THE EFFECTS OF LUBRICATING OIL CONSUMPTION ON
THE DETAILED CHARACTERISTICS OF
DIESEL PARTICULATE MATTER

by

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ABSTRACT

THE EFFECTS OF LUBRICATING OIL CONSUMPTION ON THE DETAILED CHARACTERISTICS OF DIESEL PARTICULATE MATTER

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Testing was carried out on a Cummins N14 single-cylinder heavy-duty D.I. diesel research engine with a full dilution tunnel system to quantify lubricating oil consumption (LOC) rates and determine any effects of changes in LOC rates on the particulate matter. Varying oil consumption rates and their effect on particulates were analyzed at selected operation conditions of the CARB 8-mode test cycle. The three steady-state engine operating conditions tested were mode 4 (1200RPM, 25% load), mode 5 (1200RPM, 100% load), and mode 1 (1800RPM, 100% load).

Several engine alterations, consistent with the literature, for changing LOC rates were applied. The alterations consisted of installing an oil control ring with a unit pressure 50% less than the standard value, removing the intake valve stem seals (VSS), removing the exhaust VSS, and removing all (intake and exhaust) VSS. Each of these alterations was tested individually to avoid causing interacting effects.

LOC rates were successfully quantified by measuring the calcium concentration in the exhaust particulates. For the engine operating conditions tested, no major differences in detailed PM characteristics for changes in LOC rates were found except for organic
carbon emissions at mode 5. In addition, very small changes in the particle size
distribution for the lower unit pressure oil control ring were observed for modes 5 and 1
in the size range of 150 to 250 nanometers.
DEDICATION

To my parents,
for continuously supporting me in all that I have done.
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CHAPTER 1 – INTRODUCTION

1.1 Motivation

Motor vehicle fuel efficiency has been of major concern for the past few decades due to air pollution concerns. Most notably, the Energy Policy and Conservation Act, a 1975 amendment of the Motor Vehicle Information and Cost Savings Act, requires that new passenger cars meet at least 27.5 mpg on average by 1985. For this, a company fleet average fuel consumption rate must be calculated by testing, on a United States Environmental Protection Agency (EPA) specified test procedure, a certain percentage of all vehicles sold in the U.S. This Corporate Average Fuel Economy (CAFE) must be met, otherwise considerable fines of $5 per 0.1 mpg under the CAFE value for each vehicle sold are issued. In the years since 1975, the CAFE regulation has been changed to also include light duty trucks as well as passenger cars. [1]

Another notable regulation affecting fuel economy, and more recently, is the Kyoto Agreement resulting from United Nation (UN) talks in Kyoto, Japan in December of 1998 regarding climate changes with major concern on greenhouse gases, most notably carbon dioxide (CO₂). In response, the European Union (EU) agreed to decrease greenhouse gases, CO₂ in particular, to eight percent below the 1990 values by around 2010. This led to agreements and regulations that mandate large fuel economy improvements, which will hopefully lead to reduced motor vehicle CO₂ emissions. [1]
Diesel engines have an inherent advantage over gasoline engines in regard to fuel efficiency. Thus, diesel engines are slowly becoming more popular, especially in respect to light-duty applications. The benefit of higher fuel efficiency for diesels not only allows a lower emission rate of CO₂, but also of carbon monoxide (CO), hydrocarbons (HC), and evaporative hydrocarbons than the emission rates from gasoline engines. Improvements in diesel fuel and diesel engine technology continue to decrease the emission of these pollutants. [1,2,3]

Diesel engines are already currently used in a wide variety of medium- and heavy-duty applications due to their high power to weight ratio. This fact and the fact that diesels are slowly increasing popularity among light-duty applications have increased the need for diesel engines to meet current and future regulations for all the regulated emissions.

The regulated emissions from diesel engines include the oxides of nitrogen (NOₓ) and particulate matter (PM). In addition to the strict regulations that are already in place regarding these emissions, the United States Environmental Protection Agency (U.S. EPA) has created even more stringent regulations that will be implemented in the near future. The regulation on NOₓ is for reducing ozone, a byproduct of reactions between NOₓ and hydrocarbons in the atmosphere. PM is regulated due to risks associated with human health [1]. Recent advances in diesel engine technology have greatly reduced these emissions, but future regulations are going to require substantial improvements regarding diesel emissions.
Along with emission regulations, many countries have instated regulations regarding the fuel composition. The European Union has mandated the use of 50 ppm maximum sulfur content starting in 2005. This is an additional tightening of the regulation of 300 ppm sulfur content that was implemented in 2000. The decrease in sulfur content lowers PM emissions and aids in facilitating such advanced technologies as DeNOx catalysts. [4]

Similar to the steps taken by the European Union, the U.S. EPA has put in place regulations regarding diesel fuel sulfur content. The regulation of 15 ppm maximum sulfur content will take effect on June 1, 2006 for diesel fuel refiners. For retail stations and fleets, the regulation of 15 ppm sulfur diesel fuel will not be in effect until September 1, 2006. [5]

### Table 1.1 Heavy-Duty Diesel Emissions Phase-In Schedule [5].

<table>
<thead>
<tr>
<th>Standard (g/bhp-hr)</th>
<th>Model Year of Phase-In*</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>NOx</em></td>
<td>2007</td>
</tr>
<tr>
<td>0.2</td>
<td>50%</td>
</tr>
<tr>
<td>NMHC</td>
<td>0.14</td>
</tr>
<tr>
<td>PM</td>
<td>0.01</td>
</tr>
</tbody>
</table>

* Percentages represent percent of sales.

Along with the fuel sulfur content regulations, the EPA has released stringent heavy-duty diesel regulations for NOx, non-methane hydrocarbons (NMHC), and PM to be phased in from 2007 to 2010. Table 1.1 shows the phase-in schedule for these emissions. It is important to note that the EPA set the heavy-duty diesel and heavy-duty gasoline
emission standards to the same values as listed in Table 1.1. The only difference is that the heavy-duty gasoline standards have a slightly different phase-in schedule. [5]

The PM regulations are only in regard to mass concentration, such as the 2007 year U.S. EPA PM regulations of 0.01 g/bhp-hr. The regulations do not take into account size distributions, number concentrations, or detailed chemical characteristics. The regulations do not take health risks into account of PM characteristics. The level of health risk is thought to depend on chemical characteristics and size. A smaller size of particulate would be more likely to travel further into lung tissue. This involves the concern of whether or not the recent reductions of diesel exhaust PM mass concentrations are a result of an overall decrease of particulate production or just a shift to a smaller size range of particulates. These concerns lead to the need of looking at the detailed chemical composition and size distributions. [1]

There have been several studies in the past showing differences in particulate matter emission concentration as a result of fuel composition and operating condition. There have only been a limited number that looked at the effect on diesel particulate matter chemical composition and size distribution. Similarly, there are several studies relating the effects of lubrication oil consumption (LOC) on exhaust PM concentrations and the soluble organic fraction (SOF), but there are only a few that investigate the effects on particulate detailed chemical composition and size distributions.
1.2 Objectives
The main focus of this research is to investigate the size distributions and detailed chemical composition of diesel particulate matter (PM) produced by a modern heavy-duty direct injection (DI) diesel engine for selected engine operating conditions, LOC rates, and LOC sources. The detailed chemical composition of PM includes sulfates, trace metals, and elemental carbon/organic carbon (ECOC). Size distribution data were collected along with particle number concentrations.

1.3 Approaches
A previously augmented full dilution tunnel system in the Cummins N14 engine laboratory of the University of Wisconsin-Madison’s Engine Research Center (ERC) was used to measure size distributions and detailed chemical composition of diesel particulate matter (PM). The dilution tunnel system is comprised of a primary full dilution tunnel (PDT), a secondary dilution tunnel (SDT), and a residence time chamber (RTC).

Multiple ports in the RTC immediately following the SDT allow for data collection by means of a Scanning Mobility Particle Sizer (SMPS), Tapered Element Oscillating Microbalance (TEOM), Fourier Transform Infrared (FT-IR) Spectrometer, and 47 mm diameter filters for metals, elemental carbon, organic carbon, sulfate, and PM2.5 concentration analyses. Single ports in the engine exhaust surge tank and PDT allow for emission and dilution ratio data to be collected through the use of an FT-IR Spectrometer.
The SMPS (TSI model 3936L10) measures particle number concentrations and size distributions of PM in the RTC. The TEOM (Rupprecht & Patashnick (R & P) Model 1105) measures real-time PM mass concentrations in the RTC. The REGA 670 FT-IR gas analyzer consists of a Nexus 670 FT-IR spectrum analyzer, a ThermoNicolet 2 meter gas cell, and a REGA sampling bench.

The fuel used in the current experiment is a BP ARCO ultra low sulfur (EPA) diesel (ULSD) #2 fuel with 14 ppm sulfur content. The engine lubrication oil used in the current experiment is 15W-40 mineral base oil.

1.4 Layout of Thesis

This thesis consists of a total of six chapters: Introduction, Literature Review, Experimental Setup, Experimental Design and Engine Operating Conditions, Results, and Conclusions and Recommendations.

Chapter 2 is composed of an extensive literature review of the following: fundamentals of soot formation including soot kinetics, models, and experimental measurements; composition, structure, dynamics and behavior, size distributions, and factors that alter size distribution of PM; and sources and effects of lubricating oil consumption (LOC).
Chapter 3 describes the experimental setup in detail. The discussion will entail the Cummins N14 laboratory setup, which includes the engine, engine bench, the full-dilution tunnel system, and the several data collection instruments.

Chapter 4 describes the engine operating test conditions, the properties of the fuel and engine lubrication oil used, and the various LOC mechanisms tested.

Chapter 5 will present the LOC rates for each of the points in the test matrix and the detailed chemical composition and size distributions of PM which are analyzed and compared in regard to the respective LOC rate and mechanism. The detailed chemical composition analysis is comprised of EC, OC, sulfates, and trace metals. The size distribution analysis entails number and volume concentrations.

In Chapter 6, the conclusions of the current study are presented, along with a list of recommendations for future work.
<table>
<thead>
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This chapter provides an overview of the literature regarding soot formation, oxidation, modeling, and measurement techniques and also the effect of oil consumption on total particulate matter emission and soluble organic fraction. It will also provide an exhaustive literature review on the effects of oil consumption on the detailed chemical characteristics and size distribution of diesel particulate matter.

2.1 Fundamentals of Soot Formation

Soot particles are primarily composed of carbon atoms with smaller amounts of hydrogen and oxygen. They are composed of 20 to 30 nm spherules each containing $10^5$ carbon atoms with an approximate H/C ratio of 0.1. The production of soot occurs during the high temperature combustion process of hydrocarbons and occurs in only a few milliseconds as low molecular weight hydrocarbons are essentially converted to solid carbon. The end emission rate of soot from a flame or combustor is a result of a competition between soot formation and oxidation. [6,7]

2.1.1 Soot Kinetics

Soot production cannot be simply summed up in a formation rate value alone. Multiple specific processes are involved to create the final physical and chemical form of the soot.
These processes include particle inception, surface growth, collisional coagulation, and soot oxidation.

2.1.1.1 Particle Inception
The pyrolysis of hydrocarbons produces smaller unsaturated hydrocarbons, particularly acetylene [8,9,10]. These aliphatic hydrocarbons provide a source for producing the first aromatic species in the initial soot production step [11]. Polycyclic aromatic hydrocarbons (PAHs) are formed by the growth of the aromatic species by the addition of other aromatic and smaller alkyl species. Acetylene and PAH are widely regarded as soot particle precursors [6,8]. Further growth of PAH leads to the smallest identifiable soot particles with a diameter on the order of 1 nm [8]. This size of particle has a negligible amount of soot loading, even with large numbers [6].

2.1.1.2 Surface Growth
Surface growth accounts for the process by which most of the solid-phase material is produced [6]. During this process, gas phase material is added to the active sites on the particles by way of chemical reactions [7]. The primary growth species in hydrocarbon flames is acetylene, although PAHs may also participate [7]. This process only increases the amount of soot on a mass basis, and does not alter the number of particles [8].
2.1.1.3 Collisional Coagulation

Collisional coagulation does not change the amount of soot on a mass basis; it only alters the number of particles. During this process, particles that are formed during the particle inception process collide and agglomerate, thus decreasing the number of particles. This process is physical in nature, whereas the surface growth process is chemical. [6, 8]

2.1.1.4 Soot Oxidation

Soot oxidation can occur throughout the soot formation process. This process is primarily an attack by oxygen (O$_2$) and the hydroxyl radical (OH) on the soot to form gaseous products such as carbon monoxide (CO) and carbon dioxide (CO$_2$) [6, 8, 12]. Studies have shown that the hydroxyl radical may be more important than oxygen for the process of soot oxidation [6, 13].

2.1.2 Soot Models

There are an ever increasing number of models that aim to predict the amount of soot produced from the combustion of hydrocarbons. Generally speaking, the models can be classified into one of the following categories: empirical; semi-empirical, and detailed chemistry models. As the name suggests, empirical models work entirely off of correlations to experimental data. Semi-empirical equations are based on a combination of the soot formation rate equations and experimental data. Detailed models are the most elaborate, with all or most of the detailed chemical reactions of soot formation and oxidation used to predict soot production rates. [7]
2.2 Composition and Structure of Diesel Particulate Matter (PM)

PM is not only carbonaceous material (i.e. soot), but it is also composed of ash, volatile organics, and sulfur compounds. Typical composition proportions of diesel particulate matter is shown in Figure 2.1. The total SOF and absolute amounts of oil and fuel contributed SOF are highly dependant on engine design and operating conditions. Further details regarding SOF will be discussed in the following sections.

![Figure 2.1](image)

**Figure 2.1** Typical diesel particulate matter (PM) composition from a modern heavy-duty diesel engine tested under a heavy-duty transient cycle, adapted from [14].

A schematic showing the typical structure of diesel engine exhaust particulate matter is shown in Figure 2.2 and is dependant on fuel sulfur content. Although it depends on the engine operating condition, nearly all of the soot is significantly oxidized. Thus, only a small fraction survives and is exhausted as solid agglomerates. A small amount of non-oxidized fuel and lubricating oil are emitted in the exhaust as volatile or soluble organic
fraction (SOF), of which contains polycyclic aromatic hydrocarbons. The sulfur that is in
the fuel is mostly combusted to SO$_2$, with a small amount forming SO$_3$ and sulfates. The
metal compounds that originate from the fuel and lubricating oil form a small amount of
inorganic ash. [14,15]

**Figure 2.2** Schematic structure of diesel particulate matter (PM), adapted from [14].

2.3 **Dynamics and Behavior of Diesel Particulate Matter (PM)**

The processes that the particulate matter undergoes in its path from the combustion
chamber through the dilution system and finally to the sampling system must be well
understood to ensure that valid measurements are obtained. These processes include
adsorption/desorption, condensation/evaporation, coagulation, thermophoretic deposition,
diffusional deposition, inertial deposition, electrostatic deposition, gravitational
deposition, and chemical reactions.
2.3.1 Physical Processes

In regard to experimental research, physical processes are a significant source of test-to-test variation. The physical processes include adsorption/desorption, condensation/evaporation, coagulation, thermophoretic deposition, diffusional deposition, inertial deposition, and electrostatic deposition. Each of the deposition processes can be a source for reentraining particles. The reentrainment of particles occurs in a very unpredictable manner. Therefore, measures should be taken to avoid each type of deposition. [15]

2.3.1.1 Adsorption/Desorption

Soot particles have extremely large specific surface areas that are available for adsorption. As a result, they are able to adsorb large quantities of gases and vapors. The saturation ratio does not necessarily have to be high for there to be a large amount of mass adsorbed to the particle surface. As the saturation ratio increases, more of the active sites are filled. If the saturation ratio remains sufficiently large, the adsorbing material begins creating an additional layer on top of the previous. Adsorption is affected by the saturation ratios of the various organic species, the available particle surface area for adsorption, adsorption energy, and time for adsorption to occur. [15,16]

2.3.1.2 Condensation/Evaporation

Homogeneous nucleation is the formation of new particles from vapor, which occurs when the saturation ratio is greater than unity. Similarly, condensation occurs under the same circumstances, except that it does not create new particles. The process of
condensation is a mass transfer from vapor to existing particles, which creates additional particulate mass. Evaporation works against these processes whenever the saturation ratio is less than unity by decreasing particle mass. [16]

2.3.1.3 Coagulation
Coagulation is a particle to particle collision that leads to agglomeration. This process does not change the total PM mass concentration, but does have an effect on the particle size. The ratio of the residence time to the characteristic time for coagulation influences the amount of coagulation that takes place. The characteristic time for coagulation is inversely proportional to particle concentration, and thus dilution ratio. [16]

2.3.1.4 Thermophoretic Deposition
Thermophoretic deposition can take place whenever there is a temperature gradient due to a cool wall. The phenomenon causing this is called thermophoresis, where more vigorous collisions occur on the high temperature side than the low temperature side of the particle. This causes the particle to move towards the cool region, and thus towards or onto the cool wall. [15,16]

2.3.1.5 Diffusional Deposition
Diffusional deposition occurs for particles lost by means of a concentration gradient through the boundary layer. This process is more of a problem for highly turbulent flow, where there is an increasingly thin boundary layer. The diffusion coefficient varies
inversely with particle diameter. As a result, diffusional deposition is most important for
particles smaller than about 0.05 µm in diameter. It is difficult to completely eliminate
diffusional deposition, but it can be reduced by using short sample lines. [15,16]

2.3.1.6 Inertial Deposition

Inertial deposition affects the larger size particles and occurs during non-isokinetic
sampling and in bends and contractions, when the particles cannot follow the fluid
streamlines as a result of their inertia. To reduce the effect, sharp corners and abrupt
changes in diameter should be avoided. [15,16]

2.3.1.7 Electrostatic Deposition

Electrostatic deposition can be a large problem for diesel emission sampling if the correct
measures are not taken. Particles produced by diesel combustion have a significant
bipolar charge. Properly grounding the sampling system reduces the losses associated
with this type of deposition. To further reduce the effects, avoid Teflon sample lines,
which are prone to a large build-up of electrostatic charge. Rather, grounded metal
sample lines, such as stainless steel, should be used. [15,16]

2.3.1.8 Gravitational Deposition

Particle loss through gravitational deposition is usually very small for diesel particulates.
The impact of gravitational deposition can be reduced by avoiding long horizontal
sections of sample line where large particles could easily settle out. [15,16]
2.3.2 Chemical Processes

Chemical processes play a significant role in nucleation and adsorption/desorption. As mentioned previously, physical processes are involved in the adsorption/desorption process, but so are chemical interactions between the adsorbed species and the particle surface.

