-1.00	1.00	0.37	0.34	0.34	3.34	3.19	3.22
8	+++	30.0	0.38	14	M	1.00	1.00	-1.05	0.43	0.38	0.37	6.17	5.74	5.81
9	00A	22.4	0.33	54	M	-0.01	0.00	0.95	0.32	0.32	0.32	5.24	5.22	5.26
10	0A0	22.6	0.38	35	M	0.01	1.00	0.00	0.32	0.31	0.31	5.03	5.03	5.06
11	0a0	22.6	0.28	34	M	0.01	-1.00	-0.05	0.46	0.42	0.42	4.98	4.50	4.51
12	00a	22.5	0.33	16	M	0.00	0.00	-0.95	0.42	0.39	0.38	4.35	3.89	3.92
13	++-	30.0	0.28	13	M	1.00	-1.00	-1.10	0.46	0.52	0.51	4.20	4.60	4.66
14	++-	15.1	0.38	55	M	-0.99	1.00	1.00	0.22	0.25	0.25	2.80	3.12	3.16
15	+-	15.1	0.38	16	M	-0.99	1.00	-0.95	0.26	0.30	0.30	2.10	2.32	2.34
16	00a	22.5	0.33	15	M	0.00	0.00	-1.00	0.37	0.40	0.39	3.69	3.86	3.88
17	---	15.0	0.27	55	M	-1.00	-1.20	1.00	0.36	0.36	0.36	3.16	3.28	3.31
18	+++	30.0	0.28	52	M	1.00	-1.00	0.85	0.40	0.42	0.41	6.67	6.58	6.65
19	0A0	22.5	0.38	34	M	0.00	1.00	-0.05	0.31	0.31	0.31	4.83	4.97	5.00
20	---	15.0	0.28	16	M	-1.00	-1.00	-0.95	0.41	0.43	0.43	2.23	2.39	2.40
21	+++	30.0	0.38	52	M	1.00	1.00	0.85	0.33	0.32	0.32	7.74	7.66	7.75
22	++-	30.0	0.28	14	M	1.00	-1.00	-1.05	0.58	0.52	0.51	5.07	4.65	4.72
23	+++	15.1	0.38	55	M	-0.99	1.00	1.00	0.26	0.25	0.25	3.25	3.12	3.16
24	0a0	22.6	0.28	35	M	0.01	-1.00	0.00	0.41	0.42	0.42	4.39	4.53	4.55
25	+-	15.0	0.37	16	M	-1.00	0.80	-0.95	0.30	0.31	0.30	2.36	2.23	2.26
26	a00	15.0	0.33	36	M	-1.00	0.00	0.05	0.31	0.29	0.29	2.79	2.55	2.59
27	A00	29.9	0.33	33	M	0.99	0.00	-0.10	0.35	0.37	0.36	5.87	5.95	6.03
28	00A	22.5	0.33	54	M	0.00	0.00	0.95	0.30	0.32	0.32	5.00	5.24	5.28
29	000	22.5	0.33	34	M	0.00	0.00	-0.05	0.33	0.34	0.34	4.35	4.53	4.56
30	+++	30.0	0.38	14	M	1.00	1.00	-1.05	0.43	0.38	0.37	6.22	5.74	5.81
31	00a	22.5	0.33	15	M	0.00	0.00	-1.00	0.45	0.40	0.39	4.54	3.86	3.88
32	+++	15.0	0.38	55	M	-1.00	1.00	1.00	0.25	0.25	0.25	3.18	3.08	3.13
33	a00	15.0	0.33	36	M	-1.00	0.00	0.05	0.29	0.29	0.29	2.58	2.55	2.59
34	A00	30.0	0.33	33	M	1.00	0.00	-0.10	0.35	0.37	0.36	5.61	5.97	6.05
35	+++	30.1	0.38	52	M	1.01	1.00	0.85	0.36	0.32	0.32	8.35	7.69	7.76
36	+++	30.0	0.28	51	M	1.00	-1.00	0.80	0.42	0.42	0.41	6.68	6.53	6.60
37	0A0	22.5	0.38	34	M	0.00	1.00	-0.05	0.28	0.31	0.31	4.41	4.97	5.00
38	000	22.5	0.32	35	M	0.00	-0.20	0.00	0.32	0.35	0.35	4.17	4.53	4.56
39	0a0	22.5	0.28	34	M	0.00	-1.00	-0.05	0.41	0.42	0.42	4.38	4.48	4.50
40	---	15.0	0.27	16	M	-1.00	-1.20	-0.95	0.41	0.46	0.45	2.18	2.49	2.49
41	++-	30.0	0.27	13	M	1.00	-1.20	-1.10	0.57	0.55	0.54	4.89	4.57	4.64
42	++-	15.1	0.28	54	M	-0.99	-1.00	0.95	0.36	0.34	0.34	3.33	3.20	3.22
43	++-	30.0	0.37	13	M	1.00	0.80	-1.10	0.40	0.39	0.38	5.75	5.51	5.58
44	00A	22.5	0.33	54	M	0.00	0.00	0.95	0.31	0.32	0.32	5.10	5.24	5.28
45	+-	15.1	0.38	16	M	-0.99	1.00	-0.95	0.27	0.30	0.30	2.26	2.32	2.34
46	+++	15.1	0.38	55	S	-0.99	1.00	1.00	0.23	0.25	0.25	2.97	3.12	3.16
47	A00	30.0	0.33	33	S	1.00	0.00	-0.10	0.31	0.37	0.37	5.29	5.97	6.05
48	---	15.0	0.28	17	S	-1.00	-1.00	-0.90	0.45	0.43	0.43	2.42	2.41	2.42
49	++-	30.0	0.28	13	S	1.00	-1.00	-1.10	0.51	0.52	0.51	4.68	4.60	4.66
50	++-	15.1	0.28	55	S	-0.99	-1.00	1.00	0.37	0.34	0.34	3.37	3.22	3.24
51	0A0	22.5	0.38	34	S	0.00	1.00	-0.05	0.30	0.31	0.31	4.73	4.97	5.00
52	+++	30.0	0.38	52	S	1.00	1.00	0.85	0.35	0.32	0.32	8.26	7.66	7.75
53	a00	15.0	0.33	36	S	-1.00	0.00	0.05	0.31	0.29	0.29	2.88	2.55	2.59
54	00A	22.5	0.33	54	S	0.00	0.00	0.95	0.28	0.32	0.32	4.75	5.24	5.28
55	000	22.5	0.33	15	S	0.00	0.00	-1.00	0.36	0.40	0.39	3.76	3.86	3.88
56	++-	30.0	0.38	14	S	1.00	1.00	-1.05	0.36	0.38	0.38	5.38	5.74	5.81
57	000	22.5	0.33	34	S	0.00	0.00	-0.05	0.35	0.34	0.34	4.62	4.53	4.56
58	+++	30.1	0.28	52	S	1.01	-1.00	0.85	0.41	0.42	0.42	6.70	6.59	6.66
59	+-	15.0	0.38	17	S	-1.00	1.00	-0.90	0.31	0.30	0.30	2.53	2.31	2.33
60	0a0	22.5	0.28	34	S	0.00	-1.00	-0.05	0.43	0.42	0.42	4.66	4.48	4.50
61	A00	30.0	0.33	33	S	1.00	0.00	-0.10	0.35	0.37	0.37	5.94	5.97	6.05
62	---	15.0	0.28	16	S	-1.00	-1.00	-0.95	0.41	0.43	0.43	2.20	2.39	2.40
63	000	22.5	0.33	15	S	0.00	0.00	-1.00	0.39	0.40	0.39	3.92	3.86	3.88
64	++-	30.0	0.27	14	S	1.00	-1.20	-1.05	0.53	0.54	0.53	4.75	4.63	4.69
65	+-	15.0	0.37	16	S	-1.00	0.80	-0.95	0.31	0.31	0.30	2.44	2.23	2.26
66	+++	15.0	0.37	55	S	-1.00	0.80	1.00	0.27	0.25	0.25	3.30	3.02	3.07
67	+++	30.0	0.38	52	S	1.00	1.00	0.85	0.35	0.32	0.32	8.20	7.66	7.75
68	000	22.5	0.33	34	S	0.00	0.00	-0.05	0.37	0.34	0.34	5.05	4.53	4.56
69	++-	30.0	0.38	14	S	1.00	1.00	-1.05	0.36	0.38	0.38	5.30	5.74	5.81
70	00A	22.6	0.33	54	S	0.01	0.00	0.95	0.32	0.32	0.32	5.26	5.27	5.30
71	a00	15.0	0.33	36	S	-1.00	0.00	0.05	0.32	0.29	0.29	2.94	2.55	2.59
72	0A0	22.5	0.38	35	S	0.00	1.00	0.00	0.31	0.31	0.31	4.99	5.01	5.04
73	0a0	22.5	0.28	34	S	0.00	-1.00	-0.05	0.42	0.42	0.42	4.63	4.48	4.50
74	+++	30.1	0.28	51	S	1.01	-1.00	0.80	0.37	0.42	0.42	6.13	6.54	6.61
75	++-	15.0	0.28	55	S	-1.00	-1.00	1.00	0.35	0.34	0.34	3.25	3.19	3.22
76	+-	15.1	0.37	17	S	-0.99	0.80	-0.90	0.29	0.30	0.30	2.40	2.28	2.30
77	00A	22.5	0.33	54	S	0.00	0.00	0.95	0.34	0.32	0.32	5.82	5.24	5.28
78	++-	14.9	0.38	55	S	-1.01	1.00	1.00	0.25	0.25	0.25	3.29	3.04	3.10
79	++-	30.1	0.37	14	S	1.01	0.80	-1.05	0.37	0.39	0.38	5.37	5.57	5.65
80	+++	30.0	0.28	52	S	1.00	-1.00	0.85	0.40	0.42	0.42	6.61	6.58	6.65
81	00a	22.6	0.33	15	S	0.01	0.00	-1.00	0.37	0.40	0.39	3.98	3.88	3.90
82	+++	30.1	0.38	52	S	1.01	1.00	0.85	0.35	0.32	0.32	8.19	7.69	7.76
83	000	22.6	0.33	34	S	0.01	0.00	-0.05	0.35	0.34	0.34	4.76	4.56	4.58
84	---	15.1	0.28	16	S	-0.99	-1.00	-0.95	0.44	0.43	0.43	2.46	2.41	2.42
85	++-	15.0	0.37	55	S	-1.00	0.80	1.00	0.2	0.25	0.25	2.49	3.02	3.07
86	+++	30.0	0.28	52	S	1.00	-1.00	0.85	0.4	0.42	0.42	6.68	6.58	6.65
87	000	22.3	0.33	34	S	-0.03	0.00	-0.05	0.34	0.34	0.34	4.69	4.49	4.51
88	---	15.1	0.29	16	S	-0.99	-0.80	-0.95	0.42	0.41	0.41	2.33	2.34	2.34
89	++-	30.0	0.28	51	S	1.00	-1.00	0.80	0.42	0.42	0.42	6.85	6.53	6.60
90	++-	30.0	0.28	14	S	1.00	-1.00	-1.05	0.54	0.52	0.51	5.06	4.65	4.72

