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EFFECTS OF FUEL PROPERTIES AND OXIDIZING CATALYSTS ON DIESEL EMISSIONS

By

Emad Afifi Abdalgawad ©

A thesis to the Faculty of Graduate Studies and Research in Partial
Fulfillment of the requirement for the degree of Master of Science

Department of Mechanical Engineering

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Mr. Emad Abdalgawad
1670 Tompkins Wynd.
Edmonton, Alberta
T6R 2Y5, Canada

Date: Jan 7th 2002

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommended to the Faculty of Graduate studies and Research for acceptance, a thesis entitled “Effects of Fuel Properties and Oxidizing Catalysts on Diesel Emissions” submitted by Emad Abdalgawad in partial fulfillment of the requirement for the degree of Master of Science.

Dr. David Checkel

Dr. B A Fleck

Dr. WB Kindzierski

Date: 28 Dec /01

DEDICATION

I would like to thank my father and my mother for teaching me the values of seeking knowledge and higher education. I dedicate this work to their ever lasting support.

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ABSTRACT

Engine technology, fuel technology and exhaust after treatment are the emission control methods for internal combustion engines. This experimental study investigates low sulfur/aromatic diesel fuel as one possible fuel technology for particulate matter (PM) reduction and the effect of an exhaust after treatment method, diesel oxidizing catalyst (DOC), on nitrogen oxides (NOx). Each major chapter of this thesis has been written as a stand-alone paper. The first chapter is an introduction to air pollution from mobile sources. The next study investigates the effect of fuel properties on PM emission from diesel engines, as a fuel technology approach for PM reduction. The last study investigates the effect of DOC on NOx emission from diesel engines, as an exhaust after treatment approach that may affect NOx control. The conclusions are low sulfur/aromatic diesel fuel significantly reduces PM , while DOC slightly increases NOx emission from the tested diesel engines.

PREAMBLE

Diesel engines are reliable and efficient sources of power. Due to the diffusion flame combustion in diesel engines, they emit excessive amounts of PM and NOx. The effect of low sulfur/aromatic diesel fuel on PM emission, as well as the effect of DOC on NOx emission from diesel engines were investigated in a number of studies. Some studies reported that low sulfur/aromatic diesel has no effect on PM reduction, while other studies reported that it reduces PM. Similarly, some studies reported that DOC has no effect on NOx reduction, while other studies reported that DOC reduces NOx.

Due to these inconclusive results, the objectives of this thesis are to investigate:

- The effects of low sulfur/aromatic diesel on PM emissions from diesel engines,
- The effects of DOC on NOx emissions from diesel engines.

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ABBREVIATIONS

CO - Carbon Monoxide
CO_2 - Carbon Dioxide
H_2O - Water
HC - Unburnt Hydrocarbon
PM - Particulate Matter
NOx - Nitrogen Oxides
N_2 - Nitrogen
SOF - Soluble Organic Fraction
SO_4 - Sulfate Compound
NO - Nitrogen Oxide
NMHC- Non-methane hydrocarbon
SCR - Selective Catalytic Reduction
EGR - Exhaust Gas Recirculation
EPA - Environmental Protection Agency
DPF - Diesel Particulate Filter
DOC - Diesel Oxidize Catalyst

Chapter 1

INTRODUCTION

CHAPTER 1: INTRODUCTION

Abstract

The scope of this study is to experimentally investigate the impact of

- Diesel Fuel with Low sulfur and aromatic on PM emissions.
- Diesel Oxidizing Catalyst on NOx emissions from diesel engines.

The objective of this chapter is to provide background information on automotive air pollution, emission test cycles, diesel engine regulations and automotive air pollution control technology.

Automotive air pollution investigation provides an overview on the adverse effects of the regulated emissions from diesel engines on human health and the environment. A comparison between automotive and industrial emissions is highlighted. A comparison between diesel and petrol (gasoline) engines is also highlighted. The formation mechanisms of NOx and PM are likewise outlined.

Emission test cycles are briefly discussed. The advantages and disadvantages of transient and steady-state emission test cycles are summarized. The current and the proposed diesel engines' emission regulations are provided.

To meet the proposed diesel engines' regulations, emission control technologies must be applied to diesel engines. Different techniques for emission control technologies are introduced.

1.1 Diesel Engine Exhaust Emissions

The objectives of this section are to introduce automotive air pollution and provide an overview of the adverse effects of the regulated emissions from diesel engines on human health and the environment. These topics are covered in more extensive detail by Heywood [1] and Cooper & Alley [2].