Nucleation forms particles from gaseous organic species [15,16]. This process occurs at much higher pressures than saturation pressure and is the process by which the number of the smallest particles (nuclei mode) is dramatically increased in diesel particulate matter. Nucleation occurs more easily when there is insufficient particle surface for adsorption. The dilution of the exhaust particles with air is also a factor in the nucleation process [17].

Nucleation can occur by two methods: homogeneous nucleation or heterogeneous nucleation. Homogeneous nucleation forms molecular clusters from vapor molecules and requires much higher supersaturation values than heterogeneous nucleation in order to form a particle. Heterogeneous nucleation causes the growth of nuclei particles; therefore it is also referred to as nucleated condensation. Heterogeneous nucleation can occur at lower saturation values than those required for homogeneous nucleation. [15,16]
In diesel exhaust, nucleation can occur at saturation ratios below supersaturation. It is thought that heterogeneous nucleation of volatile organics occurs due to the presence of sulfuric acid and metallic ash nuclei particles. [15]

2.4 Size Distributions of Diesel Particulate Matter (PM)

Particle size distributions can be classified as either bimodal or lognormal form. The former is composed of two peaks; a peak in the nuclei mode size range of 5 to 50 nm and another in the accumulation size range of 50 to 1000 nm. The lognormal form is characterized by having a peak number of particles at a diameter much smaller than the mean diameter. Figure 2.3 shows typical engine exhaust number and mass weighted particle size distributions.

![Figure 2.3](image-url)

Figure 2.3 Typical engine exhaust number and mass weighted particle size distributions, adapted from [14].
2.4.1 Effect of Engine Type and Operating Conditions

Engine type and operating conditions greatly influence the particle number concentrations and size distributions. Greenwood et al. compared particulate size distributions from a diesel, gasoline and compressed natural gas (CNG) vehicles and found that at low loads, the diesel vehicle emitted higher number concentrations of particulates than gasoline or CNG. However, at high road loads all three vehicle types produced comparable numbers of particulates. [18]

![Figure 2.4](image-url) Specific number (left) and volume (right) size distributions under CARB 8-mode test cycle, adapted from [20].
The operating condition of an engine has a profound effect on the particle number concentrations and size distributions [19,20]. Figure 2.4 shows the influence of various speed and load conditions on the number and volume distributions (assuming spherical particles) for a heavy-duty diesel engine.

2.4.2 Effect of Dilution Conditions

There are multiple dilution parameters that can have an effect on particle size distributions, such as dilution ratio, relative humidity, and residence time. Dilution ratio mainly influences the nuclei mode particles, rather than the accumulation mode [21]. This is due to the accumulation mode particles being primarily composed of carbon agglomerates, whereas the nuclei mode particles are primarily volatile organics [15,22].

Residence time has been found to have interacting effects on nuclei mode particles with dilution ratio and dilution temperature. For a low dilution ratio and low temperature, residence time shows a strong influence on nanoparticle number concentrations. Whereas, for high dilution ratio and high temperature, residence time has a negligible effect on nanoparticle number concentrations. [21]

In regard to relative humidity (RH), one study found there to be a significant effect on particle size distributions, specifically in the nanoparticle size range; whereas, another study found there to be no significant effect. The given explanation for this is that the RH effects may depend on the chemical composition of the nanoparticles. [21,23]
2.5 Chemical Analysis of Diesel Particulate Matter (PM)

The composition of diesel particulate matter (PM) is an agglomeration of carbonaceous material, organic compounds, sulfur compounds, and trace elements. Organic carbon (OC) has been found to be a substantial component in fine particulate matter, especially nanoparticles [15,22]. Polycyclic organic matter (POM) and volatile organic compounds (VOC) are considered to be hazardous to the health of human beings [23]. As a result, POM and VOC are included in the Environmental Protection Agency’s (EPA) list of Mobile Source Air Toxics (MSATs) [24].

The structure of diesel fuel components ranges from chains of 10 to 25 carbon atoms; whereas the structure of lubricating components ranges from chains of 16 to 40 carbon atoms. It has been found that a major source of particulate matter is the heavier components, such as lubricating oil and the components of fuel with higher boiling points. Due to the chemical structure differences of the oil and fuel, relative contributions to diesel particulate matter can be measured, such as by gas chromatography to separate SOF into fuel and oil derived portions. [25]

2.6 Effect of Fuel Composition on Diesel Exhaust

The composition of the fuel has significant effects on the emitted diesel particulate matter [20]. For this reason, regulations are being implemented that control the composition of the fuel, specifically the fuel sulfur content [23]. The reduction of sulfur in the fuel has multiple benefits: First, there is a fuel efficiency improvement for vehicles with exhaust
gas treatment catalysts (i.e. NOx Storage Traps) by reducing the frequency that they need to be regenerated. Secondly, the reduction in sulfur directly reduces the amount of SOx emitted. This is most beneficial for vehicles fitted with oxidation catalysts that have a tendency to oxidize SO$_2$ to sulfate, an ultra fine particulate material (UFPM). [4] Finally, and maybe most importantly, the lower sulfur content reduces the formation of nuclei mode particles. It has been shown that the use of a low sulfur diesel fuel resulted in a decrease of nanoparticle concentrations without affecting the accumulation mode [21].

2.7 Lubricating Oil Consumption Origins

The magnitude of oil consumption is very different from one source of oil consumption to another, and the effect of each origin location is significant. The environment that the consumed oil is exposed to has a major effect on the emitted form of the oil, such as whether or not the oil is emitted as PM. The effects of such origins and relative estimates of oil consumption magnitude from each origin are further explained in the following subsections.

2.7.1 Piston/Liner Lubricating Oil Consumption

Oil migration past the piston rings is one of the two major sources of oil consumption. It is generally thought that oil consumption from this mechanism is the dominant source [25]. The piston, piston rings, and liner become a complex assembly in regard to controlling oil consumption, especially when exposed to varying speeds and loads. There are a substantial number of aspects in these components alone that need to be considered
when looking at oil consumption; such as piston ring kinematics, piston oil drainage, piston secondary motion, piston ring conformability, liner deformation, and cylinder liner surface. [26]

The dynamics of the piston rings can lead to instabilities if not designed properly. These instabilities will likely cause substantial increases in oil consumption. Similarities in oil consumption between motoring transient tests and corresponding steady state motoring tests would suggest that no significant piston ring instabilities occur for the tested speed [27].

Mori et al. conducted a study in which the unit pressure of the piston oil control ring was altered to vary oil consumption. It was found that 20 to 30 percent of the oil consumed by this method ended up as PM. [28]

2.7.2 Valve Stem Lubricating Oil Consumption

The valve stem seals are the other major source of oil consumption and thus must be considered in regard to particulate emissions [25]. In a heavy-duty diesel engine, it has been found by Mori et al. that all of the oil leakage from the exhaust valve stem seals results in an increment of PM. Also, approximately 10 to 30 percent of the oil leaked from the intake valve stem seals end up as PM. [28]
Inoue et al. found that the total oil leaking from all the valve stem seals has a relatively high conversion ratio of 60 to 75 percent for their particular engine. Further tests concluded that the exhaust valve stem seals had a conversion ratio of 90 percent, whereas the intake valve stem seals had a conversion ratio of about only 20 percent. Additional research by Inoue et al. showed that any oil leaking from the exhaust valve stem seals or turbocharger had a high conversion ratio. However, any consumed oil originating from the positive crankcase ventilation (PCV) system, intake valve stem seals, or past the piston rings had a fairly low conversion ratio. It was concluded that any oil passing through the combustion chamber would have a low conversion rate. This was found to be especially true for increasing loads. [29]

2.7.3 Positive Crankcase Ventilation (PCV) Lubricating Oil Consumption

In comparison to the other sources of lubricating oil consumption, the PCV system usually causes very small amounts of LOC. For a study on diesel particulate emissions, Inoue et al. found that the conversion ratio of oil contributed from the PCV system reaches only 15 to 20% even under light loads. (Conversion ratio refers to the amount of oil being converted to PM.) It was concluded that oil aspirated into the combustion chamber as a mist is mostly combusted. Thus, the combination of low oil conversion rates to PM and relatively low LOC rates, led to the conclusion that the LOC from the PCV has a negligible effect on PM emissions. [29]
2.7.4 Turbocharger Lubricating Oil Consumption

Similar to the PCV system, the turbocharger contribution to the overall LOC rate is extremely small. Inoue et al. found that the conversion ratio of turbocharger oil leakage to be as much as 70%. This is much greater than the conversion rate for the PCV system. [29]

2.7.5 Speed and Load Effects on LOC

Speed and load have a substantial effect on the overall LOC rate. It has been found in many studies that oil consumption rate increases with increasing speed and increasing load [30,31,32,33]. The difference between the minimum and maximum oil consumption rate for a speed/load map is often found to be an order of magnitude or more. Although there could be a substantial amount of oil consumption at a given speed/load point, it does not necessarily mean that all of that oil is converted to PM.

The respective load has a profound effect on the conversion of consumed oil to PM. Numerous past studies have shown that as load increases the percentage of consumed oil that contributes to PM dramatically decreases. This is due to the much higher combustion and exhaust temperatures of the higher loads, which easily combusts most of the leaked oil. At lower loads, where the combustion temperatures are lower, the oil is not so easily combusted. Thus, much of the leaked oil is converted to PM at lower loads. [28, 31,34,35,36]
2.7.6 Oil Properties Effect on LOC

The effects of oil properties, such as viscosity and volatility, are somewhat minimal in comparison to the other factors causing oil consumption. Even though these effects are small, proper selection of lubricating oil cannot be neglected in the process of producing a low oil consuming engine, especially with the goal of decreasing PM emissions. [27]

Manni et al. concluded that at a high-power condition SAE20 oil showed a 20 percent lower oil consumption rate than SAE40 oil of the same volatility. In the same study, a comparison of different volatility SAE 40 oils was conducted. It was found that a lower volatility SAE40 and a multi-grade 10W-40 gave slight oil consumption rate improvements over a higher volatility SAE40, 8 and 5 percent, respectively. [37]

However, Laurence et al. found that total particulate emission increased with decreasing viscosity. It was concluded that this was caused by the lower viscosity oil having a larger oil consumption rate. [35]

Andrews et al. found that the lubricating oil combustion efficiency was not predominately controlled by the lubricating oil properties, but rather the engine design and operating conditions. [36]
2.8 Effects of Lubricating Oil on Diesel Particulate Matter

Research on the effects of lubricating oil consumption (LOC) on diesel particulate matter has been generally limited to the total PM and soluble organic fraction (SOF) emissions. The cause of such limited study is a result of regulations based upon only mass emission rates. Therefore, there is limited previous research on size distribution and detailed chemical characteristics. This is especially true in regard to LOC effect on PM.

PM is composed of a solid fraction, a soluble organic fraction, and sulfates. The solid fraction is composed mainly of carbon, with a C/H ratio of 4 to 11. The density of the solid carbon fraction is approximately 2g/cc. Lubricating oil derived metal ash compounds add to the solid fraction. SOF has a much lower density and C/H ratio than the solid carbon, with values of 0.5 to 1.0, and 0.8 g/cc for density. Most of the SOF found in PM is absorbed onto the surface of the 20 to 50 nm particles of the solid carbon fraction. Lubricating oil is the source of approximately 75% of the total SOF. An important fact is that SOF is a major source of polycyclic aromatic hydrocarbons (PAH) in diesel particulates. PAH, a potential carcinogen, usually contains 2 to 6 benzene rings.[38]

2.8.1 Total Particulate Matter (PM)

Engine oil can be a significant source of total PM emissions, with contributions ranging from 1.5 to 48%, depending on LOC rate and operating condition [25,39]. Consumed oil has the potential of being present in both the solid fraction and soluble fraction of the
particulates or possibly be completely combusted into gaseous emissions. The ratio of the completely combusted lubricating oil to the total LOC rate is known as the combustion efficiency. Typical combustion efficiencies range from 40 to 85%, and is highly dependent on engine design and operating condition [36]. The amount of lubricating oil that is not completely combusted is known as the survival rate or conversion rate. Typical survival or conversion rates range from 0 to 70%, and are also highly dependent on engine design and operating condition [31,34,40].

2.8.2 Soluble Organic Fraction (SOF)

Advances in diesel engine technology have improved the combustion of the fuel and thus have considerably decreased the fuel contribution to the soluble organic fraction (SOF). As a result, the relative oil contribution to SOF has increased.

The lubricating oil that remains in some hydrocarbon form is considered as oil-SOF. The amount of consumed oil that contributes to SOF is largely dependent on engine design and operating condition. Previous studies have shown that all of the oil contribution to the particulate is extractable and thus adding to the SOF of the PM [39]. As a result, lubricating oil is a major source of the SOF, ranging from 16 to 80 mass percent [39].

There is an interesting interaction between fuel and oil in regard to SOF. First, the sulfates that are formed primarily from the fuel sulfur content have a tendency to scrub out hydrocarbons from the gas phase [41]. The attraction of sulfates is primarily towards
lubricating oil hydrocarbons [42]. This effect increases the contribution of oil to SOF. Secondly, there is an effect of lubricant parameters on fuel-derived SOF. An increase in oil on the liner prevents additional fuel from participating in the combustion event through the fuel absorption and desorption process [35]. This directly leads to increases in the fuel-derived SOF. This phenomenon is also seen in other studies, such as the one by Manni et al., where differences in oil properties, thus differences in LOC, led to changes in the fuel-derived SOF [37].

2.8.3 Size Distributions

Size distribution change as a result of LOC is one of the most controversial topics in regard to LOC. There have been few studies in regard to the LOC effect on size distribution.

Ziemann et al., through Nano-DMA/TDPBMS (Thermal Desorption Particle Beam Mass Spectrometer) analyses and Nano-TDMA (Tandem Differential Mobility Analyses) volatility measurements, found that the organic component of diesel nanoparticles is almost entirely composed of unburned lubricating oil [22].

Johnson et al. found that exhaust sulfate levels have a significant effect on nuclei-mode particle concentration [43]. Any sulfur content in the lubricating oil, combined with lubricating oil consumption, would potentially contribute to this phenomenon.
Through the use of an Aerosol Time of Flight Mass Spectrometer (ATOFMS), Okada et al. found that lubricating oil makes a significant contribution to particles around 0.42 µm. This was found by measuring the percentage of particles containing calcium for each size from 0.2 µm to 3.0 µm. A peak around 0.42 µm was found for multiple operating conditions, and thus multiple LOC rates.

### 2.8.4 Detailed Chemical Characteristics

Research regarding effects of LOC on the detailed chemical characteristics of PM is extremely rare.

Ziemann et al., through TDPBMS measurements, found that more than 70 percent of the organic component of diesel particles is composed of unburned lubricating oil. The percentage is found to be 95 percent when the measurement technique resolution is improved through the use of Fischer-Tropsch fuel. [22]

Through the use of filter based measurements, Okada et al. found that calcium shows the highest emissions in PM of all the trace metal compounds. Calcium was found in the lubricating oil and was less than 0.1 ppm in the fuel used for this experiment. Therefore, the calcium found in the particulates was assumed to originate primarily from the lubricating oil and thus is a good metric for measuring LOC. It was also found that increments of calcium emission correlate with increments in organic carbon (OC) emission. Also, through the use of an ATOFMS, Okada et al. found shifts in the particle
size where the peak percentage of particles containing elemental carbon (EC) was located. [30]

The ATOFMS results indicated that OC is preferentially distributed among different particle sizes. In general, the ATOFMS measurements agreed with the filter-base measurements in regard to OC. Both measurements showed that lighter loads yield a higher OC proportion in the PM. A greater percentage of smaller particles contain OC in comparison to the larger particles. As load increases, the fraction of OC containing particles decreases. [30]

A study by Williams et al. found an interesting result in regard to polycyclic aromatic compounds (PAC). It was found that the lubricating oil acts as a sink for PAC originating from the fuel. Thus, as the oil is consumed, it acts as a source of PAC, and therefore polycyclic aromatic hydrocarbons, in particulate emissions. [34]

2.9 Lubricating Oil Consumption (LOC) Measurement Methods

There is a multitude of methods used for measuring the lubricating oil consumption rate. As usual, each method has advantages and disadvantages. Also, the method of choice is highly dependant on the specifics of the application. The first concern is in regard to time resolution of the results. A method that has a poor time resolution, such as filter-base measurements, can only be used for steady state engine operating conditions. A method that has fast time response, such as methods incorporating the use of mass spectrometers,
could be used for either steady state or transient engine operating conditions. In general, all of the oil consumption measurement methods can be classified in either one of two categories: tracer method or gravimetric methods.

2.9.1 Tracer Lubricating Oil Consumption (LOC) Measurement Methods

The tracer LOC measurement method involves doing a mass balance on an element or compound of interest that is contained in the oil based on the exhaust emission levels. These elements or compounds are either originally present in the oil or can be added for purpose of LOC measurement. A few examples of elements that are usually found in engine oil in reasonable amounts are calcium, sulfur, phosphorus, manganese, magnesium, and iron. A few examples of added elements or compounds are tritium, additional sulfur, or radioactive tracers, such as C14 n-octacosane and 1,2-dibromo-82-octadecane. Along with taking a measurement of the concentration of the element or compound of interest, the total exhaust flow must also be recorded or calculated.

With the tracer method, there are a few very important assumptions. First, the tracer must be evenly distributed throughout the oil. Second, the tracer uniformly follows the flow of oil that ends up as consumed oil. Third, the concentration of the tracer in the oil is constant relative to the measurement time. Fourth, there are no additional sources of the tracer element to the particulate that are not measured. A good example of this is iron. Iron has a relatively high concentration in used oil, but can easily change with operating condition and further wear of the engine. This addition of iron is not easily measured. A
widely used example is sulfur. Sulfur is found in the ambient air in the form of sulfur dioxide, but this can be easily corrected for. Thus, any contributions of sulfur from intake air, dilution air, or fuel can be removed by simple calculation.