M : Mineral Oil, S: Synthetic Oil

APPENDIX C : Brake-specific Gaseous Emissions (CO₂, CO, THC, and NO_x) Data

State No.	CO ₂ (g/bhp-hr)						CO (g/bhp-hr)						THC (g/bhp-hr)						NO _x (g/bhp-hr)					
	Mineral Oil			Synthetic Oil			Mineral Oil			Synthetic Oil			Mineral Oil			Synthetic Oil			Mineral Oil			Synthetic Oil		
	Avg	S.D.	COV	Avg	S.D.	COV	Avg	S.D.	COV	Avg	S.D.	COV	Avg	S.D.	COV	Avg	S.D.	COV	Avg	S.D.	COV	Avg	S.D.	COV
1	1.08	0.04	0.03	1.15	0.06	0.05	0.00	0.00	-	0.00	0.00	-	0.07	0.00	0.05	0.06	0.01	0.13	0.01	0.01	0.57	0.01	0.00	0.53
2	0.93	0.05	0.06	0.97	0.08	0.08	0.00	0.00	0.55	0.00	0.00	1.41	0.07	0.01	0.19	0.04	0.01	0.33	0.01	0.01	0.59	0.01	0.00	0.04
3	0.77	0.05	0.06	0.78	0.02	0.02	0.00	0.00	-	0.00	0.00	1.41	0.06	0.00	0.06	0.06	0.01	0.16	0.04	0.00	0.12	0.03	0.01	0.19
4	0.68	0.07	0.10	0.73	0.01	0.02	0.00	0.00	-	0.00	0.00	-	0.07	0.00	0.04	0.07	0.01	0.11	0.15	0.04	0.28	0.13	0.07	0.57
5	0.59	0.05	0.09	0.59	0.06	0.11	0.00	0.00	-	0.00	0.00	-	0.06	0.01	0.12	0.06	0.00	0.05	0.14	0.01	0.08	0.14	0.05	0.38
6	1.14	0.06	0.05	1.06	0.05	0.05	0.01	0.00	0.45	0.00	0.00	0.94	0.07	0.01	0.14	0.08	0.01	0.10	0.01	0.01	0.67	0.01	0.00	0.39
7	1.04	0.14	0.14	0.94	0.03	0.03	0.00	0.00	0.57	0.00	0.00	1.73	0.07	0.01	0.10	0.08	0.02	0.25	0.04	0.01	0.17	0.03	0.00	0.16
8	0.86	0.07	0.09	0.86	0.01	0.01	0.01	0.01	1.54	0.00	0.00	1.73	0.07	0.01	0.13	0.08	0.01	0.17	0.03	0.00	0.13	0.04	0.01	0.22
9	0.77	0.02	0.02	0.79	0.06	0.08	0.00	0.00	-	0.00	0.00	1.73	0.07	0.01	0.09	0.06	0.02	0.28	0.04	0.00	0.05	0.03	0.00	0.07
10	0.75	0.06	0.08	0.70	0.01	0.01	0.00	0.00	1.73	0.00	0.00	-	0.07	0.01	0.10	0.08	0.01	0.10	0.11	0.01	0.09	0.12	0.01	0.06
11	1.42	0.16	0.12	1.38	0.04	0.03	0.01	0.01	0.52	0.00	0.01	1.73	0.09	0.01	0.11	0.09	0.02	0.20	0.01	0.00	0.29	0.01	0.01	0.84
12	1.05	0.03	0.03	1.01	0.03	0.02	0.00	0.01	1.72	0.00	0.00	1.12	0.08	0.03	0.32	0.07	0.01	0.18	0.02	0.01	0.33	0.01	0.00	0.27
13	0.90	0.00	0.00	0.83	0.08	0.10	0.00	0.00	1.12	0.00	0.00	1.00	0.07	0.01	0.08	0.07	0.00	0.02	0.03	0.00	0.03	0.04	0.00	0.07
14	1.01	0.05	0.05	0.84	0.03	0.04	0.01	0.00	0.33	0.00	0.00	-	0.10	0.01	0.14	0.10	0.01	0.09	0.10	0.02	0.23	0.09	0.02	0.22
15	0.81	0.01	0.01	0.81	0.03	0.04	0.00	0.00	0.15	0.01	0.01	1.39	0.08	0.03	0.35	0.09	0.01	0.15	0.08	0.01	0.07	0.07	0.02	0.24

Avg = Average, S.D. = Standard Deviation, COV = Coefficient of Variance

APPENDIX D : Elemental Carbon (EC)/Organic Carbon (OC), Ions, Trace Metals Analysis: Procedure and Data from Desert Research Institute (DRI)

D1 Thermal/Optical Carbon Analysis Method (EC/OC Analysis)[85]

The Elemental Carbon/Organic Carbon (EC/OC) analysis was done using a DRI Model 2001 Thermal/Optical Carbon Analyzer. The analyzer operates based on the preferential oxidation of EC and OC at different temperatures in an oxidizing and non-oxidizing environment respectively.

The particulate samples for analysis were collected on pre-fired quartz filters to ensure the absence of any residual carbon contamination. A small sample punch is taken from the exposed filter for the analysis.

The filter was first subjected to a non-oxidizing helium (He) atmosphere. In this stage, the organic carbon compounds are volatilized. The volatilized compounds are then oxidized in an oxidizer (heated manganese dioxide, MnO_2). The oxidized products are then reduced to methane (CH_4) in a methanator (hydrogen enriched nickel catalyst), concentration of which is measured by a flame ionization detector (FID).

The above mentioned OC part of the analysis is done for four fractions (four temperature steps) as follows:-

- 1) OC_1 : Organic fraction volatilized between ambient and 120°C .
- 2) OC_2 : Organic fraction volatilized between 120 and 250°C .
- 3) OC_3 : Organic fraction volatilized between 250 and 450°C .
- 4) OC_4 : Organic fraction volatilized between 450 and 550°C .

The optical component of the analyzer is used for pyrolysis correction of OC reported. There are chances for some of the OC to be charred into EC as a result of pyrolysis, and the reported OC fraction may be underestimated. The correction is done by continuously monitoring the filter reflectance and for transmittance throughout the analysis. The optical component consists of a helium-neon laser and a photo detector. The reflectance and transmittance, which would depend upon the quantity of light absorbing EC, would decrease as pyrolysis take place and increase as EC is oxidized during the EC analysis stage.

During the EC analysis stage, oxygen is added to the helium at temperatures greater than 550°C. This oxidizes the EC into CO₂, which is then reduced to CH₄ and detected by the FID.

The EC is reported as three fractions as follows:-

- 1) EC1: EC fraction oxidized at temperature 550°C.
- 2) EC2: EC fraction oxidized at temperature between 550 and 700°C.
- 3) EC3: EC fraction oxidized at temperature between 700 and 800°C.

The complete EC/OC results are shown in Table D1 with the uncertainty associated with the measurements.

D2 Trace Metal Analysis [86]

X-ray fluorescence (XRF) technique was used by DRI to determine the trace metal concentration in the particulate samples collected.

Figure D1 illustrates the XRF principle [87]. An inner shell electron of the metal atom is excited by an incident photon from the X-ray source. When an electron gets de-excited from a higher energy level to fill the void, the energy differences between the shells appear as an X-ray. The X-ray spectrum acquired by the detector will have several characteristic peaks, the energy of which helps to determine the elements present. The intensity of the peaks provides a measure of the concentration of the particular element.

Figure D 1 The Principle of XRF and the typical XRF Detection Arrangement [87]

The instrument used by DRI was a Kevex EDX-771 energy dispersive X-ray spectrometer. It used a 200 watt Rhodium target tube as an excitation source. The detector was cryogenically cooled Lithium-drifted silicon with a 5mm Be window and a resolution of 158eV.

The samples for the analysis were collected on 90mm Teflon-membrane filters. The complete results for the trace metals analysis is shown in Table D2. Ca and Zn were the only elements present in quantities significantly greater than the uncertainty levels involved. Magnesium (Mg) and phosphorus (P) are also generally present in the case of diesel engine lubricant derived PM in detectable quantities. This was not the case in this study. This could be attributed to the low levels of detergents, dispersants required in gaseous engine lubricants. The low levels of phosphorus also show less loss of the anti-wear component of the additives. The lower levels of Zn (which is also a major element of the anti-wear component, ZDDP or zinc dialkyl-dithio-phosphate) compared to Ca can also be attributed to the lower loss of anti-wear agents.

D3 Ions Analysis (Ion Chromatography) [88]

Water-soluble nitrates, sulfates, nitrites, chloride and ammonium were measured using an ion chromatograph (IC), by DRI. The particulate was also checked for the presence of soluble sodium and potassium ions.

The tests were performed using the samples collected on the quartz filters for the EC/OC analysis. The water soluble ions were extracted using de-ionized distilled water. The analysis was done using a Dionex Model DX-500 ion chromatograph. The technique is based on separation of ions and polar molecules based on the change of properties of the molecules.

Table D3 shows the ion analysis results. Sulfates are usually found in detectable quantities in lubricant derived particulate along with nitrates. For the operating states tested in this study, none of the water soluble ions were found in notable amounts. Sulfates were almost zero or less than the uncertainty levels. The reason could be the very low concentration of sulfur for both test oils, which was less than 800 ppm, whereas the sulfur levels in typical diesel engine lubricants are around three to four times higher. Nitrate was the only water soluble ion found in detectable levels but was found in trace quantities in the order of 0.05 to 0.25 mg/bhp-hr (Table D3). The nitrates were higher for the mineral oil compared to synthetic oil for all operating states, similar to the organic fraction, Ca, and Zn results. The complete ions analysis results are shown in Table D4.