Radioactive tracers, such as C14 n-octacosane, can also be used to determine the relative participation of the oil in the particulates. This measurement method is called isotope dilution, where the isotope concentration is compared to the total element concentration. After doping the oil with the compound containing the isotope, the ratio of the isotope to the element total in the oil is measured. The comparison of this concentration to the concentration of the isotope in the particulate allows for a relative participation of oil in the particulate to be calculated. [39]

Tracer LOC measurement methods can usually be classified in one of two categories described below: filter-based or real-time tracer measurements.

**2.9.1.1 Filter-Based Tracer Measurements**

The use of a filter assumes that the filter can trap the tracer. If sulfur is used as the tracer, a potassium carbonate treated quartz filter must be used to capture the gas phase sulfur dioxide. A large portion of the sulfur emitted from the engine is in the form of sulfur dioxide. The rest is in various sulfur containing compounds.
Additionally, the sample duration should be sufficiently long to obtain enough of the tracer on the filter to be easily measured. After obtaining a sample, it must be analyzed to obtain tracer concentration in regard to the flow rate through the filter. An example of an instrument that would be used for such an analysis is an inductively coupled plasma mass spectrometer (ICPMS).

2.9.1.2 Real-Time Tracer Measurements
Real-time tracer measurements need some type of instrument or analyzer to provide a fine time resolution of data on the tracer concentration. Various spectrometers are usually chosen for this application, such as mass spectrometers or Fourier Transform Infrared (FT-IR) spectrum analyzers.

2.9.2 Gravimetric Lubricating Oil Consumption Measurement Methods
This type of method is very tedious and time consuming. The engine must be run long enough to accumulate enough LOC so that it can be measured accurately. There is often a large amount of variability inherent in this method due to the minute amounts of oil consumed relative to the amount of oil in the engine. To add to this, oil hang up in various locations in the engine and fuel dilution are continual problems.

On the upside, this method is a more direct approach to measuring oil consumption. There are very few assumptions needed in comparison to the tracer method. In addition, there is no need for exhaust flow values, as there is with the tracer method.
2.9.2.1 Drain and Weigh Method

For the drain and weigh method, the engine is first completely drained of oil and previously broken-in oil of a measured weight is put back into the engine. The engine is run for an extended period of time under the desired conditions. A usual duration for the engine test is 4 to 6 hours. After the engine is run, the oil is completely drained and weighed again. The difference between two weights represents the amount of oil consumed.

2.9.2.2 Constant Weight Method

The constant weight method involves the use of a dry sump system to continually measure the weight of the reservoir. As oil is consumed by the engine, less oil is stored in the reservoir. This method has less variability than the drain and weigh, due to less operator involvement, but involves a more complicated measurement system. [44]

2.9.2.3 Constant Oil Level Method

The constant oil level method attempts to measure differences in the oil height of the sump. For real-time measurements with this method, the running of the engine in itself causes complications by creating fluctuations in the surface of the oil in the sump. Also, if the top surface area of the oil in the sump is large, then a relatively large amount of oil must be consumed to lower the oil height in the sump. AVL has produced such a device that measures the changes in height of the oil in the sump. [45,46,47]
<table>
<thead>
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<th></th>
<th>Reference</th>
</tr>
</thead>
</table>


For the current experiment, the crankcase ventilation is exhausted to the building exhaust system. Therefore, the effects of a PCV system are not explored in this study.

For the current experiment, simulated turbocharging is achieved through pressurizing the intake air and inducing back pressure in the exhaust system with a gate valve. Therefore, the effects of turbocharger LOC on PM are not explored in this study.
CHAPTER 3 – EXPERIMENTAL SETUP

This chapter describes the experimental setup in terms of the engine bench setup, full-dilution tunnel system, and methods of data collection. Further details regarding the engine bench setup and full-dilution tunnel system can be found in [47] and [20], respectively.

3.1 Research Engine

The single-cylinder diesel research engine is adapted from an in-line six-cylinder Cummins N14-series engine, which is a 4 valve, 4-cycle diesel with low swirl, turbocharging, and centrally located direct-injection. The engine is designed with a quiescent combustion chamber and a shallow dish piston. A schematic of the engine bench is shown in Figure 3.1.

The production Cummins N14-series engine is used for a variety of purposes, including agriculture, construction, military, medium-duty trucks, and heavy-duty trucks. Depending on the application, the rated powers vary from 234.9 kW to 391.5 kW with peak torques ranging from 1281.2 N-m to 2508.14 N-m. The in-line, six-cylinder, production version of the single-cylinder engine used in the current study has a peak torque of 1599.8 N-m at 1200 rpm. Engine specification values are given in Table 3.1. It should also be noted that the research engine is attached to a spring-mounted isolation
pad and also utilizes a balancing box with two counter-rotating weights that is timed with
the movement of the piston.

![Schematic of the Cummins N14 engine bench layout](image)

**Figure 3.1** Schematic of the Cummins N14 engine bench layout, adapted from [20].

**Table 3.1** Cummins N14 Engine Specification.

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Cummins N14-series Research DI Diesel Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle</td>
<td>4-stroke</td>
</tr>
<tr>
<td>Combustion / Piston Chambers</td>
<td>Quiescent / Shallow Dish</td>
</tr>
<tr>
<td>Number of Intake / Exhaust Valves</td>
<td>2 / 2</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>13.1:1</td>
</tr>
<tr>
<td>Swirl Ratio</td>
<td>1.4</td>
</tr>
<tr>
<td>Bore/Stroke/Displacement</td>
<td>139.7 mm / 152.4 mm / 2333 cc</td>
</tr>
<tr>
<td>Combustion Chamber Diameter</td>
<td>97.8 mm</td>
</tr>
<tr>
<td>Connecting Rod Length</td>
<td>304.8 mm</td>
</tr>
<tr>
<td>Piston Pin Offset</td>
<td>None</td>
</tr>
<tr>
<td>Injection System</td>
<td>Unit Injector, Direct Injection</td>
</tr>
<tr>
<td>Nozzle Dimension / Spray Angle</td>
<td>$8 \times \phi 0.2$ mm / 152°</td>
</tr>
<tr>
<td>Length/Diameter of holes (l/d)</td>
<td>4.1</td>
</tr>
</tbody>
</table>
3.2 Laboratory Equipment

This section is an overview of the laboratory equipment, such as the dynamometer, fuel system, cooling system, intake system, exhaust system, and dilution tunnel system.

3.2.1 Engine Dynamometer

The dynamometer is a 225 horsepower General Electric DC dynamometer capable of motoring and absorbing load. It can be controlled to within 2 rpm of a set point by the Reliance Electric MaxPakPlus VS Drive dynamometer control system used in this study.

3.2.2 Fuel System

A rotary vane pump delivers fuel from a 5 gallon fuel tank through a Micro Motion model C6 mass flow meter to a stainless steel tank. The stainless steel tank serves as a reservoir for the production Cummins N14 fuel pump to supply fuel to the engine at a pressure of 1.14 MPa (164.7 psi). The production Cummins N14 fuel pump is not attached to the engine; rather, it is driven by an electric motor away from the engine. During motoring of the engine, an actuator on the fuel pump redirects the fuel to circulate in a loop exterior to the engine and through the heat exchanger.

The fuel injector timing and injected mass are controlled by a personal computer through the use of Shaft8 software developed by Sandia National Laboratories. Injection pressure is magnified by actuation of a camshaft. A diagram of the Cummins N14 CELECT fuel injector and operation is shown in Figure 3.2.
Figure 3.2 Schematic of the Cummins N14 CELECT fuel injector and operation, adapted from [48].
3.2.3 Cooling System

For the current study, an auxiliary cooling system that consists of a pump, heat exchanger, and coolant tank was utilized. The cooling system requires approximately 4 gallons of a 50/50 mixture of antifreeze and distilled water to fill.

3.2.4 Intake and Exhaust System

Simulated boost conditions are created in the intake and exhaust systems to replicate the corresponding engine operating conditions of the production engine. To accomplish this, the pressure of the air coming from the UW-Madison Physical plant is first regulated before passing through critical flow orifices that control the mass flow of the air. After flowing through the orifices, the intake air temperature is controlled to within 2 °C for steady-state conditions by two 4.5 kW Chromalox air heaters and an Omega electronic temperature controller. Lastly, before the intake air enters the engine, it passes through a surge tank of approximately 20 gallons.

As mentioned previously, the exhaust system conditions are also controlled to simulate boost conditions. The pressure of the exhaust system, including the exhaust surge tank, is controlled by the adjustment of a gate valve. There are two main gate valves in the exhaust system. When the dilution tunnel system is utilized, the gate valve between the exhaust surge tank and dilution tunnel is adjusted to achieve the desired exhaust back pressure, while the other gate valve is closed. When the dilution tunnel system is not
needed, the opposite scenario takes place and the exhaust is vented to the building air. Figure 3.1 shows the organization of the exhaust and intake systems.

### 3.2.5 Dilution Tunnel System

The dilution tunnel system was previously augmented to include a secondary dilution tunnel with a residence time chamber, as shown in Figure 3.3. Depending on the engine operating condition, the dilution ratios range from 6.5 to 10 in the primary dilution tunnel (PDT) and 13 to 20 in the secondary dilution tunnel (SDT). Gaseous emission measurements were taken with the FT-IR from engine out exhaust, the PDT (near the inlet for the SDT), and at the bottom of the residence time chamber (RTC). Scanning mobility particle sizer (SMPS), tapered element oscillating microbalance (TEOM), and filter samples are taken from the ports near the bottom of the RTC. The RTC was designed to have a residence time of between 30 to 60 seconds. Also, the relative humidity of the RTC is measured with wet-bulb and dry-bulb thermometers.

To establish the primary flow through the SDT and RTC, a large volume of sample is pulled through a 142 mm filter at the bottom of the RTC by five vacuum pumps. The five vacuum pumps are needed to ensure choked flow through the critical flow orifices that control the flow to approximately 195 LPM at standard temperature and pressure. Iso-kinetic sampling is achieved by pulling a small additional sample from the bottom of the RTC and adjusting the flow rate accordingly. Iso-kinetic sampling is monitored by use of an inclined manometer to measure the pressure difference between the PDT and SDT, as
shown in Figure 3.3. The derivation for the iso-kinetic flow calculation is given in Appendix A. For a more detailed description and schematics of the dilution tunnel system, see [20].

Figure 3.3 Schematic of the sampling system in the Cummins N14 engine bench, adapted from [20].

3.3 Engine Bench Measurement System

The measurement system for the Cummins N14 engine includes the following: in-cylinder pressure transducer, load cell, optical encoder, and an instrumented injector push
tube with a strain gauge. This section describes the use of each of these instruments. For further detail regarding each of the topics, refer to [20] and [47].

3.3.1 In-Cylinder Pressure Measurement
The cylinder pressure transducer is a quartz AVL Model QC33C and is water cooled with distilled water. To amplify the signal from the pressure transducer, a KISTLER Type 5010 charge amplifier was used.

3.3.2 Engine Torque Measurement
For measuring engine torque, a model RL20000B-300 Stainless Steel S-beam load cell (Rice Lake Weighing Systems, Rice Lake, WI) is utilized. The load cell is connected to a 24 inch lever arm that is attached to the dynamometer. On the opposite side of the dynamometer are two dampers.

3.3.3 Engine Crank Angle Measurement
The use of a BEI model H-25 shaft encoder results in 0.25 crank angle degrees of resolution for the crankshaft position. The shaft encoder creates two square wave signals with a frequency of 1440 cycles per revolution and a marker pulse once per revolution. The 1440 cycles per revolution, or 4 cycles per degree, create the 0.25 crank angle degree of resolution.
3.3.4 Fuel Injection Pressure Measurement

The Cummins Engine Company supplied an instrumented injector push tube for the use of measuring injection pressure. The push tube was instrumented with a strain gauge in a Wheatstone bridge circuit format.

The injection pressure trace can be calculated by knowing a few simple parameters. These parameters include the load on the push tube, rocker arm ratio, and the plunger diameter. The rocker arm ratio for the engine of the current study is 1.4:1 and the plunger diameter is 0.6362 cm$^2$. To obtain the injection pressure, the load on the push tube must be divided by the rocker arm ratio and the plunger diameter.

3.3.5 Data Acquisition System

The data acquisition system includes a National Instrument NI-DAQ, a Dell Pentium III with a PCI-MIO-16E-1 Multiple I/O board, and BNC-2090 BNC adapter. For the current study, this system was used to record cylinder and injection pressure traces.

3.4 Gaseous Emissions Measurement

Gaseous measurement instruments include a total hydrocarbon analyzer for measuring propane equivalent hydrocarbon levels and a Fourier Transform-Infrared (FT-IR) gas spectrometer for measuring CO-high, CO$_2$, NOx, and SO$_2$. Other equipment used in conjunction with the FT-IR for measuring SO$_2$ levels will also be described in this section.
3.4.1 Total Hydrocarbon Analyzer

The total hydrocarbon analyzer is a GOW-MAC Model 23-500 that utilizes the flame ionization method of detection (FID). Basically, such an instrument measures the change in gap resistance between two electrodes due to changes in the quantity of ionized carbon atoms from the burning of hydrocarbons in a hydrogen flame. For calibration of the instrument, compressed nitrogen and compressed 108 ppm propane with nitrogen balance were used as the zero and span gases, respectively. Compressed air and 40% hydrogen with helium balance were used as the air and fuel, respectively. For more information regarding the GOW-MAC total hydrocarbon analyzer, refer to [49].

3.4.2 Fourier Transform-Infrared (FT-IR) Spectrum Analyzer

The REGA 670 FT-IR gas analyzer consists of a Nexus 670 FT-IR spectrum analyzer, a ThermoNicolet 2 meter gas cell, and a REGA sampling bench. Through infrared spectroscopic techniques, the FT-IR determines the chemical species concentrations within a gas sample. The principle components of the FT-IR spectrometer are shown in Figure 3.4.

Infrared light is absorbed at distinct frequencies by each chemical species. The magnitude of absorbance is directly proportional to the concentration of the respective species. To account for multiple chemical species in a sampled gas, Beer’s law is modified to show that the absorbance of a gas is equal to the sum of the products of the absorptivity, pathlength, and concentration of all species present in the sample. Thus, using this
methodology and calibration curves relating infrared absorbance to species concentration, concentrations can be obtained for each species in the sample that absorbs light in the FT-IR sampling range. Examples of species that do not absorb light in the frequency range that the FT-IR samples include the noble gases, diatomic nitrogen, and diatomic oxygen. The species that are sampled by the FT-IR spectrometer with the current diesel emissions calibration are given in Table 3.2.

Figure 3.4 FT-IR Spectrometer Layout, adapted from [50].
Table 3.2 FT-IR Spectrometer Species List for Diesel Gaseous Emissions Calibration.

<table>
<thead>
<tr>
<th>Species</th>
<th>Methane</th>
<th>1,3-Butadiene</th>
<th>Acetaldehyde</th>
<th>Ammonia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon monoxide high</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>Ethyne</td>
<td>iso-Butylene</td>
<td>HC3</td>
<td>Carbonyl sulfide</td>
</tr>
<tr>
<td>Nitric oxide</td>
<td>Ethene</td>
<td>Formaldehyde</td>
<td>HC5</td>
<td>NOx</td>
</tr>
<tr>
<td>Nitrogen dioxide</td>
<td>Ethane</td>
<td>Water</td>
<td>HC8</td>
<td>Total Hydrocarbons</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>Propene</td>
<td>Sulfur dioxide</td>
<td>HCA</td>
<td>Non Methane Hydrocarbons</td>
</tr>
</tbody>
</table>

To allow the sampled gas to be compared to the calibration curves, the pressure and temperature of the sample must be the same as it was for the calibration gases. Therefore, it is necessary to control the temperature and pressure within the gas cell. This is done with the REGA sampling bench, which regulates the temperature and pressure of the sample as it passes through the gas cell to 165 °C and 650 torr.

3.4.3 Clamshell Furnace with Quartz Process Tube

A Lindberg/Blue, Model TF55035A-1 clamshell style furnace with a quartz process tube was used to combust the sulfur to sulfur dioxide (SO₂). The furnace is rated up to 1100 °C and 8 kW on 120 volt single-phase. For the experiments the furnace was set to 900 °C. A quartz process tube was used for its high temperature capabilities and inert chemical nature. The tube measures 1 inch in diameter and 24 inches long. At each end of the tube, it contracts down to an outside diameter (O.D.) of ¼ inch. The quartz is then degraded to Pyrex, where it is fused to ¼ inch O.D. stainless steel for connecting sample lines using compression fittings. The tube is filled with quartz beads that are 3 mm in diameter. The beads are held in place at each end with 9 micron quartz wool.
The quartz tube, quartz beads, and quartz wool were all obtained from Quartz Scientific, Inc. of Fairport Harbor, Ohio. The quartz furnace tube is a two-piece system with a tube main portion and a topvent, both with spring hooks for connecting the two pieces. The seal between the two pieces is created by an external ground section on the larger end of the tube that fits into the internal ground taper of the topvent.

3.4.4 Sample Dryer

Water contained in the sample can interfere with the components that the FT-IR measures, especially for constituents of low concentration. Therefore, for accurately measuring exhaust gas components at low concentrations, such as SO₂, the water in the sample must be greatly reduced. In addition to water interfering with the FT-IR measurement of SO₂, condensed water can easily remove SO₂ from the sample flow by oxidizing it to sulfuric acid. Thus, a method for removing water from the sample flow is needed without condensing it.

The most suitable method found for accomplishing this was a Perma Pure sample dryer (Model PD-50T-12KS) with Kynar fittings and stainless steel shell. This dryer has 50 Nafion tubes, each of 12 inches in length. The Nafion tubes are made of a copolymer of tetrafluoroethylene (Teflon) and perfluoro-3,6-dioxa-4-methyl-7-octene-sulfonic acid. This copolymer leads to a very high water-of-hydration allowing the Nafion membrane to absorb 13 molecules of water for every sulfonic acid group in the polymer. The membrane is highly selective and thus minimally affects other compounds that may be in
the sample. Perma Pure claims that SO$_2$ is not affected by the Nafion membrane and thus is totally retained. For more information on this device, refer to [903].

### 3.5 Diesel Particulate Matter (PM) Measurement

This section describes each of the methods used for characterizing the particulate matter and for measuring LOC. For further detail regarding each of the particulate matter measurement methods, refer to [20].

#### 3.5.1 Filter Measurement

The filter measurements taken include PM2.5 concentration and detailed chemical composition from the RTC and an exhaust sulfur concentration measurement taken from the PDT. The samples taken from the RTC were first flowed through a PM2.5 cyclone separator of an AIHL design that is Teflon coated aluminum. The total flow through the cyclone was set to approximately 24 LPM by critical flow orifices to achieve the PM 2.5 \( \mu \text{m} \) cut point size. From the cyclone, the diluted exhaust sample was then pulled through the filter train and critical flow orifices by a vacuum pump.

The filter train was composed of four 47 mm filters arranged in parallel, each of which was followed by a critical flow orifice. Three Teflon membrane filters (Gelman Teflo, 2 \( \mu \text{m} \) pore size) and a baked quartz fiber filter (Pallflex Tissuequartz 2500 QAO) were used. Two Teflon membrane filters were used for gravimetric determination of the PM2.5 concentration and were analyzed for sulfate ions (SO$_4^{2-}$) by ion chromatography. The
third Teflon membrane filter was analyzed by inductively coupled plasma mass spectrometry (ICPMS) for trace metals. The quartz fiber filter was analyzed for the elemental and organic carbon (EC/OC) content with a Sunset Laboratories (Forest Grove, OR) Carbon Analyzer.

Additional filters were used for measuring the concentration of sulfur emitted by the engine. Specifically, the sulfur tracer method was implemented for measuring the LOC rate. For this method, a sulfur mass balance calculation was carried out upon the engine and primary dilution tunnel system. The implemented filter method measures sulfur content only in the form of sulfur dioxide (SO$_2$) and sulfate levels. It does not measure the organic sulfur level. Therefore, all of the sulfur in the sample must be combusted to SO$_2$ through the use of a furnace.

To avoid the removal of SO$_2$ by the condensation of water, the SO$_2$ measurement was obtained from the PDT dilute exhaust rather than directly from engine out. From the PDT, the sample flowed through a clamshell type furnace with a quartz process tube to combust all of the sulfur to SO$_2$. To further avoid removal of SO$_2$ by the condensation of water, the sample then flowed through a sample dryer before being pulled through sulfate and SO$_2$ collecting filters. The SO$_2$ filters used were quartz fiber (Pallflex Tissuequartz 2500 QAO) with a potassium carbonate coating. The preparation of the coated quartz filters is included in Appendix B. The furnace and dryer were described in section 3.4.3 and 3.4.4, respectively.
Sulfur dioxide levels were measured from the building compressed air to correct for background levels of SO\textsubscript{2} in the intake and dilution air. The derivation for the LOC rate calculation can be found in Appendix C.

### 3.5.2 Scanning Mobility Particle Sizer (SMPS)

Particle number concentration and size distributions were measured with a TSI Model 3936L10 scanning mobility particle sizer (SMPS). The sample was drawn from a port near the bottom of the RTC. The principle components of the SMPS include a TSI Model 3077 Kr-85 Aerosol Neutralizer, a TSI Model 3081 Long Differential Mobility Analyzer (LDMA), and a TSI Model 3010 Condensation Particle Counter (CPC). The LDMA was operated in underpressure mode due to sampling near atmospheric pressure from the RTC. For further details, refer to [20].

### 3.5.3 Tapered Element Oscillating Microbalance (TEOM)

Real-time PM concentration (mg/m\textsuperscript{3}), total PM mass (g), and PM mass rate (g/sec) in the RTC were measured with a Rupprecht & Patashnick (R & P) tapered element oscillating microbalance (TEOM) Model 1105 diesel particulate monitor. For this study, the sample flow rate was set at 3 liters per minute and the temperature at the filter was kept at 48 °C. For further details, refer to [20].


Thermo Nicolet Corporation, Introduction to Fourier Transform Infrared Spectrometry, 2001
CHAPTER 4 – EXPERIMENTAL DESIGN AND ENGINE OPERATING CONDITIONS

4.1 Engine Operating Conditions

The engine operating conditions chosen for this study were obtained from the California Air Resource Board (CARB) 8-mode test cycle, shown in Figure 4.1. The most interesting modes to study in regard to oil consumption are Mode 5 and 1, the peak torque and rated power cases, respectively. It is believed that the tested engine has the highest lubricating oil consumption (LOC) rates at these two modes, especially at Mode 1, where the engine is at rated speed and full load [30,31,32,33,51]. Therefore, these two cases were chosen as points of research for this study. For comparison purposes, Mode 4 was also chosen to be studied. Due to the low load of Mode 4, there was thought to be low combustion efficiencies of the oil, i.e. providing a high conversion-to-PM rate for the oil at this mode. In contrast, at Modes 1 and 5, there is expected to be high combustion efficiencies of the oil (i.e. low conversion rates) because of the high combustion and exhaust temperatures (1250-1300 °F). [31,34,36]
4.2 Lubrication Oil Consumption Modes

There are multiple mechanisms that cause LOC, such as positive crankcase ventilation (PCV), turbocharger oil leakage, leakage of the valve stem seals (VSS), and migration of oil past the piston rings. The Cummins N14 research engine has simulated turbocharger conditions for intake and exhaust pressures and temperatures. The crankcase ventilation is exhausted directly to the building exhaust. Therefore, the primary sources of oil consumption possible on the studied engine are through all the VSS and past the piston rings. In addition, the VSS source can be thought of as two independent sources: intake VSS and exhaust VSS, along with their combined effect. Therefore, this study involves
the LOC effect on particulates for the intake VSS, the exhaust VSS, the combined effect of intake and exhaust VSS, and the piston rings.

The LOC rate from each of these sources was changed and comparisons were made between each source and to the stock LOC rate condition of the engine (base case). The LOC rate from the VSS will be altered by removing the valve stem rubber seals for each respective source. For instance, changing the LOC rate from the intake valve stem seals involved removing the rubber portions from each of the intake VSS. Changing the LOC rate in regard to the combined effect of intake and exhaust VSS involved removing the rubber seals from each VSS. The LOC rate from the piston rings was altered by installing a lower unit pressure oil control ring (50% of stock unit pressure) supplied by Cummins.

Replications of selected engine setups and operating conditions were completed to quantify the experimental variance. Mode 5 was replicated four times for the base case with increased dilution ratio to quantify the day-to-day variance. Modes 4 and 1 were repeated three and two times, respectively, at the base case setup with increased dilution ratio. The “No Exhaust or Intake VSS” and “50%OCR” cases were each repeated twice for the three engine operating conditions. The base case with the standard dilution ratio for this testing was used as the baseline case for comparison of the altered LOC rate cases.
4.3 Lubricating Oil and Test Fuel

The oil used in this study is mineral based 15W-40 oil. The concentrations of selected components in the oil are shown in Table 4.1. The oil has sufficient concentration of calcium to determine oil consumption rates through mass balances in the exhaust [30].

<table>
<thead>
<tr>
<th>OS#</th>
<th>OS142383</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vis Grade</td>
<td>15W-40</td>
</tr>
</tbody>
</table>
| Calcium      | 0.3412%  *
| Nitrogen     | 0.0978%  |
| Phosphorus   | 0.1156%  |
| Sulfur       | 0.4913% **|
| Sulphated Ash| 1.3504%  |
| Zinc         | 0.1269%  |
| SPEC GRAVITY | 0.9055   |
| TBN          | 10.2366  |
| SULPHATED ASH %mass | 1.4 |
| EVAP LOSS @250C %wt | 11.5 |
| HTHSR cPs    | 4.31     |
| KV @ 100C cSt| 15.15    |
| KV @ 40C cSt | 111.6    |
| VI           | 142      |

The BP ARCO ULSD Fuel (15 ppm sulfur) was chosen for this study for two main reasons: The upcoming EPA regulations mandate the use of 15 ppm sulfur fuel starting in 2006. Also, the metals (particularly calcium) content is sufficiently low to allow accurate LOC measurements to be obtained through mass balance of selected components in regard to the metal concentration in the oil. The concentrations of selected components
are listed in Table 4.2. The diesel fuel carbon number distribution in weight percent can be found in Appendix D. The average carbon number of this fuel is 17.8 with an average molecular weight of 251.1.

<table>
<thead>
<tr>
<th>TESTS</th>
<th>RESULTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>API GRAVITY, 60/60°F</td>
<td>38.8</td>
</tr>
<tr>
<td>DENSITY, 15°C</td>
<td>0.8305</td>
</tr>
<tr>
<td>VISCOSITY @40°C, cSt</td>
<td>2.43</td>
</tr>
<tr>
<td>DISTILLATION D86, °F</td>
<td>IBP</td>
</tr>
<tr>
<td>10%</td>
<td>401</td>
</tr>
<tr>
<td>20%</td>
<td>427</td>
</tr>
<tr>
<td>30%</td>
<td>452</td>
</tr>
<tr>
<td>40%</td>
<td>475</td>
</tr>
<tr>
<td>50%</td>
<td>499</td>
</tr>
<tr>
<td>60%</td>
<td>524</td>
</tr>
<tr>
<td>70%</td>
<td>550</td>
</tr>
<tr>
<td>80%</td>
<td>579</td>
</tr>
<tr>
<td>90%</td>
<td>616</td>
</tr>
<tr>
<td>95%</td>
<td>646</td>
</tr>
<tr>
<td>EPT</td>
<td>673</td>
</tr>
<tr>
<td>SULFUR, ppm</td>
<td>14 *</td>
</tr>
<tr>
<td>HEAT OF COMBUSTION, Btu/lb gross</td>
<td>19627</td>
</tr>
<tr>
<td>CETANE NUMBER (IQT)</td>
<td>52.9</td>
</tr>
<tr>
<td>CETANE INDEX ASTM D976</td>
<td>52</td>
</tr>
<tr>
<td>FLASH POINT, °C</td>
<td>65</td>
</tr>
<tr>
<td>SFC AROMATICS, WT.%</td>
<td>22.1</td>
</tr>
<tr>
<td>MONO-AROMATICS</td>
<td>19.4</td>
</tr>
<tr>
<td>PNA’S</td>
<td>2.7</td>
</tr>
<tr>
<td>CARBON, HYDROGEN WT.%:</td>
<td>CARBON</td>
</tr>
<tr>
<td></td>
<td>86.98</td>
</tr>
<tr>
<td></td>
<td>HYDROGEN</td>
</tr>
<tr>
<td></td>
<td>NITROGEN</td>
</tr>
</tbody>
</table>

*IQT* - Ignition Quality Tester

* Measured by Galbraith Labs to be 18 ppm.
4.4 Diesel Particulate Matter Sampling Procedure

There were three main methods by which the particulates were sampled in this study: 47mm filters, TEOM, and SMPS. The procedures associated with each measurement method are described in the following sub-sections.

4.4.1 Filter Sampling Procedure

The filter sampling procedure involved acquiring filter samples from the bottom row of sampling ports in the residence time chamber (RTC). There were four 47 mm filters: a Teflon filter for PM2.5 mass concentration and sulfates, a second Teflon filter for duplicate PM2.5 and duplicate sulfates, a third Teflon filter for trace metals analysis, and a quartz fiber filter for elemental and organic carbon (EC/OC). Samples were collected on the filter for exactly one hour.

For the filters, this procedure was followed:
1. Place the 47 mm filters in the respective holders. (Use a definer ring for EC/OC.)
2. Initiate flow through the RTC with the 142 mm filter using a ‘dummy’ filter.
3. Allow the dilution tunnel system to achieve steady state temperatures.
4. Turn off main flow pumps for the 142 mm filter.
5. Place a ‘good’ 142 mm filter into the holder.
6. Turn on main flow pumps for the 142 mm filter.
7. Immediately, open the valve leading to the filters, turn on the associated vacuum pump, and start a stop watch simultaneously.
8. Allow filters to sample for one hour. During which, record required information in loghsheets (see Appendix E) and record data (see following sections of this chapter).
9. At exactly one hour, stop flow through all filters. Remove filters, place them in their respective labeled petri dishes, wrap with Teflon tape, and place in clean air box.
4.4.2 SMPS Measurement Procedure

Data were collected during the one-hour filter test with the scanning mobility particle sizer (SMPS) starting immediately after filter sampling begins. The SMPS was setup to collect data every 5 minutes, creating 10 to 12 data points for each test. For more information regarding this instrument, please refer to [20].

4.4.3 TEOM Measurement Procedure

Data were collected twice during the one-hour filter test with the tapered element oscillating microbalance (TEOM). A data point was collected once in the first half hour and once in the second half hour of each test. A data point consisted of allowing the TEOM to sample for approximately 20 minutes and taking an average. For more information regarding this instrument, please refer to [20].

4.5 Gaseous Emissions Measurement Procedure

Gaseous emission measurements were obtained with a Fourier Transform Infrared (FT-IR) gas analyzer. Samples were taken from the exhaust surge tank (engine out emissions), primary dilution tunnel, and secondary dilution tunnel.

Before taking any sample with the FT-IR, a background sample was taken with dry air. The background sample is used to remove any instrument artifacts associated with the measurement path in the FT-IR. While dilution air is flowing through the dilution tunnel and before introducing any exhaust into the dilution tunnel system, a sample of the
dilution air was taken with the FT-IR for ambient CO₂ levels used for dilution ratio calculations. During each of the one hour filter measurements, samples were taken with the FT-IR from the exhaust surge tank, primary dilution tunnel, and secondary dilution tunnel. The FT-IR was allowed to sample for ten minutes at each location, thereby allowing two measurements at each location during the one hour test.

Sulfur dioxide and sulfates were measured with filters during the one-hour filter test using three filters arranged in series. The sample flowed from the PDT to a furnace set at 900 °C and then through a Nafion® membrane sample dryer before flowing through the filters. The series of three filters consisted of a Teflon filter for mass and sulfate analysis followed by two quartz fiber filters with a potassium carbonate coating to capture the gas phase sulfur dioxide. Sulfur dioxide was also measured with the FT-IR by sampling from the PDT for 15 minutes immediately following the one-hour filter test.
This goes in the Appendix:

<table>
<thead>
<tr>
<th>CARBON NUMBER</th>
<th>DISTRIBUTION, wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C6</td>
<td>0</td>
</tr>
<tr>
<td>C7</td>
<td>0.12</td>
</tr>
<tr>
<td>C8</td>
<td>0.61</td>
</tr>
<tr>
<td>C9</td>
<td>2.71</td>
</tr>
<tr>
<td>C10</td>
<td>5.45</td>
</tr>
<tr>
<td>C11</td>
<td>8.3</td>
</tr>
<tr>
<td>C12</td>
<td>10.3</td>
</tr>
<tr>
<td>C13</td>
<td>11.6</td>
</tr>
<tr>
<td>C14</td>
<td>9.99</td>
</tr>
<tr>
<td>C15</td>
<td>9.41</td>
</tr>
<tr>
<td>C16</td>
<td>8.18</td>
</tr>
<tr>
<td>C17</td>
<td>8</td>
</tr>
<tr>
<td>C18</td>
<td>7.1</td>
</tr>
<tr>
<td>C19</td>
<td>5.64</td>
</tr>
<tr>
<td>C20</td>
<td>4.22</td>
</tr>
<tr>
<td>C21</td>
<td>2.89</td>
</tr>
<tr>
<td>C22</td>
<td>2.26</td>
</tr>
<tr>
<td>C23</td>
<td>1.64</td>
</tr>
<tr>
<td>C24</td>
<td>0.92</td>
</tr>
<tr>
<td>C25</td>
<td>0.41</td>
</tr>
<tr>
<td>C26</td>
<td>0.19</td>
</tr>
<tr>
<td>C27</td>
<td>0.04</td>
</tr>
<tr>
<td>C28</td>
<td>0.01</td>
</tr>
<tr>
<td>C29</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>99.99</td>
</tr>
</tbody>
</table>

Average carbon number: 17.8
average molecular weight: 251.1


50 Thermo Nicolet Corporation, Introduction to Fourier Transform Infrared Spectrometry, 2001

51 Richardson, Dan and others. Private Communication. 16 December 2002.
CHAPTER 5 – RESULTS

This chapter is divided into three main sections. The first section compares the combustion process between each engine setup to confirm that the observed particulate matter (PM) changes are the result of lubricating oil consumption (LOC) effects and not the result of combustion changes from test to test. The second section presents the results of the LOC rate measurements. The third section presents the effects of varying LOC rates and sources on diesel PM.

Unless otherwise noted, the graphed error bars represent 95% confidence intervals based upon the standard deviation of replicate measurements or the propagation of the measurement uncertainties.

5.1 Combustion Analysis

The effects of LOC on particulates are likely to be small in comparison to changes in the combustion process from differences in engine operating parameters, such as injection timing or intake air pressure. The engine operating condition parameters were held as constant as possible, although very slight variances from the set values are possible. For instance, the exhaust pressure may have changed by as much as 0.2 psi during the one-hour test. It is possible for a deviance such as this to alter the combustion process. Therefore, to make valid comparisons regarding the effects of various LOC rates on PM,
the combustion processes for each engine setup of a given mode must be shown to be the same.

This section is divided into two sub-sections, covering the effects of each engine setup on the combustion process. The heat release data for each run is presented first to show that the engine did not significantly vary from test to test in the experiment. The second section compares the measured gaseous emissions.

5.1.1 Heat Release and Performance Analysis

The engine alterations were found to have an insignificant effect on the performance and combustion processes of the engine, as shown in Figures 5.1 – 5.4. Figures 5.1 through 5.3 show the gross apparent heat release rates for modes 4, 5, and 1, respectively. These figures show that there are no significant differences in heat release rates from test to test for each mode. Figure 5.4 compares the brake horsepower (BHP) for each mode. The “50%OCR” tests for modes 4 and 5 show a slight increase in BHP. This is most likely due to a decrease in friction from the lower unit pressure OCR.

The specific fuel consumption (SFC) is plotted in Figure 5.5 for each test condition and mode. There are no significant differences in SFC from run to run. The error bars in Figures 5.4 and 5.5 represent two times the standard deviation for the tested conditions within each respective engine operating mode.
Figure 5.1 Mode 4 gross apparent heat release for tested engine configurations.

Figure 5.2 Mode 5 gross apparent heat release for tested engine configurations.
Figure 5.3 Mode 1 gross apparent heat release for tested engine configurations.