Table D1 EC/OC Results : Raw Data From DRI

QID	O1TC	O1TU	O2TC	O2TU	O3TC	O3TU	O4TC	O4TU	OPTC	OPTU	OPTTC	OPTTU	OCTC	OCTU	E1TC	E1TU	E2TC	E2TU	E3TC	E3TU	ECTC	ECTU	TCTC	TCTU
WVU90Q020	279.898	86.123	717.914	157.045	540.602	49.648	119.951	20.857	35.963	15.030	74.055	9.685	1694.328	68.588	63.897	9.998	10.158	3.294	0.000	0.902	38.092	15.330	1732.420	68.372
WVU90Q021	630.080	193.844	2585.663	565.520	551.545	50.612	121.023	21.037	45.847	19.025	74.380	9.723	3934.158	156.214	61.221	9.600	13.158	3.640	0.000	0.902	28.533	11.705	3962.691	152.539
WVU90Q022	929.453	285.941	3579.392	782.857	480.575	44.377	111.390	19.424	67.203	27.715	105.452	13.477	5168.012	204.820	92.347	14.272	13.105	3.633	0.000	0.902	38.249	15.391	5206.261	199.899
WVU90Q023	415.409	127.806	739.486	161.763	333.474	31.640	90.391	15.932	14.122	6.471	42.785	6.071	1592.881	64.678	33.296	5.528	9.489	3.225	0.000	0.902	28.663	11.754	1621.545	64.268
WVU90Q024	341.488	105.068	4314.000	943.523	510.197	46.974	107.941	18.848	26.070	11.076	56.697	7.643	5299.695	210.012	50.198	7.968	6.499	2.960	0.000	0.902	30.627	12.493	5330.322	204.629
WVU90Q025	744.954	229.183	1374.242	300.577	780.557	70.909	140.538	24.316	84.523	34.789	145.638	18.409	3124.813	124.402	116.729	17.963	28.147	5.869	0.762	0.902	61.114	24.217	3185.928	123.044
WVU90Q026	390.170	120.043	1978.028	432.627	373.850	35.100	81.708	14.501	43.963	18.262	69.630	9.159	2867.719	114.318	59.924	9.407	9.706	3.247	0.000	0.902	25.666	10.635	2893.386	111.966
WVU90Q027	705.865	217.158	3562.618	779.189	1109.513	100.275	141.581	24.492	146.151	60.016	199.233	25.039	5665.727	224.448	174.997	26.821	24.236	5.238	0.000	0.902	53.083	21.103	5718.810	219.446
WVU90Q028	1233.875	379.592	5474.587	1197.355	1842.905	166.018	223.247	38.316	121.748	50.021	183.847	23.132	8896.362	351.974	150.482	23.090	33.365	6.741	0.000	0.902	62.098	24.599	8958.460	343.165
WVU90Q029	371.831	114.401	2706.112	591.864	1079.401	97.581	110.511	19.278	23.256	9.966	69.693	9.166	4291.111	170.266	61.656	9.664	8.037	3.087	0.000	0.902	46.437	18.536	4337.548	166.802
WVU90Q030	917.527	282.272	2752.078	601.917	518.739	47.725	61.869	11.282	0.000	2.885	42.018	5.987	4250.212	168.656	31.791	5.317	10.227	3.301	0.000	0.902	42.018	16.835	4292.231	165.077
WVU90Q031	221.323	68.107	910.196	199.093	374.563	35.161	45.896	8.782	0.000	2.885	28.205	4.552	1551.978	63.105	22.984	4.124	5.220	2.872	0.000	0.902	28.205	11.582	1580.183	62.742
WVU90Q032	599.604	184.469	2549.575	557.628	577.647	52.913	64.538	11.710	0.000	2.885	43.522	6.152	3791.363	150.596	35.364	5.820	8.158	3.098	0.000	0.902	43.522	17.413	3834.885	147.680
WVU90Q033	1157.933	356.229	1029.958	225.284	642.041	58.608	126.634	21.978	22.122	9.522	67.745	8.936	2978.689	118.669	48.329	7.694	19.416	4.497	0.000	0.902	45.623	18.222	3024.311	116.921
WVU90Q034	380.034	116.925	515.856	112.865	631.107	57.639	88.043	15.544	54.647	22.599	85.041	11.001	1669.686	67.637	71.709	11.166	13.333	3.661	0.000	0.902	30.395	12.406	1700.080	67.173
WVU90Q035	347.371	106.877	2600.758	568.822	954.466	86.416	94.325	16.583	22.326	9.601	52.107	7.116	4019.247	159.563	45.612	7.296	6.495	2.960	0.000	0.902	29.781	12.174	4049.027	155.823
WVU90Q036	292.341	89.950	509.819	111.545	429.441	39.913	69.843	12.565	0.000	2.885	32.481	4.977	1301.445	53.528	25.066	4.398	7.415	3.033	0.000	0.902	32.481	13.194	1333.926	53.722
WVU90Q037	604.664	186.025	4711.333	1030.424	1471.215	132.674	129.801	22.510	42.655	17.732	97.707	12.534	6959.669	275.505	84.524	13.092	13.182	3.643	0.000	0.902	55.051	21.865	7014.720	268.910
WVU90Q038	60.474	18.675	65.405	14.630	76.934	12.241	14.067	4.637	1.160	2.924	1.160	2.889	218.041	17.116	1.160	2.171	0.000	2.705	0.000	0.902	0.000	3.426	218.041	18.731
WVU90Q039	45.472	14.083	48.932	11.132	65.902	11.709	7.579	4.173	0.000	2.885	0.000	2.885	167.885	16.208	0.000	2.164	0.000	2.705	0.000	0.902	0.000	3.426	167.885	17.959

QID	Quartz filter ID
O1TC	Organic Carbon Fraction 1 concentration (µg/filter)
O1TU	Organic Carbon Fraction 1 concentration (µg/filter) uncertainty
O2TC	Organic Carbon Fraction 2 concentration (µg/filter)
O2TU	Organic Carbon Fraction 2 concentration (µg/filter) uncertainty
O3TC	Organic Carbon Fraction 3 concentration (µg/filter)
O3TU	Organic Carbon Fraction 3 concentration (µg/filter) uncertainty
O4TC	Organic Carbon Fraction 4 concentration (µg/filter)
O4TU	Organic Carbon Fraction 4 concentration (µg/filter) uncertainty
OPTC	Pyrolyzed organic carbon, thermal method, transmittance concentration (µg/filter)
OPTU	Pyrolyzed organic carbon, thermal method, transmittance concentration (µg/filter) uncertainty
OPTRC	Pyrolyzed organic carbon, thermal method, reflectance concentration (µg/filter)
OPTRU	Pyrolyzed organic carbon, thermal method, reflectance concentration (µg/filter) uncertainty
OCTC	Organic carbon, thermal method, reflectance concentration (µg/filter)
OCTRU	Organic carbon, thermal method, reflectance concentration (µg/filter) uncertainty
E1TC	Elemental Carbon Fraction 1 concentration (µg/filter)
E1TU	Elemental Carbon Fraction 1 concentration (µg/filter) uncertainty
E2TC	Elemental Carbon Fraction 2 concentration (µg/filter)
E2TU	Elemental Carbon Fraction 2 concentration (µg/filter) uncertainty
E3TC	Elemental Carbon Fraction 3 concentration (µg/filter)
E3TU	Elemental Carbon Fraction 3 concentration (µg/filter) uncertainty
ECTC	Elemental carbon, thermal method, reflectance concentration (µg/filter)
ECTRU	Elemental carbon, thermal method, reflectance concentration (µg/filter) uncertainty
TCTC	Total Carbon concentration (µg/filter)
TCTU	Total Carbon concentration (µg/filter) uncertainty