Figure 5.4 Brake horsepower for tested engine configurations.
5.1.2 Gaseous Emissions

The gaseous emissions are not the focus of this research, but are good indicators of changes in combustion. Therefore, the oxides of nitrogen (NOx), carbon monoxide (CO), and total hydrocarbons (THC) are shown in this section to ascertain if there were any combustion changes from test to test. This comparison provides additional verification to the heat release comparisons given in section 5.1.1.
5.1.2.1 Oxides of Nitrogen (NOx)

Figure 5.6 shows that there were no significant differences found for mode 4 in regard to specific NOx emissions. There seems to be some significant differences for modes 5 and 1. These differences are mainly found in the first two tests. These two tests are not part of the primary group of tests used for this study.

![Diagram showing specific NOx emission for tested engine configurations.]

**Figure 5.6** Specific NOx emission for tested engine configurations.

The mode 5 base case is also significantly different from the other tests. Further investigation of this revealed that the gaseous emission measurements at this data point may be erroneous. The CO2 level was found to be approximately 7% higher than the
other mode 5 tests. A large change such as this indicates a difference in combustion due to an increase in fuel flow rate. However, the fuel flow, heat release, engine torque, and engine temperatures do not support this. Therefore, the gaseous emissions for the mode 5 base case are not considered in further comparisons.

5.1.2.2 Carbon Monoxide (CO)

Figure 5.7 shows the specific carbon monoxide emissions. There are no indications of erroneous or different tests, although the CO results for mode 1 do show a slight increasing trend, however the absolute values of these emissions are quite small.

![Figure 5.7 Specific CO emission for tested engine configurations.](image-url)


5.1.2.3 Total Hydrocarbons (THC)

![Graph showing specific THC emissions for tested engine configurations.](image)

**Figure 5.8** Specific THC emission for tested engine configurations. Note: Measured with FT-IR.

Figures 5.8 and 5.9 show the hydrocarbon emissions as measured by the FT-IR and GOW-MAC total hydrocarbon analyzer, respectively. Due to the large error bars associated with the FT-IR THC measurements, there are no statistically significant differences shown in Figure 5.8. Total hydrocarbon FID data was only available for the runs shown in Figure 5.9. The error bars shown for those data sets that have more than one measurement per run, thus allowing a standard deviation to be calculated. The only noticeable trend is that both graphs indicate an increase in hydrocarbon emission for the
first “50%OCR” mode 5 case. However, this increase is small and would likely be shown as within the experimental error if error bars were put on each data point in Figure 5.9.

![Figure 5.9 Specific THC emission for tested engine configurations. Note: Measured with FID.](image)

5.2 LOC Rate Measurement

To understand the effects of LOC on PM, the rates of LOC must be measured. As described in Chapter 2 of this report, there are numerous methods for quantifying the LOC rate. Each method has advantages and disadvantages depending on the specifics of the experiment. For the current study, involving steady state tests, calculating the LOC rate from filter-based measurements is suitable.
Two LOC rate measurement methods were attempted for the current study. The first involved a mass balance of selected metals. The second method involved a mass balance of sulfur. These methods are presented in the following two sub-sections.

5.2.1 LOC Rate Measurement by Metals Mass Balance

The most abundant metal in the lubricating oil is calcium; followed by zinc, manganese, and magnesium. The metal concentrations in the fuel used in this experiment are below the 0.1 ppm detection limit of the measurement technique. Therefore, these metals are valid to be used in LOC rate measurement techniques, assuming that the metals in the oil obey the same consumption mechanisms as the oil and that there are no additional sources of these metals. The LOC rates can be determined by measuring the exhaust metal concentrations and carrying out calculations using the known metal concentration in the oil for the metal of interest. Assuming that all of the consumed metal from the oil is converted to particulate matter (PM), the exhaust metal concentration can be obtained by filter measurements. At the time of writing, the used oil was still in the process of being analyzed for metal concentrations. Therefore, the LOC rates in this report are calculated with Equation 5.1 using the fresh oil metal concentrations. Although the relative trends of LOC are valid, the absolute calculated values of LOC may not be entirely accurate due to the use of metal concentrations for fresh oil.

\[
\text{LOCrate} = \frac{Metal_{\text{mass on filter}} \cdot \text{DilutionRatio} \cdot FuelFlow_{\text{mass rate}} \cdot (1 + \frac{Air_{\text{mass rate}}}{Fuel_{\text{mass rate}}})}{FilterFlowRate \cdot MetalConc_{\text{by Mass in Oil}} \cdot ExhaustDensity}
\] (5.1)
The values obtained from the metals analysis of the particulates were compared to assess the tracking of the metals for the calculation of LOC rates. From these comparisons, calcium, zinc, and copper were found to be strongly correlated, suggesting that different consumption mechanisms for each metal were not affecting the results. As a result, the lubricating oil concentrations in the residence time chamber (RTC) were calculated using calcium, zinc, and copper. The concentration of copper in the oil was not known for fresh or used oil, so the value of the copper concentration in the oil was altered until a trendline with a slope of one was found for LOC rates calculated by copper plotted against LOC rates calculated by calcium. Graphs of zinc and copper plotted against calcium in regard to calculated oil concentration in the RTC are shown in Figures 5.10 and 5.11.

Figure 5.10 shows that zinc has a strong correlation to calcium, with most of the uncertainty intervals crossing the 1:1 slope line. Figure 5.11 shows the correlation between copper and calcium. At medium and higher levels of oil consumption, the correlation becomes worse. At low levels of oil consumption, the correlation between copper and calcium is better than the correlation between zinc and calcium in this region. These changes suggest that additional sources of zinc and copper may be a factor. Besides from the lubricating oil, there are no known sources of calcium in the engine. However, it is possible that engine components contain copper and zinc, such as the valve guides. Thus, any wear of these components may contribute to the copper and zinc concentrations in the exhaust, thereby altering the calculated LOC rates. Therefore,
calcium will be used to calculate the LOC rates throughout this study. Previous studies on this engine have shown that calcium can be used to measure LOC rates [30].

The dynamic blank metal values were all found to be insignificantly different from zero. Therefore, the metal values of the dynamic blanks are not included in further calculations. For comparison, Figure 5.12 shows the effect of subtracting the dynamic blank values. The inclusion of the dynamic blank has little effect on the absolute values, although slight increases in the uncertainty intervals occur. For the current study, the absolute values of LOC rates are not as large of a concern as is the comparison between LOC rates. The derivation of the formula for calculating LOC rates (Equation 4.1) is included in Appendix F.

![Figure 5.10](image-url)  

**Figure 5.10** LOC rates calculated by zinc versus calcium for all modes.
Figure 5.11 LOC rates calculated by copper versus calcium for all modes. Note: Copper percent in oil altered.

Figure 5.12 LOC rates calculated by zinc versus calcium for all modes. Note: Including the average value of dynamic blanks in the calculation.
Figures 5.13 through 5.15 show the LOC rates calculated from calcium concentrations in the particulate matter without including the dynamic blank values in the calculations. The error bars depict the 95% confidence intervals which take into account any measurement uncertainties.

![Figure 5.13](image-url)  
**Figure 5.13** Mode 4 LOC rates measured by calcium.
Figure 5.14 Mode 5 LOC rates measured by calcium.

Figure 5.15 Mode 1 LOC rates measured by calcium.
For mode 4 (1200RPM, 25% load), the LOC rates are not significantly different from zero. Mode 5 (1200RPM, 100% load) and mode 1 (1800RPM, 100% load), show significant differences in oil consumption for the individual engine setups. For mode 5 and 1, the removal of the intake valve stem seals (VSS) and the installation of a lower (50%) unit pressure oil control ring (OCR) show a moderate increase in oil consumption over the “Base” case. For mode 1, the lower unit pressure OCR caused a larger increase in LOC than the removal of the intake VSS. Also, the lower unit pressure OCR resulted in larger increases of LOC rates for mode 1 in comparison to mode 5. These results are consistent with the findings of Kawatani et al. [31]. In regard to lowering the unit pressure of the oil control ring, the increase of oil consumption rate is larger for higher engine speeds. The lower oil consumption rate of the second “50%OCR” test is possibly due to further break-in of the oil control ring as a result of the running time accumulated during the first “50%OCR” test.

An interesting result is the decrease of LOC rate by the removal of the exhaust VSS. A study by Marlin et al. [53] has shown that the removal of the exhaust VSS can allow exhaust gases to flow through the valve guide and into the rocker housing due to the higher pressures in the port (back-pressure from turbocharger) than in the rocker housing. A flow such as this impedes the migration of oil down the valve stem and through the valve guide. This explanation is supported by noticeable valve guide wear that occurred during testing without the exhaust VSS.
The four consecutive “Base-Alt DR” (stock engine configuration with a higher dilution ratio) tests in Figure 5.14 show that the measured oil consumption rate changed slightly during those four days of testing. The measured LOC rates show only a very slight change from the last “Base-Alt DR” case to the “Base” case which was done much later in the test sequence.

It should be noted that the calculated LOC rates (0.5 to 1.5 g/hr) are small in comparison to those found in literature for multi-cylinder engines which range from 0.68 to 200 g/hr [33,44,52] depending on engine design, load, and primarily on speed. There are numerous possible reasons for this: the metal in the oil is not being consumed in the same manner as the oil; the metal is being lost due to deposition throughout the exhaust and sampling system; the metal is not being collected on the particulate filters; or the concentration of the metal in the oil used to calculate LOC rates is incorrect. The last reason is the most likely reason due to the use of the metal concentration in the fresh oil rather than the used oil.

5.2.2 LOC Rate Measurement by Sulfur Mass Balance

Similar to the LOC rate measurement using a mass balance of metals, this method involved a mass balance of a component within the exhaust. However, there are many additional sources of sulfur than just the lubricating oil. Sulfur is also present in the fuel and the air. The concentration in the tested fuel is known as being 14 ppm. To obtain the quantity of SO₂ in the ambient air, FT-IR and filter measurements were taken for each
test from the PDT without the addition of engine exhaust. Sulfur in the exhaust was
determined by also sampling with both methods from the PDT. The samples for both
methods were first passed through a furnace and dryer before being sampled by the FT-
IR or the filters.

The FT-IR sulfur dioxide measurements of the dilution air were higher than the
measurements of engine exhaust, 0.8 to 1.0 ppm in comparison to 0.0 to 0.8 ppm, even
when the exhaust water concentration was lowered to less than 1E-4 ppm by the sample
dryer, as for mode 4. The dilution air and intake air originate from the same source and
therefore the level of SO₂ in each are believed to be approximately equal. Also, the 14
ppm sulfur content in the fuel will add to the exhaust SO₂ concentration. Therefore,
measuring SO₂ with the FT-IR proved not to be accurate.

Only a small portion of the SO₂ filter data was available at the time of writing. Most of
the values were below the detection limit of the measurement technique. This indicated
the 1.7 LPM flow rate through the filter was too low. Therefore, the flow rate was
increased to 7.3 LPM for the following runs. All the data for the increased flow rates
were not available at the time of writing and thus no further analysis on these data is
included in this report.

In addition, the source of the engine intake air and dilution air is from the University of
Wisconsin-Madison Charter Street Physical Plant, which is also a coal-fired power plant
that does not have sulfur control for the exhaust. Therefore, this could be a source of
great variability for the intake and dilution air SO$_2$.

5.3 Effects of LOC on Diesel Particulate Matter (PM)

The effects of LOC on PM are presented in this section in regard to organic carbon (OC)
emissions, elemental carbon (EC) emissions, sulfate (SO$_4$) emissions, particulate mass
concentrations, and particle number distributions.

5.3.1 Organic Carbon, Elemental Carbon, and Sulfates

Figures 5.16 and 5.17 show the organic and elemental carbon for all cases and modes
tested. Figures 5.18 through 5.26 show the contributions of OC, EC, and sulfates for each
case tested within each of the three engine operating modes.

Organic carbon, elemental carbon, and sulfate data for mode 4 are plotted in Figures 5.18
– 5.20. All of the sulfate values for mode 4 tests were found to be below the detection
limit of the measurement technique. Taking the dilution ratio and brake horsepower of
the engine into account, the sulfate detection limit is approximately 0.0004 [g/bhp-hr].
Figure 5.16 Specific OC emission rate for all modes.

Figure 5.17 Specific EC emission rate for all modes.
Figure 5.18 Specific OC, EC, and sulfate emission rates for mode 4.

Figure 5.19 Specific EC emission rate for mode 4.
There were no significant differences in EC emission for any of the cases in Figure 5.18. However, the OC emission rates were found to significantly vary. The higher dilution rate baseline cases show higher levels of OC emission. These differences are not thought to be due to changes of the engine, rather it is believed that there is an interaction between dilution ratio and the organic carbon. This requires further investigation to completely explain.

As shown in Figure 5.18, the no intake VSS case and the second 50%OCR case are significantly different than the first no VSS case and the no exhaust VSS case in regard to OC. The oil consumption rates for mode 4 were shown in Figure 5.13 as being
indistinguishable from zero. Therefore, the OC trends cannot be directly compared to measured LOC rates.

**Figure 5.21** Specific OC, EC, and sulfate emission rates for mode 5.

**Figure 5.22** Specific EC emission rate for mode 5.
As shown in Figures 5.21 and 5.22, the tests regarding mode 5 show no significant differences in EC or sulfates, excluding the higher dilution ratio tests. However, there are significant differences in OC emission. The no intake VSS case and the no exhaust VSS case each show significant increases over the base case in regard to specific OC emission. The no intake VSS case corresponds to a higher LOC rate case and the no exhaust VSS case corresponds to a lower LOC rate case. Thus, there is a contradictory trend for these two data points in regard to the base case. The higher dilution ratio tests resulted in lower emissions of OC. This is supported by Hildemann’s [54] explanation regarding the interaction between semi-volatile material and the dilution ratio. Hildemann found that the mass rates of OC emission is independent of the dilution process, but can be affected by the total dilution ratio. This is due to changes in the gas/particle partitioning of semi-

**Figure 5.23** Specific OC emission rate for mode 5.
volatile compounds. For example, decreasing the dilution ratio will cause more semi-volatile material to be in the particle phase. This explanation of how dilution ratio affects the semi-volatile portion does not explain the mode 4 data where the opposite trend was observed.

**Figure 5.24** Specific OC, EC, and sulfate emission rates for mode 1.
Figure 5.25 Specific EC emission rate for mode 1.

Figure 5.26 Specific OC emission rate for mode 1.
As shown in Figures 5.24 – 5.26; the EC, OC, and sulfate measurements for mode 1 have identical trends to mode 5, except for the case of no exhaust VSS which shows a slightly smaller specific OC emission relative to the base case. Although these differences are present, the trends are not as easily noticed for mode 1 as they are for mode 5. This may be due to the slightly higher exhaust temperatures for mode 1, which would contribute to higher combustion efficiencies of the consumed oil [31,34,36].

### 5.3.2 Particulate Mass

Figure 5.27 shows an example of particulate mass concentration and total mass data obtained with the TEOM. The darker portion of the curves (between the vertical dashed lines) represents the time range where the data is averaged to obtain a final value, shown as the horizontal dashed line.

![Mass Concentration (MC) and Total Mass (TM)](image)

**Figure 5.27** Sample of TEOM data and averaging.
Figure 5.28 compares the TEOM mass concentration measurements to filter-based PM2.5 mass concentration measurements. The data for each of these methods refers to the mass concentration in the residence time chamber (RTC). Both measurement methods sample at the same time from the RTC, thus, a comparison such as the one given here is valid. For low concentration levels, such as those at mode 4, the TEOM and filter measurements agree very closely. As the concentration increases, the TEOM measures a higher mass concentration and uncertainty intervals. At the higher concentrations, the TEOM measurements are approximately 50% larger than the filter measurements. A partial explanation for this is that the TEOM measures the total mass concentration,
whereas the filter sample is flowed through a cyclone at a specific flow rate to obtain a 2.5 micron cut-point, thereby removing particles larger than 2.5 microns. This is only a partial explanation for the difference between the TEOM and filter measurements. If perhaps this could entirely explain the difference, it would mean that one-third of the particles from this engine at these operating modes are larger than 2.5 microns. From previous studies on this engine, it is believed that this is not true. Therefore, further studies comparing the TEOM to filter measurements are needed.

![Reconstructed Mass = EC+1.2*OC+sulfates](image)

**Figure 5.29** Reconstructed versus filter PM2.5 mass concentration for all modes.

Figure 5.29 compares reconstructed mass concentration to the PM2.5 mass concentration obtained from filters. Similar to the data presented in Figure 5.28, Figure 5.29 also compares concentrations in the RTC. As seen in Figure 5.29, the reconstructed and
gravimetrically determined mass concentration measurements agree very well. The reconstructed mass is calculated from filter based measurements and is the sum of EC, 1.2 times OC, and sulfates [55]. The EC and OC measurements are obtained from filters with a flow rate of one-fourth of the flow rate for the mass filters. Thus, the strong correlation between these two measures verifies that there are no errors in regard to the flow rates of the filters.

The confidence intervals for the reconstructed mass (vertical axis) are based upon the measurement uncertainty of EC, OC and sulfates; whereas the filter mass is based upon the standard deviation of two mass measurements obtained for each data set. To obtain the 95% confidence intervals, the standard deviation is multiplied by a t-interval multiplier. Having only one degree of freedom ($\nu = N - 1 = 2 - 1$) results in large t-intervals. Therefore, the confidence intervals for the filter mass measurements can be relatively large, depending on the difference in the two measurements. The TEOM mass concentration measurements also only have two measurements per test, which can also result in large confidence intervals as shown in Figure 5.28.

The comparison of TEOM and reconstructed mass to the gravimetrically determined mass filter measurements show that the gravimetrically determined mass filter measurements are valid. Therefore, all comparisons of PM mass concentration to other data will be based upon the filter mass measurements.
Figure 5.30 Specific PM2.5 mass concentration versus LOC rate for all modes.

Figure 5.30 shows the calculated mass concentration for each engine setup and operating condition tested. The data points with specific PM2.5 emission between 0.00 and 0.15 g/bhp-hr correspond to the mode 4 tests. The data points with specific PM2.5 emission between 0.20 and 0.30 g/bhp-hr correspond to mode 1 tests. The data points with specific PM2.5 emission between 0.30 and 0.50 g/bhp-hr correspond to mode 5 tests. Observation of this graph shows that there are no major trends regarding specific PM2.5 emission rates to LOC rates. It should be noted that the data points showing high specific PM2.5 emission rates for mode 4 correspond to the higher dilution ratio cases. Figures 5.31 through 5.36 present these data in greater detail.
Figure 5.31 Specific PM2.5 mass concentration versus LOC rate for mode 4.