Table D2 Trace Metals Results : Raw Data From DRI

TID	NAXC	NAXU	MGXC	MGXU	ALXC	ALXU	SIXC	SIXU	PHXC	PHXU	SUXC	SUXU	CLXC	CLXU	KPXC	KPXU	CAXC	CAXU	SCXC	SCXU	TIXC	TIXU
WVU90T020	0.0000	7.0809	0.0000	3.5347	0.2598	0.6254	0.0000	0.6350	0.2380	0.1990	0.0000	0.7153	0.1516	0.1225	0.2922	0.1206	3.0810	0.1492	0.0730	0.4667	0.0488	0.0841
WVU90T021	9.9733	7.2864	3.1892	3.5654	0.7683	0.6254	0.0000	0.6350	0.1028	0.1990	0.0000	0.7153	0.5194	0.1225	0.1407	0.1206	3.7411	0.1532	0.3381	0.4667	0.0000	0.0841
WVU90T022	8.9184	7.2628	5.5805	3.5808	0.0000	0.6216	0.0000	0.6350	0.1352	0.1990	0.0000	0.7153	0.3950	0.1225	0.0000	0.1168	2.5130	0.1492	0.1758	0.4667	0.0000	0.0841
WVU90T023	5.0827	7.1849	0.0000	3.5385	0.3517	0.6254	0.0000	0.6312	0.0270	0.1990	0.0000	0.7078	0.2760	0.1225	0.0000	0.1168	1.4039	0.1492	0.1596	0.4667	0.0000	0.0841
WVU90T024	17.8828	7.4490	4.6175	3.5731	0.6601	0.6254	0.0785	0.6350	0.0108	0.1990	0.0000	0.7153	0.3139	0.1225	0.0000	0.1168	2.8700	0.1492	0.0784	0.4667	0.0000	0.0841
WVU90T025	14.1661	7.3693	1.7448	3.5539	0.2543	0.6254	0.0000	0.6312	0.0703	0.1990	0.0000	0.7153	0.2002	0.1225	0.0000	0.1168	2.1559	0.1492	0.1488	0.4667	0.1353	0.0841
WVU90T026	12.8731	7.3455	0.0000	3.5347	0.0488	0.6254	0.0000	0.6350	0.0000	0.1990	0.0000	0.7115	0.1299	0.1225	0.0487	0.1168	1.8530	0.1492	0.0000	0.4667	0.0000	0.0841
WVU90T027	14.6476	7.3812	6.2243	3.5846	0.1353	0.6254	0.3490	0.6388	0.0000	0.1952	0.0000	0.7115	0.2652	0.1225	0.1894	0.1206	3.8709	0.1532	0.1866	0.4667	0.0000	0.0841
WVU90T028	16.8927	7.4250	3.6870	3.5692	0.0000	0.6216	0.0000	0.6312	0.5626	0.1990	0.0000	0.7191	0.6547	0.1263	0.2002	0.1206	5.5155	0.1532	0.4030	0.4667	0.0650	0.0841
WVU90T029	6.2675	7.2082	2.9783	3.5615	1.8503	0.6331	0.0000	0.6350	0.0054	0.1990	0.0000	0.7153	0.4762	0.1225	0.1840	0.1206	2.7618	0.1492	0.4301	0.4667	0.0000	0.0841
WVU90T030	14.9289	7.3851	1.9828	3.5577	0.9035	0.6293	0.2245	0.6350	0.0974	0.1990	0.0000	0.7153	0.1732	0.1225	0.1407	0.1206	1.1713	0.1492	0.3111	0.4667	0.0000	0.0841
WVU90T031	8.2800	7.2511	0.8413	3.5500	0.0000	0.6178	0.3111	0.6388	0.0000	0.1952	0.0000	0.7115	0.3571	0.1225	0.0000	0.1168	0.3869	0.1454	0.0135	0.4667	0.0055	0.0841
WVU90T032	4.9907	7.1849	0.0000	3.5385	0.0000	0.6216	0.5491	0.6388	0.0000	0.1990	0.0000	0.7153	0.1732	0.1225	0.1623	0.1206	1.7123	0.1492	0.2299	0.4667	0.1786	0.0841
WVU90T033	20.5283	7.5012	1.4148	3.5539	0.0000	0.6216	0.0000	0.6350	0.0000	0.1952	0.0000	0.7115	0.0000	0.1225	0.0108	0.1168	0.5600	0.1492	0.2299	0.4667	0.0000	0.0841
WVU90T034	11.4611	7.3139	2.4535	3.5577	2.1803	0.6331	0.0000	0.6350	0.0000	0.1990	0.0000	0.7153	0.2598	0.1225	0.0920	0.1206	1.9774	0.1492	0.1920	0.4667	0.0000	0.0841
WVU90T035	11.2934	7.3099	0.4464	3.5461	0.0000	0.6216	0.4734	0.6388	0.1839	0.1990	0.0000	0.7153	0.3355	0.1225	0.3192	0.1206	2.2425	0.1492	0.3002	0.4667	0.0920	0.0841
WVU90T036	18.0938	7.4530	1.6474	3.5539	1.1416	0.6293	0.7168	0.6388	0.0000	0.1990	0.0000	0.7153	0.0000	0.1225	0.0325	0.1168	0.4734	0.1454	0.0838	0.4667	0.0488	0.0841
WVU90T037	4.3686	7.1733	0.0000	3.5347	0.0000	0.6216	0.0000	0.6350	0.2597	0.1990	0.0217	0.7191	0.0542	0.1225	0.4545	0.1206	1.6312	0.1492	0.0351	0.4667	0.0000	0.0841
WVU90T038	10.2222	7.2903	0.0000	3.5347	0.0000	0.6254	0.2949	0.6388	0.0000	0.1952	0.0000	0.7115	0.2327	0.1225	0.2597	0.1206	0.0000	0.1454	0.0838	0.4667	0.0866	0.0841
WVU90T039	10.3358	7.2903	0.0352	3.5423	0.0000	0.6216	0.3057	0.6388	0.0000	0.1952	0.0000	0.7115	0.0000	0.1225	0.0000	0.1168	0.0000	0.1454	0.0000	0.4667	0.0000	0.0841
TID	VAXC	VAXU	CRXC	CRXU	MXNC	MXNU	FEXC	FEXU	COXC	COXU	NIXC	NIXU	CUXC	CUXU	ZNXC	ZNXU	GAXC	GAXU	ASXC	ASXU	SEXC	SEXU
WVU90T020	0.0000	0.0076	0.0000	0.0841	0.1813	0.1607	0.0000	0.2162	0.0000	0.0076	0.0568	0.0383	0.2245	0.0765	0.5952	0.0841	0.0000	0.2486	0.0000	0.0076	0.0000	0.1607
WVU90T021	0.0000	0.0076	0.0000	0.0841	0.0000	0.1607	0.0000	0.2162	0.0000	0.0076	0.0027	0.0383	0.0000	0.0765	0.6168	0.0841	0.0785	0.2524	0.0000	0.0076	0.0000	0.1607
WVU90T022	0.0000	0.0076	0.0000	0.0841	0.0136	0.1607	0.1812	0.2200	0.0000	0.0076	0.0000	0.0383	0.0000	0.0765	0.2273	0.0841	0.0000	0.2524	0.0000	0.0076	0.1705	0.1607
WVU90T023	0.0000	0.0076	0.0325	0.0841	0.2624	0.1645	0.1217	0.2200	0.0000	0.0076	0.0000	0.0383	0.0000	0.0765	0.2327	0.0841	0.0190	0.2524	0.0000	0.0076	0.0000	0.1607
WVU90T024	0.0000	0.0076	0.0000	0.0841	0.0000	0.1607	0.0000	0.2162	0.0000	0.0076	0.1055	0.0383	0.0622	0.0765	0.8548	0.0841	0.0000	0.2563	0.0000	0.0076	0.0000	0.1607
WVU90T025	0.0000	0.0076	0.0271	0.0841	0.0000	0.1607	0.0000	0.2162	0.0000	0.0076	0.0000	0.0383	0.0000	0.0765	0.1732	0.0841	0.0000	0.2524	0.0000	0.0076	0.0000	0.1607
WVU90T026	0.0000	0.0076	0.0271	0.0841	0.0000	0.1607	0.0000	0.2162	0.0000	0.0076	0.0000	0.0383	0.0000	0.0765	0.4545	0.0841	0.1759	0.2524	0.0000	0.0076	0.0000	0.1607
WVU90T027	0.0000	0.0076	0.0000	0.0841	0.0000	0.1607	0.0000	0.2162	0.0000	0.0076	0.0406	0.0383	0.0000	0.0765	0.8386	0.0841	0.1326	0.2524	0.0000	0.0076	0.0000	0.1607
WVU90T028	0.0000	0.0076	0.0000	0.0841	0.0000	0.1607	0.0000	0.2162	0.0000	0.0076	0.0000	0.0383	0.0000	0.0765	1.7150	0.0880	0.1759	0.2524	0.0000	0.0076	0.0000	0.1607
WVU90T029	0.0000	0.0076	0.1245	0.0841	0.0000	0.1607	0.2029	0.2200	0.0000	0.0076	0.0027	0.0383	0.0000	0.0765	0.4166	0.0841	0.0000	0.2524	0.0000	0.0076	0.0000	0.1607
WVU90T030	0.0000	0.0076	0.0920	0.0841	0.0406	0.1607	0.4409	0.2200	0.0000	0.0076	0.0190	0.0383	0.0000	0.0765	0.2219	0.0841	0.0000	0.2524	0.0000	0.0076	0.1002	0.1607
WVU90T031	0.0000	0.0076	0.1731	0.0841	0.0677	0.1607	0.0000	0.2162	0.0000	0.0076	0.0000	0.0383	0.0000	0.0765	0.2651	0.0841	0.0000	0.2524	0.0000	0.0076	0.0000	0.1607
WVU90T032	0.0000	0.0076	0.0541	0.0841	0.0000	0.1607	0.0000	0.2162	0.0000	0.0076	0.0000	0.0383	0.0000	0.0765	0.2489	0.0841	0.0000	0.2524	0.0000	0.0076	0.0623	0.1607
WVU90T033	0.0000	0.0076	0.1407	0.0841	0.0000	0.1607	0.0514	0.2200	0.0000	0.0076	0.0000	0.0383	0.0189	0.0765	0.3733	0.0841	0.0000	0.2524	0.0000	0.0076	0.3977	0.1607
WVU90T034	0.0000	0.0076	0.0000	0.0841	0.0000	0.1607	0.4301	0.2200	0.0000	0.0076	0.0622	0.0383	0.0000	0.0765	0.1137	0.0841	0.0000	0.2524	0.0000	0.0076	0.0244	0.1607
WVU90T035	0.0000	0.0076	0.1515	0.0841	0.0000	0.1607	0.0000	0.2162	0.0000	0.0076	0.0000	0.0383	0.0000	0.0765	0.4220	0.0841	0.0000	0.2524	0.0000	0.0076	0.0000	0.1607
WVU90T036	0.0000	0.0076	0.0649	0.0841	0.0515	0.1607	0.0947	0.2200	0.0000	0.0076	0.0785	0.0383	0.0676	0.0765	0.1948	0.0841	0.0000	0.2524	0.0000	0.0076	0.1434	0.1607
WVU90T037	0.0000	0.0076	0.2110	0.0841	0.0000	0.1607	0.2137	0.2200	0.0000	0.0076	0.0785	0.0383	0.0000	0.0765	0.3084	0.0841	0.0298	0.2524	0.0000	0.0076	0.0000	0.1607
WVU90T038	0.0000	0.0076	0.0541	0.0841	0.0000	0.1607	0.0000	0.2162	0.0000	0.0076	0.0244	0.0383	0.0000	0.0765	0.0000	0.0841	0.1326	0.2524	0.0000	0.0076	0.1651	0.1607
WVU90T039	0.0000	0.0076	0.0000	0.0841	0.1110	0.1607	0.0000	0.2162	0.0000	0.0076	0.0000	0.0383	0.2840	0.0765	0.0000	0.0841	0.0569	0.2524	0.0000	0.0076	0.0000	0.1607
TID	BRXC	BRXU	RBXC	RBXU	SRXC	SRXU	YTXC	YTXU	ZRXC	ZRXU	NBXC	NBXU	MOXC	MOXU	PDXC	PDXU	AGXC	AGXU	CDXC	CDXU	INXC	INXU
WVU90T020	0.0109	0.1148	0.0000	0.0841	0.0000	0.1530	0.0000	0.1148	0.0000	0.2679	0.0515	0.2066	0.0000	0.1894	0.0000	0.3520	0.0000	0.3213	0.0000	0.3978	0.0000	0.2372
WVU90T021	0.0650	0.1148	0.0000	0.0841	0.0000	0.1530	0.0000	0.1148	0.0000	0.2679	0.0000	0.2066	0.1434	0.1894	0.0000	0.3520	0.0000	0.3213	0.0000	0.3978	0.0000	0.2372
WVU90T022	0.2543	0.1148	0.0000	0.0841	0.0000	0.1530	0.0000	0.1148	0.0000	0.2679	0.1272	0.2066	0.0000	0.1894	0.0000	0.3520	0.0000	0.3213	0.0000	0.3978	0.0000	0.2372
WVU90T023	0.0487	0.1148	0.0000	0.0841	0.0000	0.1530	0.0000	0.1148	0.0000	0.2679	0.1759	0.2066	0.0000	0.1855	0.0000	0.3520	0.0000	0.3213	0.0000	0.3978	0.0000	0.2372
WVU90T024	0.0000	0.1148	0.0000	0.0841	0.0000	0.1530	0.0000	0.1148	0.0731	0.2679	0.2029	0.2066	0.1218	0.1894	0.0000	0.3520	0.0000	0.3213	0.0000	0.3978	0.0000	0.2372
WVU90T025	0.0000	0.1148																				

TID	SNXC	SNXU	SBXC	SBXU	CSXC	CSXU	BAXC	BAXU	LAXC	LAXU	CEXC	CEXU	SMXC	SMXU	EUXC	EUXU	TBXC	TBXU	HFXC	HFXU	TAXC	TAXU
WVU90T020	8.7967	0.3316	0.0000	0.5661	0.0568	0.0918	0.0000	0.0460	0.0000	0.0689	0.0000	0.1071	0.0542	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2740	0.0000	0.9219
WVU90T021	0.0000	0.3042	0.2435	0.5700	0.0243	0.0918	0.0000	0.0460	0.0000	0.0728	0.0271	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2701	0.0325	0.9181
WVU90T022	0.0000	0.3080	0.0000	0.5661	0.0000	0.0918	0.0000	0.0460	0.0000	0.0689	0.0595	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2778	0.0000	0.9143
WVU90T023	0.0000	0.3042	0.0000	0.5700	0.0000	0.0918	0.0000	0.0460	0.0000	0.0689	0.0325	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2778	0.2813	0.9181
WVU90T024	1.5527	0.3118	0.0000	0.5700	0.0000	0.0918	0.0000	0.0460	0.0433	0.0689	0.0000	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2892	0.0000	0.9143
WVU90T025	0.0000	0.3080	0.4491	0.5700	0.0838	0.0918	0.0000	0.0460	0.0000	0.0689	0.0000	0.1071	0.0000	0.1377	0.1353	0.4974	0.1623	0.1759	1.2146	1.2892	0.0000	0.9296
WVU90T026	1.0820	0.3118	0.1624	0.5661	0.0027	0.0918	0.0000	0.0460	0.0000	0.0689	0.0000	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2701	0.0000	0.9258
WVU90T027	1.4607	0.3118	0.0000	0.5700	0.0000	0.0918	0.0000	0.0460	0.0595	0.0689	0.0379	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2778	0.0000	0.9219
WVU90T028	0.8494	0.3118	0.0000	0.5623	0.0000	0.0918	0.0000	0.0460	0.0000	0.0689	0.0649	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1798	0.0000	1.2854	0.0000	0.9219
WVU90T029	3.7492	0.3195	0.0000	0.5661	0.0352	0.0918	0.0000	0.0460	0.0000	0.0728	0.0974	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	1.1497	1.2892	0.0000	0.9258
WVU90T030	0.0000	0.3080	0.0000	0.5661	0.0000	0.0918	0.0000	0.0460	0.0433	0.0689	0.0000	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2778	0.0000	0.9143
WVU90T031	0.0000	0.3080	0.0000	0.5661	0.0000	0.0918	0.0000	0.0460	0.0000	0.0689	0.0000	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2778	0.0000	0.9219
WVU90T032	0.3138	0.3118	0.0000	0.5661	0.0000	0.0918	0.0000	0.0460	0.0000	0.0689	0.0000	0.1071	0.0488	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2816	0.0000	0.9219
WVU90T033	0.0000	0.3080	0.0000	0.5623	0.0000	0.0918	0.0000	0.0460	0.0000	0.0689	0.0595	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.1813	1.2854	0.0000	0.9219
WVU90T034	0.0000	0.3080	0.0000	0.5661	0.0000	0.0918	0.0000	0.0460	0.0000	0.0689	0.0000	0.1071	0.0434	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2778	0.0000	0.9219
WVU90T035	0.8332	0.3118	0.5573	0.5700	0.0000	0.0918	0.0000	0.0460	0.0000	0.0728	0.0000	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.3007	0.0000	0.9296
WVU90T036	0.0000	0.3080	0.0000	0.5661	0.0000	0.0918	0.0000	0.0460	0.0000	0.0689	0.0000	0.1071	0.0000	0.1377	0.0216	0.4974	0.0000	0.1798	0.8088	1.2892	0.0000	0.9258
WVU90T037	18.9729	0.3566	0.0000	0.5700	0.0000	0.0918	0.0000	0.0460	0.0000	0.0689	0.0000	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2816	0.0000	0.9219
WVU90T038	9.4892	0.3316	0.0000	0.5661	0.0000	0.0918	0.0000	0.0460	0.0000	0.0689	0.0812	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.6249	1.2854	0.4598	0.9181
WVU90T039	0.0000	0.3080	0.0000	0.5661	0.0189	0.0918	0.0000	0.0460	0.0000	0.0689	0.0703	0.1071	0.0000	0.1377	0.0000	0.4974	0.0000	0.1759	0.0000	1.2816	0.0000	0.9219
TID	WOXC	WOXU	IRXC	IRXU	AUXC	AUXU	HGXC	HGXU	TLXC	TLXU	PBXC	PBXU	URXC	URXU								
WVU90T020	0.0000	1.5183	0.2002	0.2831	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T021	0.0000	1.5143	0.1191	0.2831	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T022	0.0000	1.5223	0.0000	0.2831	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T023	0.0000	1.5263	0.0000	0.2870	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T024	0.0000	1.5183	0.0542	0.2831	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T025	0.0000	1.5143	0.0758	0.2831	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T026	0.0000	1.5183	0.0001	0.2831	0.0000	0.6121	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T027	0.0000	1.5223	0.2868	0.2870	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T028	0.0000	1.5223	0.0000	0.2870	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T029	0.0000	1.5143	0.0000	0.2870	0.0758	0.6121	0.0000	0.1836	0.0000	0.1913	0.0027	0.1990	0.0000	0.3213								
WVU90T030	0.0000	1.5183	0.0000	0.2831	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.2840	0.2028	0.0000	0.3213								
WVU90T031	0.0000	1.5183	0.2760	0.2870	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T032	0.0000	1.5143	0.0000	0.2870	0.0000	0.6121	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T033	0.0000	1.5183	0.2597	0.2870	0.0000	0.6121	0.0000	0.1836	0.0000	0.1913	0.0839	0.1990	0.0000	0.3213								
WVU90T034	0.0000	1.5103	0.2111	0.2831	0.3463	0.6121	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T035	0.0000	1.5223	0.2760	0.2870	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T036	0.0000	1.5263	0.0000	0.2870	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T037	0.0000	1.5143	0.1732	0.2831	0.0000	0.6121	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T038	0.0000	1.5183	0.0000	0.2870	0.0000	0.6121	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								
WVU90T039	0.0000	1.5143	0.0000	0.2831	0.0000	0.6083	0.0000	0.1836	0.0000	0.1913	0.0000	0.1990	0.0000	0.3213								