Figure 5.32 Specific PM2.5 mass concentration vs. engine configuration for mode 4.
Figure 5.33 Specific PM2.5 mass concentration versus LOC rate for mode 5.

Figure 5.34 Specific PM2.5 mass concentration vs. engine configuration for mode 5.
Figure 5.35 Specific PM2.5 mass concentration versus LOC rate for mode 1.

Figure 5.36 Specific PM2.5 mass concentration vs. engine configuration for mode 1.
Figures 5.32, 5.34, and 5.36 show that the increased dilution ratio cases produce higher specific PM2.5 emission rates. It is believed that there was not truly such a significant change in PM2.5 emission rates from the engine. Rather, it is believed that the dilution ratio affected the particulate matter; in particular, the OC content, as previously described. With exception of the higher dilution ratio cases, there is no apparent correlation between measured mass emission and dilution ratio for the tested cases.

### 5.3.3 Particle Number Distributions

Figures 5.37 through 5.39 show the particle number distributions obtained for each engine setup and mode tested. Figure 5.40 shows the particle number distributions for the dilution air for each day of testing on the same y-axis scale as the others. For the measured size range of particles, the contribution from the dilution air is negligible compared to the engine-out particle emissions for the three engine operating modes tested.
<table>
<thead>
<tr>
<th>No Intake VSS</th>
<th>No Exh or Int VSS</th>
<th>No Exhaust VSS</th>
<th>Base</th>
<th>50% Oil Control Ring</th>
<th>50% Oil Control Ring</th>
<th>50% Oil Control Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 50 100 150 200 250 300</td>
<td>0.0</td>
<td>1.0x10</td>
<td>1.5x10</td>
<td>2.0x10</td>
<td>2.5x10</td>
<td>3.0x10</td>
</tr>
</tbody>
</table>

**Figure 5.37** Particle number distributions for mode 4.

<table>
<thead>
<tr>
<th>Base w/ Altered DR</th>
<th>Base w/ Altered DR</th>
<th>Base w/ Altered DR</th>
<th>Base w/ Altered DR</th>
<th>No Intake VSS w/ Altered DR</th>
<th>No Intake VSS</th>
<th>No Exh or Int VSS</th>
<th>No Exh or Int VSS</th>
<th>No Exhaust VSS</th>
<th>Base</th>
<th>50% Oil Control Ring</th>
<th>50% Oil Control Ring</th>
<th>50% Oil Control Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 50 100 150 200 250 300</td>
<td>0.0</td>
<td>1.0x10</td>
<td>1.5x10</td>
<td>2.0x10</td>
<td>2.5x10</td>
<td>3.0x10</td>
<td>3.5x10</td>
<td>4.0x10</td>
<td>4.5x10</td>
<td>5.0x10</td>
<td>5.5x10</td>
<td>6.0x10</td>
</tr>
</tbody>
</table>

**Figure 5.38** Particle number distributions for mode 5.
Figure 5.39 Particle number distributions for mode 1.

Figure 5.40 Particle number distributions for dynamic blanks.
Dilution parameters can have a large effect on the particulates, especially the particle size distributions. As shown in Figures 5.37 - 5.39, altering the dilution ratio to a higher value caused considerable effects in the particle number distributions. For each mode, increasing the dilution ratio increased the measured particle numbers. For modes 5 and 1, the dilution ratio effect was minimal, but the dilution ratio effect was large for mode 4. Figure 5.37 shows that the peak number concentration more than doubled for the increased dilution ratio cases. As presented in section 5.2.2.1 of this report, mode 4 has a large percentage of organic carbon. The large OC content and the fact that mode 4 has much fewer particles (in comparison to modes 5 and 1) could be factors explaining why dilution ratio had such a significant impact on the particle number concentration. To fully understand this interaction, further studies on this topic are needed.

Figures 5.37 through 5.39 each include an inset graph showing the particle number distribution for the nuclei mode range. For certain higher dilution ratio cases, modes 5 and 1 show a sudden increase in particle number concentration for the smallest particle sizes measured. For mode 1, there is also a sudden increase for a case with no exhaust and no intake VSS. Figure 5.37 shows that this feature was only seen in mode 4 cases with no exhaust VSS, including the case with no exhaust and no intake VSS. These trends are minimal and great care should be taken when making conclusions from them. It is possible that these trends are only artifacts of the dilution ratio or the instrument. Therefore, further study of the nuclei mode particle number concentrations in regard to dilution and LOC effects is needed.
In addition, the particle number concentration data for mode 4 showed interesting trends as data were recorded over a one-hour test, indicating dilution parameter effects. Figures 5.41 and 5.42 show every data set recorded during two of the one-hour mode 4 tests. Figure 5.41 is an example of how certain data sets changed during the one-hour test. This change of trend during the one-hour test only occurred during a few of the data sets for mode 4, specifically the three no intake VSS cases, base case, and the second 50%OCR case. The reason for this phenomenon is not known, but it is possible that these trends were only instrument errors or unsteady dilution conditions. The rest of the mode 4 data sets and all of the mode 5 and 1 data sets were similar to the data presented in Figure 5.42 in regard to steadiness of the data during the one-hour test.

![Graph](image)

**Figure 5.41** Unsteady sample particle number distributions for a mode 4 test.
A statistical analysis on the cases for each mode showed that there are only statistically significant differences found at a 95% confidence level for the higher dilution ratio and the 50% unit pressure oil control ring cases. The analysis was conducted using an analysis of variance (ANOVA) method and a t-interval multiplier for obtaining the confidence intervals. The ANOVA method was chosen due to its ability to include treatments with only one replication [BOX]. This analysis was applied at data points corresponding to particle diameters of 50, 100, 150, 200, and 250 nanometers. The results of the analysis are given in Figures 5.43 – 5.45. It should be noted that for the analysis of modes 4 and 5, the no intake VSS cases includes data acquired at the higher dilution ratio. This explains why the “No intake VSS” data is shifted upward in the mode 5 graph at the 50, 100, and 150 nm diameters.

**Figure 5.42** Steady sample particle number distributions for a mode 4 test.
Excluding the higher dilution ratio cases, there are no statistically significant differences in particle number for any of the cases in mode 4, as shown in Figure 5.43. In addition to the higher dilution ratio cases, Figures 5.44 and 5.45 show that the 50% unit pressure oil control ring (50%OCR) case has some significant differences from the “Base” case for modes 5 and 1. These differences occur at the 200 and 250 nm diameters for mode 5 and at the 150 and 200 nm diameters for mode 1. At each of these sizes, the 50%OCR case caused a decrease in particle number. As shown in Section 5.2.2, the LOC rate increase from the baseline case due to the 50%OCR was larger for mode 1 than mode 5.

**Figure 5.43** Statistical analysis results for particle number distribution for mode 4.
Figure 5.44 Statistical analysis results for particle number distribution for mode 5.

Figure 5.45 Statistical analysis results for particle number distribution for mode 1.


Richardson, Dan and others. Private Communication. 16 December 2002.


CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

The objectives of the current study were to quantify lubricating oil consumption (LOC) rates and determine any effects of changes in LOC rates on the particulate matter. This testing was carried out on a Cummins N14 single-cylinder heavy-duty D.I. diesel research engine with a full dilution tunnel system. Varying oil consumption rates and their effect on particulates were analyzed at selected operation conditions of the CARB 8-mode test cycle.

This chapter is divided into three main sections. The first section presents conclusions regarding the results of the LOC rate measurements. The second section presents conclusions in regard to the effects of varying LOC rates and sources on diesel particulate matter (PM). The last section offers recommendations for future work.

6.1 Lubricating Oil Consumption (LOC) Rate Measurements

Several engine alterations, consistent with the literature, for changing LOC rates were applied. The alterations consisted of installing an oil control ring with a unit pressure 50% less than the standard value, removing the intake valve stem seals (VSS), removing the exhaust VSS, and removing all (intake and exhaust) VSS. Each of these alterations was tested individually to avoid causing interacting effects.
LOC rate measurements were attempted using the sulfur trace method. The sulfur was measured in the form of sulfur dioxide (SO₂) with a FT-IR and with potassium carbonate coated quartz filters. The FT-IR measurement for SO₂ concentrations was unsuccessful. This is believed to be due to poor SO₂ calibration for such low levels and from interference of other exhaust components. A flow rate of 1.7 LPM was found to be too low to capture sufficient SO₂ on the filters for analysis. The flow rate was increased for the latter runs of the experiment, but the data using this increased flow rate were not available at the time of writing.

LOC rates were successfully quantified by measuring the calcium concentration in the exhaust particulates. Other metals, such as zinc and copper, were compared to calcium in regard to calculating LOC rates, but it was concluded that these metals were influenced somewhat by engine wear, and thus, were less not accurate measurements of LOC rates.

At mode 4 (1200RPM, 25% load), the measured LOC rates were not significantly different from zero. Therefore, no significant differences from the baseline case for this mode can be concluded.

Significant changes in LOC rate were observed at modes 5 (1200RPM, 100% load) and 1 (1800RPM, 100% load). The removal of the intake valve stem seals (VSS) and the installation of a lower unit pressure oil control ring (OCR) resulted in a moderate increase in oil consumption over the “Base” case. For mode 1, the lower unit pressure OCR
caused a larger increase in LOC than the removal of the intake VSS. Also, the lower unit pressure OCR resulted in a larger LOC rate increase for mode 1 in comparison to mode 5.

The removal of the exhaust VSS caused a significant decrease in LOC rate for modes 5 and 1. A possible reason for this is that the removal of the exhaust VSS allows exhaust gases to flow through the valve guide and into the rocker housing due to the higher pressures in the port (back-pressure from turbocharger) than in the rocker housing. The flow may impede the migration of oil down the valve stem and through the valve guide.

### 6.2 Lubricating Oil Consumption (LOC) Rate Effects on Particulate Matter (PM)

Particle size distribution, PM2.5 mass, organic carbon (OC), elemental carbon, metals and sulfate emissions measurements were made. For changes in LOC rates, there were no significant effects found for elemental carbon, PM2.5 mass, or sulfate emissions for any of the tested engine operating conditions. However, there were differences for organic carbon emission and to a slight effect for the particle size distribution.

Due to the inability to obtain valid LOC rate measurements for mode 4, no comparisons of PM characteristics to LOC rates can be made. In addition, there were no significant differences in PM characteristics found for the engine alterations tested in mode 4.

The only significant differences found for mode 5 were in regard to OC emission. The no intake VSS case and the no exhaust VSS case each resulted in a significant increase in
OC emission. The no intake VSS case corresponds to a higher LOC rate case and the no exhaust VSS case corresponds to a lower LOC rate case. Thus, there was a contradictory trend found for these two data points in regard to the base case.

There were no significant differences found for mode 1 in regard to PM characteristics. However, differences in LOC rates were found for each engine setup.

Small differences in particle size distribution were found for modes 5 and 1 for the lower unit pressure oil control ring case. These differences were found in the 200 to 250 nm particle size range for mode 5 and 150 to 200 nm size range for mode 1. The margin of deviation from the baseline case is extremely small and therefore is possibly due to other changes, such as dilution ratio and temperature, rather than real effects of changing the LOC rates.

6.3 Recommendations for Future Work

There are many tests that would lead to a better understanding of the LOC effects on the detailed characteristics of PM. The tests carried out in this study were just a starting point. Examples of additional testing that could be studied are as follows:

- For this study, specific alterations to the engine were done to change the LOC rates and measure the effects on PM characteristics. Other forms of altering oil consumption rates need to be investigated, such as mixing oil into the fuel and
slowly pumping oil into the combustion chamber, intake system, or exhaust system which would simulate oil leaked by each source of LOC.

- Use an oil with higher concentrations of sulfur and/or calcium, possibly along with a zero sulfur content fuel, and repeat the filter measurements.

- Carry out studies on medium- and light-duty diesel engines. Oil consumption is highly dependent on engine speed, and therefore studying a medium- or light-duty diesel that has a much wider engine speed operating range than heavy-duty diesels will provide a larger range of LOC rates for a given engine configuration.

- It is of interest to study the differences in LOC effects on PM between mineral-based and synthetic lubricating oil.
BIBLIOGRAPHY


APPENDIX A – ISO-KINETIC FLOW CALCULATION DERIVATION

Calculation for flow velocity in primary dilution tunnel (PDT) at secondary dilution tunnel (SDT) sampling port:

Define Dilution Ratio as:

\[ DR = \frac{V_{DE}}{V_{EE}} \]  \hspace{1cm} (1)

\[ V_{DE} = V_{EE}DR \]  \hspace{1cm} (2)

where \( V \) is the velocity of the flow, \( V \) is the volumetric flow rate, and \( A \) is the area.

\[ V = \frac{\nu}{A} \] \hspace{1cm} (7)

Combining Equations 5, 6, and 7:

\[ V_{DE} = \frac{(\dot{m}_{DF} + \dot{m}_{IA})RT_{DE}}{MW_{EE}P_{DE}A_{PD}} \cdot DR_{PDT} \] \hspace{1cm} (8)

where \( P_{DE} \) is equal to \( P_{EE} \) in the primary dilution tunnel.

\[ \dot{m}_{EE} = \dot{m}_{DF} + \dot{m}_{IA} \] \hspace{1cm} (6)

where \( \dot{m}_{DF} \) and \( \dot{m}_{IA} \) are the mass flow rates of the fuel and intake air, respectively.

\[ A_{PD} = \frac{\pi}{4}D_{PD}^2 \] \hspace{1cm} (9)
Calculation for sample flow velocity into secondary dilution tunnel (SDT) from primary dilution tunnel (PDT):

\[ V_{\text{DE}} = \frac{4(m_{\text{DE}} + m_{\text{IA}})RT_{\text{DE}}}{MW_{\text{EE}}P_{\text{DE}}\pi D^2_{\text{PDT}}} DR_{\text{PDT}} \]  

\[ MW_{\text{IA}} \approx MW_{\text{EE}} \approx 28.85 \text{ [g/mole]} \]

Combining Equations 11, 12, 13, and 14 and assuming \( P_{\text{sample--in}} = P_{\text{total--out--SDT}} \):

\[ V_{\text{sample--in--SDT}} = \frac{V_{\text{sample--in--SDT}}}{A_{\text{SDT--sample--tube}}} \]  

\[ \frac{P_{\text{sample--in}} V_{\text{sample--in--SDT}}}{RT_{\text{sample--in--SDT}}} = \frac{P_{\text{total--out--SDT}} V_{\text{total--out--SDT}}}{RT_{\text{total--out--SDT}}} DR_{\text{SDT}} \]  

\[ V_{\text{total--out--SDT}} = V_{\text{sample--in--SDT}} + V_{\text{SDT--dilution--air}} \]  

\[ V_{\text{SDT--dilution--air}} = V_{\text{total--out--SDT}} - V_{\text{sample--in--SDT}} \]  

\[ DR_{\text{SDT}} = \frac{DR_{\text{SDT--tot}}}{DR_{\text{PDT}}} \]  

\[ V_{\text{total--out--SDT}} = V_{142} + V_{\text{filter--train}} + V_{\text{SMPS,TEOM}} \]  

Assuming \( MW_{\text{DE,SDT}} \approx MW_{\text{DE,PDT}} \):

\[ V_{\text{sample--in--SDT}} = \frac{(V_{142} + V_{\text{filter--train}} + V_{\text{SMPS,TEOM}})DR_{\text{PDT}} T_{\text{sample--in--SDT}} MW_{\text{DE,SDT}}}{A_{\text{SDT--sample--tube}} DR_{\text{SDT--total}} T_{\text{total--out--SDT}} MW_{\text{DE,PDT}}} ; \]  

\[ A_{\text{SDT--sample--tube}} = \frac{\pi}{4} D^2_{\text{SDT--sample--tube}} \]  

To obtain iso-kinetic flow, \( V_{\text{DE}} \) and \( V_{\text{sample--in--SDT}} \) must be equal.
APPENDIX B – PREPARATION OF SO₂ MEASUREMENT FILTERS

SOP 3200 K₂CO₃ Impregnation of Filters for SO₂ Collection

This method was provided to the State Lab of Hygiene by Dr. Jamie Schauer and is an adaptation of a method authored by Lynn Salmon 10/6/94.

Safety- Wear a labcoat, eye protection and follow all other SLH safety protocols.

Materials
1. K₂CO₃ anhydrous
2. Teflon Sheets to line cookie sheets
3. Buchner Funnel
4. Parafilm
5. Sidearm flask
6. Vacuum source-lab vacuum in hoods
7. Lab grade distilled water
8. 500 ml volumetric flask
9. 1 liter beaker
10. Whatman 41 cellulose filters or sometimes 37mm quartz filters – See notes under “Methods”
11. Drying oven
12. Forceps
13. Petri Dishes
14. Cookie Sheets
15. Buchner Funnel
16. Parafilm
17. Wide mouth bottle for holding filters and the potassium carbonate solution on a shaker.

Purpose
Filters are coated with potassium carbonate for SO₂ collection from air samples.

Method

No prepreparation (baking) of the Whatman 41 filters is necessary. Quartz filters should be prebaked. Some projects use 37mm quartz filters. Check with the project leader to be sure you are supplying them with the correct filters.

Prepare the 20% potassium carbonate solution by measuring 500 mls of laboratory grade water in a volumetric flask and then pour the 500 mls of water into a 1 liter beaker.
Weigh 125 grams of potassium carbonate in a beaker or weighing boat on an analytic balance. Add the 125g potassium carbonate to the 500 mls of water in the 1 liter beaker. Mix well. Transfer the solution to a plastic bottle and store in the refrigerator if it is not used immediately.

Filter Impregnation

- Place a quantity of filter (50-100) in the wide mouth bottle. Add enough potassium carbonate solution to cover all filters.
- Screw the cover on the jar.
- Place the jar containing the filters on the shaker table and shake for 30 minutes.