Note: The element concentrations and uncertainties in the above are denoted by four letters. The first two denote the element, the next two denote whether it represents concentration or the uncertainty, that is, XC denotes the concentration in µg/filter, and XU denotes the uncertainty in µg/filter.

The elements denoted by the symbols in the above table, and the state number corresponding to the filters are shown in Table D5, and D6 respectively. TID denotes Teflon filter ID, and QID denotes Quartz filter ID.

Table D3 Brake-specific Nitrates

State #	Brake-specific Nitrates (mg/bhp-hr)	
	Mineral Oil	Synthetic Oil
1	0.15	0.09
2	0.12	0.06
4	0.25	0.14
5	0.18	0.09
8	0.19	0.12
11	0.20	0.05
12	0.11	0.05
14	0.14	0.09
15	0.16	0.05

Table D4 Ions Analysis Results : Raw Data From DRI

QID	CLIC	CLIU	N3IC	N3IU	S4IC	S4IU	N4CC	N4CU	NAAC	NAAU	KPAC	KPAU
WVU90Q020	0.0000	1.5600	12.1961	1.5848	3.1356	1.5710	2.9390	1.5811	0.1404	0.1212	0.2153	0.1596
WVU90Q021	0.0000	1.5600	12.0650	1.5843	0.0000	1.5600	2.7144	1.5780	0.1872	0.1389	0.1217	0.1572
WVU90Q022	0.0000	1.5600	8.3866	1.5718	0.0000	1.5600	2.8735	1.5801	0.1217	0.1150	0.1498	0.1578
WVU90Q023	0.0000	1.5600	7.8062	1.5702	0.0000	1.5600	2.9016	1.5805	0.6833	0.3863	0.1030	0.1568
WVU90Q024	0.0000	1.5600	8.1900	1.5712	0.0000	1.5600	2.5553	1.5759	0.0374	0.0958	0.0936	0.1567
WVU90Q025	0.0000	1.5600	10.1275	1.5771	0.0000	1.5600	3.0046	1.5820	0.1404	0.1212	0.1030	0.1568
WVU90Q026	0.0000	1.5600	9.1447	1.5740	3.0794	1.5706	2.5459	1.5758	1.7316	0.9543	0.1685	0.1582
WVU90Q027	0.0000	1.5600	13.6469	1.5910	0.0000	1.5600	2.8829	1.5803	0.0281	0.0949	0.1123	0.1570
WVU90Q028	0.0000	1.5600	16.1647	1.6033	2.9858	1.5699	3.1824	1.5847	0.1030	0.1093	0.1217	0.1572
WVU90Q029	0.0000	1.5600	8.5082	1.5721	0.0000	1.5600	2.7986	1.5791	0.0374	0.0958	0.0187	0.1560
WVU90Q030	0.0000	1.5600	6.3929	1.5669	0.0000	1.5600	3.4258	1.5885	0.0187	0.0942	0.1030	0.1568
WVU90Q031	0.0000	1.5600	5.0170	1.5642	3.7159	1.5754	3.2292	1.5854	0.4493	0.2636	0.2527	0.1610
WVU90Q032	0.0000	1.5600	6.1402	1.5663	3.5849	1.5743	2.5646	1.5761	0.1685	0.1315	0.1217	0.1572
WVU90Q033	0.0000	1.5600	6.5614	1.5672	3.0514	1.5704	3.9499	1.5978	0.1217	0.1150	0.2059	0.1593
WVU90Q034	0.0000	1.5600	8.0496	1.5709	0.0000	1.5600	3.0514	1.5827	0.0374	0.0958	0.1217	0.1572
WVU90Q035	0.0000	1.5600	8.9201	1.5733	0.0000	1.5600	2.8267	1.5795	0.2527	0.1672	0.2902	0.1626
WVU90Q036	0.0000	1.5600	5.3914	1.5649	0.0000	1.5600	2.7518	1.5785	0.0374	0.0958	0.1685	0.1582
WVU90Q037	0.0000	1.5600	11.0635	1.5804	0.0000	1.5600	3.0794	1.5831	0.0187	0.0942	0.1217	0.1572
WVU90Q038	0.0000	1.5600	3.6785	1.5623	0.0000	1.5600	2.4991	1.5753	0.2902	0.1846	0.1217	0.1572
WVU90Q039	0.0000	1.5600	3.6878	1.5623	0.0000	1.5600	2.3119	1.5731	0.1872	0.1389	0.1217	0.1572

Table D5 Trace Metals Analysis : Elements and Corresponding Symbols

NA	Sodium	CU	Copper	SB	Antimony
MG	Magnesium	ZN	Zinc	CS	Cesium
AL	Aluminum	GA	Gallium	BA	Barium
SI	Silicon	AS	Arsenic	LA	Lanthanum
PH	Phosphorous	SE	Selenium	CE	Cerium
SU	Sulfur	BR	Bromine	SM	Samarium
CL	Chlorine	RB	Rubidium	EU	Europium
KP	Potassium	SR	Strontium	TB	Terbium
CA	Calcium	YT	Yttrium	HF	Hafnium
SC	Scandium	ZR	Zirconium	TA	Tantalum
TI	Titanium	NB	Niobium	WO	Wolfram
VA	Vanadium	MO	Molybdenum	IR	Iridium
CR	Chromium	PD	Palladium	AU	Gold
MN	Manganese	AG	Silver	HG	Mercury
FE	Iron	CD	Cadmium	TL	Thallium
CO	Cobalt	IN	Indium	PB	Lead
NI	Nickel	SN	Tin	UR	Uranium

Table D6 Operating State Numbers and Corresponding Filter IDs

QID	TID	State Number	Test Oil
WVU90Q020	WVU90T020	15	Mineral Oil
WVU90Q021	WVU90T021	8	Mineral Oil
WVU90Q022	WVU90T022	1	Mineral Oil
WVU90Q023	WVU90T023	12	Mineral Oil
WVU90Q024	WVU90T024	2	Mineral Oil
WVU90Q025	WVU90T025	14	Mineral Oil
WVU90Q026	WVU90T026	11	Mineral Oil
WVU90Q027	WVU90T027	5	Mineral Oil
WVU90Q028	WVU90T028	4	Mineral Oil
WVU90Q029	WVU90T029	5	Synthetic Oil
WVU90Q030	WVU90T030	1	Synthetic Oil
WVU90Q031	WVU90T031	11	Synthetic Oil
WVU90Q032	WVU90T032	2	Synthetic Oil
WVU90Q033	WVU90T033	15	Synthetic Oil
WVU90Q034	WVU90T034	14	Synthetic Oil
WVU90Q035	WVU90T035	8	Synthetic Oil
WVU90Q036	WVU90T036	12	Synthetic Oil
WVU90Q037	WVU90T037	4	Synthetic Oil
WVU90Q038	WVU90T038	Background 1	
WVU90Q039	WVU90T039	Background 2	

APPENDIX E : Particle Size Distribution Data: Experimental Data with Error Bars

Figure E1 Particle Size Distribution: Mineral Oil (Speed=15 rps, Phi=0.28, Boost=20 kPa)

Figure E2 Particle Size Distribution: Mineral Oil (Speed=15 rps, Phi=0.28, Boost=60 kPa)

Figure E3 Particle Size Distribution: Mineral Oil (Speed=15 rps, $\Phi=0.33$, Boost=40 kPa)

Figure E4 Particle Size Distribution: Mineral Oil (Speed=15 rps, $\Phi=0.38$, Boost=20 kPa)

Figure E5 Particle Size Distribution: Mineral Oil (Speed=15 rps, Phi=0.38, Boost=60 kPa)

Figure E6 Particle Size Distribution: Synthetic Oil (Speed=15 rps, Phi=0.28, Boost=20 kPa)

Figure E7 Particle Size Distribution: Synthetic Oil (Speed=15 rps, $\Phi=0.28$, Boost=60 kPa)

Figure E8 Particle Size Distribution: Synthetic Oil (Speed=15 rps, $\Phi=0.33$, Boost=40 kPa)

Figure E9 Particle Size Distribution: Synthetic Oil (Speed=15 rps, $\Phi=0.38$, Boost=20 kPa)

Figure E10 Particle Size Distribution: Synthetic Oil (Speed=15 rps, $\Phi=0.38$, Boost=60 kPa)

Figure E11 Particle Size Distribution: Mineral Oil (Speed=22.5rps, Phi=0.28, Boost=20 kPa)

Figure E12 Particle Size Distribution: Mineral Oil (Speed=22.5rps, Phi=0.33, Boost=20 kPa)

Figure E13 Particle Size Distribution: Mineral Oil (Speed=22.5rps, Phi=0.33, Boost=40 kPa)

Figure E14 Particle Size Distribution: Mineral Oil (Speed=22.5rps, Phi=0.33, Boost=60 kPa)

Figure E15 Particle Size Distribution: Mineral Oil (Speed=22.5rps, Phi=0.38, Boost=40 kPa)

Figure E16 Particle Size Distribution: Synthetic Oil (Speed=22.5rps, Phi=0.28, Boost=40kPa)

Figure E17 Particle Size Distribution: Synthetic Oil (Speed=22.5rps, Phi=0.33, Boost=20kPa)

Figure E18 Particle Size Distribution: Synthetic Oil (Speed=22.5rps, Phi=0.33, Boost=40kPa)

Figure E19 Particle Size Distribution: Synthetic Oil (Speed=22.5rps, $\Phi=0.33$, Boost=60kPa)

Figure E20 Particle Size Distribution: Synthetic Oil (Speed=22.5rps, $\Phi=0.38$, Boost=40kPa)

Figure E21 Particle Size Distribution: Mineral Oil (Speed=30 rps, $\Phi=0.28$, Boost=20 kPa)

Figure E22 Particle Size Distribution: Mineral Oil (Speed=30 rps, $\Phi=0.28$, Boost=60 kPa)

Figure E23 Particle Size Distribution: Mineral Oil (Speed=30 rps, $\Phi=0.33$, Boost=40 kPa)

Figure E24 Particle Size Distribution: Mineral Oil (Speed=30 rps, $\Phi=0.38$, Boost=20 kPa)

Figure E25 Particle Size Distribution: Mineral Oil (Speed=30 rps, $\Phi=0.38$, Boost=60 kPa)

Figure E26 Particle Size Distribution: Synthetic Oil (Speed=30 rps, $\Phi=0.28$, Boost=20 kPa)

Figure E27 Particle Size Distribution: Synthetic Oil (Speed=30 rps, $\Phi=0.28$, Boost=60 kPa)

Figure E28 Particle Size Distribution: Synthetic Oil (Speed=30 rps, $\Phi=0.33$, Boost=40 kPa)

Figure E29 Particle Size Distribution: Synthetic Oil (Speed=30 rps, $\Phi=0.38$, Boost=20 kPa)

Figure E30 Particle Size Distribution: Synthetic Oil (Speed=30 rps, $\Phi=0.38$, Boost=60 kPa)

Figure E31 Particle Size Distribution: Motoring Condition (Speed=15 rps, Boost=40 kPa)

Figure E32 Particle Size Distribution: Motoring Condition (Speed=22.5 rps, Boost=40 kPa)

Figure E33 Particle Size Distribution: Motoring Condition (Speed=30 rps, Boost=40 kPa)

Figure E34 Particle Size Distribution: Motoring Condition (Speed=22.5 rps, Boost=20 kPa)

Figure E35 Particle Size Distribution: Motoring Condition (Speed=22.5 rps, Boost=40 kPa)

Figure E36 Particle Size Distribution: Motoring Condition (Speed=22.5 rps, Boost=60 kPa)