Drying Filters

- Decant the potassium carbonate solution with the filters into a Beechner or Hirsch funnel. Attach a hose to the side arm flask and place the funnel into the flask opening. Cover the flask with parafilm and turn on the vacuum to remove water from the filters. Stop the vacuum when moisture is no longer dripping from the funnel.
- With a forceps carefully separate the filters and place them on the Teflon lined cookie sheet and then into the 40-50° C drying oven for approximately 30 minutes or until they feel dry to the touch. Do not over dry, but be sure filters are not damp.
- Using a forceps transfer the individual filters into plastic petri dishes. Place the lids on the dishes and label them with the date and K2CO3.
- There is no need to line the petri dishes with foil or seal them with Teflon tape.
- Store the treated filters in the freezer until they are to be used.
APPENDIX C – LOC RATE FORMULA DERIVATION USING SO$_2$ CONCENTRATIONS

![Diagram]

Define Lubrication Oil Consumption as:

\[ LOC \left[ \frac{g}{hr} \right] = \dot{m}_{LO} \]  

(1)

Mass balance at point \( A \) for sulfur:

\[ \dot{m}_{S,DF} + \dot{m}_{S,LO} + \dot{m}_{S,IA} = \dot{m}_{S,EE} ; \]  

where \( \dot{m}_{S,xx} \) is the mass flow rate of sulfur for sample flow ‘xx’.

\[ \dot{m}_{S,xx} = Y_{S,xx} \dot{m}_{xx} ; \]  

(3)

where \( Y_{S,xx} \) is the mass concentration of sulfur in the sample flow ‘xx’, and \( \dot{m}_{xx} \) is the mass flow rate of the sample flow ‘xx’.

Substituting Equation (3) into Equation (2):

\[ Y_{S,DF} \dot{m}_{DF} + Y_{S,LO} \dot{m}_{LO} + Y_{S,IA} \dot{m}_{IA} = Y_{S,EE} \dot{m}_{EE} \]  

(4)

Rearranging Equation (4):

\[ \dot{m}_{LO} = \frac{Y_{S,EE} \dot{m}_{EE} - Y_{S,IA} \dot{m}_{IA} - Y_{S,DF} \dot{m}_{DF}}{Y_{S,LO}} \]  

(5)

\[ Y_{S,xx} = \frac{MW_S}{MW_{xx}} \chi_{S,xx} ; \]  

(6)

where \( \chi_{S,xx} \) is the volumetric concentration of sulfur in the sample flow ‘xx’.
Substituting Equation (6) into Equation (5):

\[ \dot{m}_{LO} = \frac{\Delta \dot{m}}{Y_{S,LO}} = \frac{\text{Equation 6}}{\text{Equation 5}} \]

\[ \dot{m}_{LO} = \frac{MW_{EE}}{MW_{EE}} \frac{\chi_{S,EE} \dot{m}_{EE} = \frac{MW_{LO}}{MW_{LO}} \chi_{S,LO} \dot{m}_{LO} - \frac{MW_{S}}{MW_{DF}} \chi_{S,DF} \dot{m}_{DF}}{Y_{S,LO}} \]

(7)

\[ \dot{m}_{EE} = \dot{m}_{IA} + \dot{m}_{DF}; \]

(8)

where \( O(\dot{m}_{LO}) \ll O(\dot{m}_{IA}) \approx O(\dot{m}_{DF}) \) and thus \( \dot{m}_{LO} \) can be neglected in Equation (8).

Substituting Equation (8) into Equation (7):

\[ \dot{m}_{LO} = \frac{MW_{S}}{MW_{EE}} \frac{\chi_{S,EE} (\dot{m}_{IA} + \dot{m}_{DF}) = \frac{MW_{S}}{MW_{IA}} \chi_{S,IA} \dot{m}_{IA} - \frac{MW_{S}}{MW_{DF}} \chi_{S,DF} \dot{m}_{DF}}{Y_{S,LO}} \]

(9)

Simplification leads to Equation (10):

\[ \dot{m}_{LO} = \frac{MW_{S}}{Y_{S,LO}} \left[ \frac{\chi_{S,EE} (\dot{m}_{IA} + \dot{m}_{DF}) = \frac{MW_{S}}{MW_{IA}} \chi_{S,IA} \dot{m}_{IA} - \frac{MW_{S}}{MW_{DF}} \chi_{S,DF} \dot{m}_{DF}}{MW_{EE}} \right] \]

(10)

Equation (10) is the final form of the equation needed to solve for LOC when exhaust measurements are made for engine out emissions.

### Knowns and Unknowns for Equation (10) for Cummins N14 LOC Study:

<table>
<thead>
<tr>
<th>Quantities to be measured</th>
<th>Known Quantities:</th>
<th>Known Quantity Values:</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \chi_{S,EE} ) = concentration of sulfur in diluted exhaust</td>
<td>( MW_{S} ) = molecular weight of sulfur</td>
<td>32.1 [g/mole]</td>
</tr>
<tr>
<td>( \chi_{S,IA} ) = concentration of sulfur in ambient air</td>
<td>( MW_{DF} ) = molecular weight of diesel fuel (BP ARCO)</td>
<td>251.1 [g/mole]</td>
</tr>
<tr>
<td>( \dot{m}_{DF} ) = mass flow rate of diesel fuel</td>
<td>( \chi_{S,DF} ) = mole fraction of sulfur in diesel fuel</td>
<td>0.000014</td>
</tr>
<tr>
<td>( \dot{m}_{IA} ) = mass flow rate of intake air</td>
<td>( Y_{S,LO} ) = mass fraction of sulfur in lubrication oil</td>
<td>0.004913 (must be re-analyzed)</td>
</tr>
</tbody>
</table>
For dilution tunnel measurements, the equation takes on the form of Equation (27). The derivation of Equation (27) from Equation (10) is as follows.

Mass balance at point B for sulfur:

\[ \dot{m}_{S,EE} + \dot{m}_{S,AA} = \dot{m}_{S,DE} \] (11)

\[ \dot{m}_{S,xx} = Y_{S,xx} \dot{m}_{xx} \] (12)

Substituting Equation (12) and (8) into Equation (11):

\[ Y_{S,EE} (\dot{m}_{IA} + \dot{m}_{DF}) = Y_{S,EE} \dot{m}_{EE} = Y_{S,DE} \dot{m}_{DE} - Y_{S,AA} \dot{m}_{AA} \] (13)

Substituting Equation (6) into Equation (10):

\[ \dot{m}_{LO} = \frac{Y_{S,EE} (\dot{m}_{IA} + \dot{m}_{DF}) - Y_{S,IA} \dot{m}_{IA} - MW_C Y_{S,DE} \dot{m}_{DF}}{Y_{S,LO}} \] (14)

Substituting Equation (13) into Equation (14):

\[ \dot{m}_{LO} = \frac{Y_{S,DE} \dot{m}_{DE} - Y_{S,AA} \dot{m}_{AA} - Y_{S,IA} \dot{m}_{IA} - MW_C Y_{S,DF} \dot{m}_{DF}}{Y_{S,LO}} \] (15)

Mass balance at point B for total flow:

\[ \dot{m}_{EE} + \dot{m}_{AA} = \dot{m}_{DE} \] (16)

Substituting Equation (8) into Equation (16):

\[ (\dot{m}_{IA} + \dot{m}_{DF}) + \dot{m}_{AA} = \dot{m}_{DE} \] (17)

Substituting Equation (17) into Equation (15):

\[ \dot{m}_{LO} = \frac{Y_{S,DE} (\dot{m}_{IA} + \dot{m}_{DF} + \dot{m}_{AA}) - Y_{S,AA} \dot{m}_{AA} - Y_{S,IA} \dot{m}_{IA} - MW_C Y_{S,DF} \dot{m}_{DF}}{Y_{S,LO}} \] (18)

Assuming that \( Y_{S,AA} \approx Y_{S,IA} \), results in Equation (19):

\[ \dot{m}_{LO} = \frac{Y_{S,DE} (\dot{m}_{IA} + \dot{m}_{DF} + \dot{m}_{AA}) - Y_{S,AA} (\dot{m}_{IA} + \dot{m}_{DF}) - MW_C Y_{S,DF} \dot{m}_{DF}}{Y_{S,LO}} \] (19)

\[ DR = \frac{\dot{V}_D}{\dot{V}_E} = \frac{\dot{m}_{DE}}{\dot{m}_{EE}} + \frac{\dot{m}_{AA}}{\dot{m}_{EE}} = \frac{\dot{m}_{EA}}{\dot{m}_{EE} \rho_{AA}} = 1 + \frac{\dot{m}_{AA} \rho_{EE}}{\dot{m}_{EE} \rho_{AA}} \] (20)
Solving Equation (20) for $\dot{m}_{AA}$:

$$\dot{m}_{AA} = \frac{\dot{m}_{EE}\rho_{AA}(DR-1)}{\rho_{EE}}$$  \hspace{1cm} (21)

Assuming that $T_{AA} \approx T_{EE}$ and $P_{AA} \approx P_{EE}$ after mixing and that $MW_{AA} \approx MW_{EE}$:

$$\frac{P_{AA}}{\rho_{AA}} = \frac{\rho_{EE}}{P_{EE}} = \frac{T_{AA}}{MW_{AA}} = 1$$  \hspace{1cm} (22)

Substituting Equation (22) into Equation (21):

$$\dot{m}_{AA} = \dot{m}_{EE}(DR-1)$$  \hspace{1cm} (23)

Substituting Equation (23) into Equation (19):

$$\dot{m}_{LO} = \frac{Y_{S,DE}(\dot{m}_{IA} + \dot{m}_{DF} + \dot{m}_{EE}(DR-1)) - Y_{S,AA}(\dot{m}_{EE}(DR-1) + \dot{m}_{IA}) - \frac{MW_{S}X_{S,DF} \dot{m}_{DF}}{MW_{DF}}}{Y_{S,LO}}$$  \hspace{1cm} (24)

Substituting Equation (8) into Equation (24):

$$\dot{m}_{LO} = \frac{Y_{S,DE}(\dot{m}_{IA} + \dot{m}_{DF}) - Y_{S,AA}((\dot{m}_{IA} + \dot{m}_{DF})(DR-1) + \dot{m}_{IA}) - \frac{MW_{S}X_{S,DF} \dot{m}_{DF}}{MW_{DF}}}{Y_{S,LO}}$$  \hspace{1cm} (25)

Simplifying Equation (25) leads to Equation (26):

$$\dot{m}_{LO} = \frac{Y_{S,DE}(\dot{m}_{IA} + \dot{m}_{DF})DR - Y_{S,AA}(\dot{m}_{IA}DR + \dot{m}_{DF}DR - \dot{m}_{DF}) - \frac{MW_{S}X_{S,DF} \dot{m}_{DF}}{MW_{DF}}}{Y_{S,LO}}$$  \hspace{1cm} (26)

Simplifying further leads to Equation (27):

$$\dot{m}_{LO} = \frac{DR Y_{S,DE}(\dot{m}_{IA} + \dot{m}_{DF}) - Y_{S,AA}(\dot{m}_{IA}DR + \dot{m}_{DF}DR - \dot{m}_{DF}) - \frac{MW_{S}X_{S,DF} \dot{m}_{DF}}{MW_{DF}DR}}{Y_{S,LO}}$$  \hspace{1cm} (27)

Equation (27) is the final equation needed for calculating LOC when sampling from the dilution tunnel.
## APPENDIX D – ULTRA LOW SULFUR DIESEL FUEL CARBON NUMBER WEIGHT DISTRIBUTION

<table>
<thead>
<tr>
<th>CARBON NUMBER</th>
<th>DISTRIBUTION, wt.%</th>
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</thead>
<tbody>
<tr>
<td>C6</td>
<td>0</td>
</tr>
<tr>
<td>C6</td>
<td>0</td>
</tr>
<tr>
<td>C7</td>
<td>0.12</td>
</tr>
<tr>
<td>C8</td>
<td>0.61</td>
</tr>
<tr>
<td>C9</td>
<td>2.71</td>
</tr>
<tr>
<td>C10</td>
<td>5.45</td>
</tr>
<tr>
<td>C11</td>
<td>8.3</td>
</tr>
<tr>
<td>C12</td>
<td>10.3</td>
</tr>
<tr>
<td>C13</td>
<td>11.6</td>
</tr>
<tr>
<td>C14</td>
<td>9.99</td>
</tr>
<tr>
<td>C15</td>
<td>9.41</td>
</tr>
<tr>
<td>C16</td>
<td>8.18</td>
</tr>
<tr>
<td>C17</td>
<td>8</td>
</tr>
<tr>
<td>C18</td>
<td>7.1</td>
</tr>
<tr>
<td>C19</td>
<td>5.64</td>
</tr>
<tr>
<td>C20</td>
<td>4.22</td>
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<tr>
<td>C21</td>
<td>2.89</td>
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<tr>
<td>C22</td>
<td>2.26</td>
</tr>
<tr>
<td>C23</td>
<td>1.64</td>
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<tr>
<td>C24</td>
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<td>C25</td>
<td>0.41</td>
</tr>
<tr>
<td>C26</td>
<td>0.19</td>
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<tr>
<td>C27</td>
<td>0.04</td>
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<tr>
<td>C28</td>
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<tr>
<td>C29</td>
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<td>TOTAL</td>
<td>99.99</td>
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</table>

Average carbon number: 17.8
Average molecular weight: 251.1
APPENDIX E.1 – DATA SHEET FOR RECORDING FILTER INFO.

UW-MADISON

LOC Engine Emissions Tests

ERC – April & May, 2003

ERC Test Number*: __________________________
Date: ______________________________
Operator Name: Nathan Forster / John Stetter
Engine Fuel: BP ARCO ULSD Fuel
Operating Mode: __________________
Sample Label Sticker: ____________________

Comments: LOC Effect Study.

Sampling Conditions:

<table>
<thead>
<tr>
<th></th>
<th>Start of Test</th>
<th>Start of Hot Soak</th>
<th>End of Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient Temp</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ambient Rh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residence Chamber Temp</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Residence Chamber Rh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main Vacuum Pressure (1,2,3,4)</td>
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</tr>
<tr>
<td>5 FH Vacuum Pressure (7)</td>
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</tr>
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</table>

Flows:

<table>
<thead>
<tr>
<th>Cyclone Bank #1</th>
<th>Pre-loading Check Units: LPM</th>
<th>Post-loading Check Units: LPM</th>
<th>WSLH Filter Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERC-X-TF1-SO4/MASS</td>
<td>[72] 8.784 LPM</td>
<td>[72] 8.784 LPM</td>
<td>CB-EL-47T-</td>
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<tr>
<td>ERC-X-TF2-SO4/MASS</td>
<td>[74] 8.815 LPM</td>
<td>[74] 8.815 LPM</td>
<td>CB-EL-47T-</td>
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<tr>
<td>ERC-X-TF3-Metals</td>
<td>[63] 7.6 LPM</td>
<td>[63] 7.6 LPM</td>
<td>Metals</td>
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<tr>
<td>ERC-X-QFC-ECOC</td>
<td>[55] 2.0 LPM</td>
<td>[55] 2.0 LPM</td>
<td>ECOC</td>
</tr>
<tr>
<td>ERC-X-TF4-SO4/MASS</td>
<td>[60] 7.268 LPM</td>
<td>[60] 7.268 LPM</td>
<td>CB-EL-47T-</td>
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<tr>
<td>ERC-X-QFC1-SO2</td>
<td>LPM</td>
<td>LPM</td>
<td>K2CO3</td>
</tr>
<tr>
<td>ERC-X-QFC2-SO2</td>
<td>LPM</td>
<td>LPM</td>
<td>K2CO3</td>
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</table>
## APPENDIX E.2 – DATA SHEET FOR RECORDING DILUTION TUNNEL INFORMATION

<table>
<thead>
<tr>
<th>Mode:</th>
<th>Fuel:</th>
<th>Test Date:</th>
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<tbody>
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</table>

<table>
<thead>
<tr>
<th>SMPS File Name (i.e. 20030411m615)</th>
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<table>
<thead>
<tr>
<th>TEOM File Name (i.e. 411m6_1)</th>
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<th><em>2</em></th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
</tbody>
</table>

| Primary Dilution Orifice (in Hg) | _| |
|----------------------------------|---|
| Primary Dilution Air Pressure (psig) | _|
| Secondary Dilution Air Pressure (psig) | _|
| Heated Filter Temperature (°F) | _|
| RTC1 Temperature (#3) (°F) | _|
| RTC2 Temperature (#4) (°F) | _|
| RTC3 Temperature (#5) (°F) | _|
| RTC4 Temperature (#6) (°F) | _|
| RTC Pressure (psia) | _|
| Upstream Pressure Main Orifices (psia) | _|
| Upstream Temperature Main Orifices (#7) (°F) | _|
| Primary Dilution Air Temperature (#17) (°F) | _|
| Primary Diluent Temperature (#18) (°F) | _|
| Secondary Diluent Temperature (#19) (°F) | _|
| Secondary Dilution Air Temperature (#20) (°F) | _|
## APPENDIX E.3 – DATA SHEET FOR RECORDING ENGINE INFO.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Valves</th>
<th>TVO_TVC</th>
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</thead>
<tbody>
<tr>
<td>Mode 1</td>
<td>2 &amp; 4</td>
<td>t290_25</td>
</tr>
<tr>
<td>Mode 2</td>
<td>2 &amp; 4</td>
<td>t247_25</td>
</tr>
<tr>
<td>Mode 3</td>
<td>2 &amp; 4</td>
<td>t210_25</td>
</tr>
<tr>
<td>Mode 4</td>
<td>3 &amp; 4</td>
<td>t185_15</td>
</tr>
<tr>
<td>Mode 5</td>
<td>2 &amp; 4</td>
<td>t340_30</td>
</tr>
<tr>
<td>Mode 6</td>
<td>3 &amp; 4</td>
<td>t294_15</td>
</tr>
<tr>
<td>Mode 7</td>
<td>3 &amp; 4</td>
<td>t230_15</td>
</tr>
<tr>
<td>Mode 8</td>
<td>2</td>
<td>t150_15</td>
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### Pressure File Name (i.e. 010103m615)

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<td>Fuel Additive</td>
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<td>Engine Speed</td>
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<td>Fuel accumulated mass</td>
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<tr>
<td>Time for fuel accumulated mass</td>
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<td>Fuel flowrate (from Micro Motion)</td>
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<td>Micro Motion Pressure</td>
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<tr>
<td>Blow-by (Cummins Method)</td>
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<tr>
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<td>H2O Temperature</td>
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<td>Pressure Trans. Coolant Temp</td>
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<td>Fuel Pressure</td>
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<td>Coolant Pressure (Bad Data)</td>
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<td>Exhaust Pressure</td>
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<tr>
<td>Intake Air Temperature</td>
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<tr>
<td>Downstream Air Temperature</td>
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<tr>
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<tr>
<td>Exhaust Temperature</td>
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<tr>
<td>Intake Air Pressure</td>
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<td>Downstream Air Pressure</td>
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<td>Atm. Pressure</td>
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<td>Stoich. AF ratio (est.)</td>
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**APPENDIX E.4 – DATA SHEET FOR RECORDING FTIR INFO.**

**Note:** Do not forget to sample dilution air with & without cart before adding exhaust to dilution tunnel!!
Repeat the above procedure at the end of the testing also.

<table>
<thead>
<tr>
<th>Dilution Air FTIR Series File Name (cart):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilution Air FTIR Series File Name (no cart):</td>
</tr>
</tbody>
</table>

Set Date: Mode: Fuel:

**FTIR Series File Name:**

Series file name structure: `yyyymmdd_m*_hhmm`  
(yearmonthday_m{mode#}_24hourminute)

**FTIR Series File Name for Cart:**

<table>
<thead>
<tr>
<th>Filter Test</th>
<th>FTIR Stable* Time</th>
<th>Measurement Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Time</td>
<td>[min]</td>
<td>[min]</td>
</tr>
<tr>
<td></td>
<td>during eng out</td>
<td>just a reminder</td>
</tr>
</tbody>
</table>

- 00: 01. gaseous emissions (engine out)
- 10: 02. primary dilution tunnel
- 20: 03. RTC4
- 30: 04. gaseous emissions (engine out)
- 40: 05. primary dilution tunnel
- 50: 06. RTC4

**THC**

Record THC before starting FTIR and filter tests.
Let THC analyzer sample until stable for one minute before taking reading.

**THC Analyzer Parameters**

<table>
<thead>
<tr>
<th>1</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Pressure</td>
<td>Air Pressure</td>
</tr>
<tr>
<td>Fuel Pressure</td>
<td>Fuel Pressure</td>
</tr>
<tr>
<td>Sample Pressure</td>
<td>Sample Pressure</td>
</tr>
<tr>
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<td>THC min reading</td>
</tr>
<tr>
<td>min and max of a 30 second time span</td>
<td>min and max of a 30 second time span</td>
</tr>
<tr>
<td>THC max reading</td>
<td>THC max reading</td>
</tr>
</tbody>
</table>
APPENDIX F – LOC RATE FORMULA DERIVATION USING EXHAUST METAL CONCENTRATIONS

Define Dilution Ratio as:

\[ DR = \frac{V_{DE}}{V_{EE}} \]  

(1)

Mass balance at point B for component ‘w’:

\[ \dot{m}_{w, EE} + \dot{m}_{w, AA} = \dot{m}_{w, DE} ; \]  

where \( \dot{m}_{w, xx} \) is the mass flow rate of component ‘w’ in sample flow ‘xx’.

\[ \dot{m}_{w, xx} = Y_{w, xx} \dot{m}_{xx} ; \]  

(3)

\[ \dot{m}_{EE} = \dot{m}_{IA} + \dot{m}_{DF} ; \]  

(4)

where \( Y_{w, xx} \) is the mass concentration of component ‘w’ in the sample flow ‘xx’, and \( \dot{m}_{xx} \) is the mass flow rate of the sample flow ‘xx’.

Substituting Equation (3) and (4) into Equation (2):

\[ Y_{w, EE} \dot{m}_{EE} = Y_{w, EE} (\dot{m}_{IA} + \dot{m}_{DF}) = Y_{w, DE} \dot{m}_{DE} - Y_{w, AA} \dot{m}_{AA} \]  

(5)

\[ Y_{w, xx} = \frac{MW_{w}}{MW_{xx}} \chi_{w, xx} ; \]  

(6)

where \( \chi_{w, xx} \) is the volumetric concentration of component ‘w’ in the sample flow ‘xx’.

Substituting Equation (6) into Equation (5):

\[ \frac{MW_{w}}{MW_{EE}} \chi_{w, EE} \dot{m}_{EE} = \frac{MW_{w}}{MW_{EE}} \chi_{w, EE} (\dot{m}_{IA} + \dot{m}_{DF}) = \frac{MW_{w}}{MW_{DE}} \chi_{w, DE} \dot{m}_{DE} - \frac{MW_{w}}{MW_{AA}} \chi_{w, AA} \dot{m}_{AA} \]  

(7)

Simplifying Equation (7) and assuming \( MW_{AA} \approx MW_{EE} \approx MW_{DE} \):

\[ \chi_{w, EE} \dot{m}_{EE} = \chi_{w, EE} (\dot{m}_{IA} + \dot{m}_{DF}) = \chi_{w, DE} \dot{m}_{DE} - \chi_{w, AA} \dot{m}_{AA} \]  

(8)
Solving the DR definition for mass flow rate results in Equation (9):

\[
DR = \frac{\dot{V}_{DE}}{\dot{V}_{EE}} = \frac{\dot{m}_{DE}}{\dot{m}_{EE} \rho_{EE}} = \frac{\dot{m}_{AA} \rho_{AA}}{\dot{m}_{EE} \rho_{EE}} = 1 + \frac{\dot{m}_{AA} \rho_{AA}}{\dot{m}_{EE} \rho_{EE}} \tag{9}
\]

Solving Equation (9) for \( \dot{m}_{AA} \) and \( \dot{m}_{DE} \):

\[
\dot{m}_{AA} = \frac{\dot{m}_{EE} \rho_{AA} (DR - 1)}{\rho_{EE}}, \quad \dot{m}_{DE} = \frac{\dot{m}_{EE} \rho_{DE} DR}{\rho_{EE}} \tag{10,11}
\]

Assuming that \( T_{DE} \approx T_{AA} \approx T_{EE} \) and \( P_{DE} \approx P_{AA} \approx P_{EE} \) after mixing and that \( MW_{DE} \approx MW_{AA} \approx MW_{EE} \):

\[
\frac{\rho_{AA}}{\rho_{EE}} = \frac{\frac{P_{AA}}{MW_{AA} T_{AA}}}{\frac{P_{EE}}{MW_{EE} T_{EE}}} = 1, \quad \frac{\rho_{DE}}{\rho_{EE}} = \frac{\frac{P_{DE}}{MW_{DE} T_{DE}}}{\frac{P_{EE}}{MW_{EE} T_{EE}}} = 1 \tag{12,13}
\]

Substituting Equation (12) into Equation (10):

\[
\dot{m}_{AA} = \dot{m}_{EE} (DR - 1) \tag{14}
\]

Substituting Equation (13) into Equation (11):

\[
\dot{m}_{DE} = \dot{m}_{EE} DR \tag{15}
\]

Substituting Equation (15) and Equation (14) into Equation (8):

\[
\chi_{w,EE} \dot{m}_{EE} = \chi_{w,EE} (\dot{m}_{IA} + \dot{m}_{DF}) = \chi_{w,DE} \dot{m}_{EE} DR - \chi_{w,AA} \dot{m}_{EE} (DR - 1) \tag{16}
\]

Simplification of Equation (16) leads to Equation (17):

\[
\chi_{w,EE} = \chi_{w,DE} DR - \chi_{w,AA} (DR - 1) \tag{17}
\]

Equation (17) is the final equation needed for calculating the concentration of component ‘w’ in the engine out exhaust when correcting for dilution ratio effects. This equation is used when the dilution air has significant amounts of the component of interest, such as sulfur dioxide. Otherwise, the term including the concentration in the Ambient Air can be neglected, such as for metal, OC, EC, and sulfate concentrations.
To obtain an engine-out mass rate emission of the component of interest, Equation (17) is modified in the following manner.

Substituting Equation (6) into Equation (17):

\[
Y_{w,EE} \frac{MW_{EE}}{MW_w} = Y_{w,DE} \frac{MW_{DE}}{MW_w} DR - Y_{w,AA} \frac{MW_{AA}}{MW_w} (DR - 1) \tag{18}
\]

Simplifying and assuming that the dilution air contains none of the component of interest:

\[
Y_{w,EE} MW_{EE} = Y_{w,DE} MW_{DE} DR \tag{19}
\]

Assuming that \( MW_{DE} \approx MW_{EE} \):

\[
Y_{w,EE} = Y_{w,DE} DR \tag{20}
\]

For the current experiment, the diluted exhaust concentrations were measured with filters that had a specific sample flow rate pulled through each filter. Therefore the following is true:

\[
Y_{w,DE} = \frac{m_{w,\text{filter}}}{\nu_{\text{filter}} \rho_{EE}} \tag{21}
\]

where \( m_{w,\text{filter}} \) is the mass of the component of interest collected on the filter;
\( \nu_{\text{filter}} \) is the volumetric flow rate through the filter of air at STP;
and \( \rho_{EE} \) is the density of the exhaust at STP.

To obtain the total component mass flow, multiply the mass concentration of the component of interest by the total exhaust flow.

\[
m_{w,x} = Y_{w,x} \dot{m}_x \tag{22}
\]

Substituting Equation (20) and (22) into Equation (21):

\[
\dot{m}_{w,EE} = Y_{w,DE} \dot{m}_{EE} DR = \frac{m_{w,\text{filter}}}{\nu_{\text{filter}} \rho_{EE}} DR \dot{m}_{EE} ; 
\tag{23}
\]

\[
\dot{m}_{EE} = FF(1 + AF) ; \tag{24}
\]

where FF is the fuel flow rate and AF is the Air/Fuel ratio.

To obtain the lubricating oil consumption rate (LOC), divide the component mass rate by the concentration of the respective component in the oil as shown below.

\[
LOC = \frac{m_{w,\text{filter}} DR(1 + AF) FF}{\nu_{\text{filter}} \rho_{EE} Y_{w,oil}} ; \tag{23}
\]

where \( Y_{w,oil} \) is the mass concentration of the component of interest, w, in the oil.
APPENDIX G – DILUTION RATIO CALCULATION DERIVATION

Define Dilution Ratio as:

\[ DR = \frac{V_{DE}}{V_{EE}} \]  

(1)

Mass balance at point B for the exhaust component of interest:

\[ \rho_{AA} A_{AA} V_{AA} Y_{k,AA} + \rho_{DE} A_{DE} V_{DE} Y_{k,DE} = \rho_{EE} A_{EE} V_{EE} Y_{k,EE} ; \]  

(2)

where \( Y_{k,xx} \) is the mass concentration of species ‘k’ in sample flow ‘xx’.

\[ AV = V ; \]  

(3)

where \( V \) is volume flow rate and \( V \) is velocity.

\[ \rho_{AA} V_{AA} Y_{k,AA} + \rho_{DE} V_{DE} Y_{k,DE} = \rho_{EE} V_{EE} Y_{k,EE} \]  

(4)

Mass balance at point B for the total mass flow:

\[ \rho_{AA} A_{AA} V_{AA} + \rho_{DE} A_{DE} V_{DE} = \rho_{EE} A_{EE} V_{EE} \]  

(5)

\[ AV = V \]  

(6)

\[ \rho_{AA} V_{AA} + \rho_{DE} V_{DE} = \rho_{EE} V_{EE} \]  

(7)

\[ \rho_{AA} V_{AA} = \rho_{EE} V_{EE} - \rho_{DE} V_{DE} \]  

(8)

Combining Equations (4) and (8) and rearranging:

\[ \left( \rho_{EE} V_{EE} - \rho_{DE} V_{DE} \right) Y_{k,AA} + \rho_{DE} V_{DE} Y_{k,DE} = \rho_{EE} V_{EE} Y_{k,EE} \]  

(9)

\[ \rho_{EE} V_{EE} Y_{k,AA} - \rho_{DE} V_{DE} Y_{k,AA} + \rho_{DE} V_{DE} Y_{k,DE} = \rho_{EE} V_{EE} Y_{k,EE} \]  

(10)

\[ \rho_{DE} V_{DE} Y_{k,DE} - \rho_{DE} V_{DE} Y_{k,AA} = \rho_{EE} V_{EE} Y_{k,EE} - \rho_{EE} V_{EE} Y_{k,AA} \]  

(11)

\[ V_{DE} (\rho_{DE} Y_{k,DE} - \rho_{DE} Y_{k,AA}) = V_{EE} (\rho_{EE} Y_{k,EE} - \rho_{EE} Y_{k,AA}) \]  

(12)

\[ \frac{V_{DE}}{V_{EE}} = \frac{\rho_{EE} Y_{k,EE} - \rho_{EE} Y_{k,AA}}{\rho_{DE} Y_{k,DE} - \rho_{DE} Y_{k,AA}} \]  

(13)

Substituting volumetric concentration for mass concentration:

\[ Y_{k,xx} = \frac{MW_{k}}{MW_{xx}} \chi_{k,xx} \]  

(14)

where \( \chi_{k,xx} \) is the volumetric concentration of species ‘k’ in sample flow ‘xx’.
Factoring out $MW_k$ and $\frac{\rho_{EE}}{\rho_{DE}}$:

\[
\frac{\nu_{DE}^k}{\nu_{EE}^k} = \frac{\rho_{EE} MW_k \chi_{k,EE}^k - \rho_{EE} MW_k \chi_{k,AA}^k}{\rho_{DE} MW_k \chi_{k,DE}^k - \rho_{DE} MW_k \chi_{k,AA}^k}
\]

(15)

Assuming that $MW_{AA}$ is approximately equal to $MW_{DE}$:

\[
\frac{\nu_{DE}^k}{\nu_{EE}^k} = \frac{\rho_{EE} MW_{AA} \frac{\chi_{k,EE} MW_{AA}}{MW_{DE}} - \chi_{k,AA}^k}{\rho_{DE} MW_{AA} \frac{\chi_{k,DE} MW_{AA}}{MW_{DE}} - \chi_{k,AA}^k}
\]

(19)

Using the Ideal Gas Law:

\[
P = \frac{\rho_{xx} R_U T}{MW_{xx}}
\]

(20)

\[
\rho_{xx} = \frac{P \times MW_{xx}}{R_U T}
\]

(21)

Assuming that the pressure and temperature of the gases are equal at the time of analysis:

\[
\frac{\rho_{EE} MW_{EE}}{\rho_{DE} \frac{R_U T}{MW_{DE}}} = \frac{MA_{EE}}{MW_{DE}}
\]

(22)

Substituting Equation (22) into (19) results in the following equation:
\[
\frac{V_{DE}}{V_{EE}} = \frac{MW_{AA}}{MW_{EE}} \frac{\chi_{k,EE} - \chi_{k,AA}}{\chi_{k,DE} - \chi_{k,AA}}
\]

(23)

Assuming \( MW_{AA} \approx MW_{EE} \approx MW_{DE} \), results in the final dilution ratio formula:

\[
DR = \frac{V_{DE}}{V_{EE}} = \frac{\chi_{k,EE} - \chi_{k,AA}}{\chi_{k,DE} - \chi_{k,AA}}
\]

(24)

The following compares \( MW_{AA} \) and \( MW_{EE} \):

(BP ARCO 14ppm sulfur fuel was used in these calculations.)

\( MW_{AA} \) calculation:

\[
(1.000\text{[mole of O}_2\text{]})(32.0[\text{g/mole of O}_2]) + (3.773\text{[mole of N}_2\text{]})(28.0[\text{g/mole of N}_2])
\]

\[
= 137.644[\text{g/4.773 moles of Air}]
\]

\[
= 28.838[\text{g/mole of Air}] = MW_{AA}
\]

\( MW_{EE} \) calculation: (H/C = 1.89 for BP ARCO 14ppm Sulfur fuel)

**Stoichiometric Condition:**

\[
C_{1}H_{1.89} + 1.4725(O_2+3.773N_2) \rightarrow CO_2 + 0.945H_2O + 5.556N_2
\]

\[
(1.000[\text{mole of CO}_2])(44.0[\text{g/mole of CO}_2]) + (0.945[\text{mole of } H_2O])(18.0[\text{g/mole of } H_2O])
\]

\[
+ (5.556[\text{mole of } N_2])(28.0[\text{g/mole of } N_2])
\]

\[
= 216.578[\text{g/7.501 moles of Exhaust}]
\]

\[
= 28.873[\text{g/mole of Exhaust}] = MW_{EE}
\]

The following shows reasoning for \( MW_{AA} \approx MW_{EE} \):

\[
\frac{MW_{AA}}{MW_{EE}} = \frac{28.838}{28.873} = 0.999
\]

Therefore, \( MW_{EE} \approx MW_{DE} \) is also justifiable due to \( MW_{AA} \approx MW_{EE} \) and the assumption of \( MW_{AA} \approx MW_{DE} \).
APPENDIX H – ENGINE OPERATING PARAMETERS FOR TESTED MODES

<table>
<thead>
<tr>
<th>Engine Mode</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
<th>Mode 5</th>
<th>Mode 6</th>
<th>Mode 7</th>
<th>Mode 8</th>
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<tbody>
<tr>
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<td>2 &amp; 4</td>
<td>2 &amp; 4</td>
<td>3 &amp; 4</td>
<td>2 &amp; 4</td>
<td>3 &amp; 4</td>
<td>3 &amp; 4</td>
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<td>t247_25</td>
<td>t210_25</td>
<td>t185_15</td>
<td>t130_30</td>
<td>t129_15</td>
<td>t123_15</td>
<td>t115_15</td>
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<td>50%</td>
<td>20%</td>
<td>100%</td>
<td>75%</td>
<td>50%</td>
<td>10%</td>
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<td>BP</td>
<td>BP</td>
<td>BP</td>
<td>BP</td>
<td>BP</td>
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<tr>
<td>Fuel Additive</td>
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<td>0%</td>
<td>0%</td>
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<td>0%</td>
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<td>70.7</td>
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<td>Stoich. A/F Ratio (est.)</td>
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APPENDIX I – UNIT CONVERSIONS FOR TESTED MODES

Average Unit Conversion Factors for Tested Modes:

<table>
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<tr>
<th></th>
<th>Multiply by: [g/bhp-hr] to get [mg/m³]</th>
<th>[g/hr] to get [g/bhp-hr]</th>
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</thead>
<tbody>
<tr>
<td>Mode 4</td>
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<td>Mode 5</td>
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<td>Mode 1</td>
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<td>0.0065</td>
</tr>
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### APPENDIX J – ANALYZED FILTER DATA

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<th>Engine Config</th>
<th>Eng Out PM Mass Rate</th>
<th>Eng Out SO4 Rate</th>
<th>Eng Out OC Rate</th>
<th>Eng Out EC Rate</th>
<th>LOC Rate</th>
</tr>
</thead>
<tbody>
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<td>SO4 Unc</td>
<td>EC Unc</td>
<td>OC Unc</td>
<td>LOC Rate Unc</td>
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