Diesel engines convert the chemical energy contained in the fuel to mechanical power. Diesel fuel is injected under pressure into the engine cylinder where it mixes with hot, highly compressed air and the combustion occurs. An ideal combustion of hydrocarbon fuels yields only carbon dioxide (CO_2), water vapor (H_2O), nitrogen (N_2) and oxygen (O_2). However, complete combustion never occurs due to the dissociation of combustion products, incomplete combustion of fuels and chemical reaction between combustion products. The exhaust gases discharged from engines contain several constituents that are harmful to human health and to the environment.

The high temperature of combustion products tends to dissociate carbon dioxide to carbon monoxide. Incomplete combustion yields particulate mater (PM), CO and unburnt hydrocarbons (HC). Due to the high temperature of combustion, a reaction occurs between nitrogen and oxygen, contained in the ambient air, forming NOx.

Hydrocarbon fuels are not pure hydrocarbons but they contain other elements. For instance, diesel fuel may contain sulfur which reacts when burnt to form sulfur dioxide (SO_2), some traces of sulfur trioxide (SO_3) and sulfuric acid (H_2SO_4). Although combustion products contain a lot of species, the regulated engine emissions in North America are CO, HC, PM and NOx.

Carbon monoxide (CO)

When engines operate in enclosed spaces, such as underground mines, tunnels or warehouses, carbon monoxide can accumulate in the work place and cause headaches and dizziness. High doze of CO may cause death.

Hydrocarbons (HC)

HC emission in enclosed spaces causes eye irritation and choking sensations. Hydrocarbons are major contributors to the characteristic diesel exhaust smell. Hydrocarbons are an important component of smog formation.

Diesel particulate matter (PM)

PM is defined by the US Environmental Protection Agency (US EPA) regulations and sampling procedures, as a complex aggregate of solid and liquid materials. Its origin is carbonaceous particles generated in the engine cylinder during combustion.

The primary carbon particles agglomerate and combine with several other organic and inorganic components of diesel exhaust. PM consists of:

- Solids - dry carbon particles, commonly known as soot.
- SOF - heavy hydrocarbons adsorbed and condensed on the carbon particles, called Soluble Organic Fraction.
- SO_4 - sulfate fraction.

The actual composition of PM will depend on engine type and the engine's operating conditions, for example load and speed.

Diesel particulate is generally less than 2 microns. The primary (nuclei) carbon particles have a diameter of 0.02 - 0.03 microns, while the agglomerated particles' diameter is in the 0.08 to 1 micron range. This size range is respirable and has a negative health impact on humans. It has been classified by several government agencies as either "human carcinogen"or "probable human carcinogen". It is also reported to increase the risk of heart and respiratory diseases.

Nitrogen oxides (NOx)

NOx is generated from the reaction of nitrogen and oxygen under the high pressure and temperature conditions in the engine combustion chamber. NOx consists mostly of nitric oxide (NO) and a fraction of nitrogen dioxide (NO_2). Nitrogen dioxide is very toxic. NOx emissions are also a serious environmental concern because of their role in the formation of smog and ground level ozone.

In brief, the exhaust emission regulations of diesel engines are essential due to the harmful effect of diesel exhaust on human heath and the environment.

1.2 Automotive and Industrial Emissions

This section is a comparison between emission from automotive applications and industrial sources. The comparison is based on emission control technologies. Moreover, human and environment exposure to air pollution from both sources are discussed. Industrial air pollution control technologies are covered in detail by Cooper and Alley [2].

Power plants and oil refineries are examples of industrial emission sources. Industrial emission sources are often referred as point sources and automotive sources referred as mobile or line sources. Line sources are more a general expression for emission from different mobile sources such as cars and trucks on highways.

Applying air pollution control in industrial facilities is easier than mobile application due to the size factor. Furthermore, human exposure to air pollution from mobile sources is more direct exposure compared with industrial sources because mobile applications are often used within highly populated areas.

The advantages of industrial emission sources over automotive sources are the size difference that facilitates better exhaust after treatment and using stacks provides better emission dilution.

Power plants successfully apply selective catalytic reaction (SCR) to control NOx emissions. SCR uses ammonia (NH_3) to reduce NOx to nitrogen and water in the presence of a catalyst. SCR technology is not practical in automotive applications due to the extra space and weight needed to store ammonia.

PM emissions from industrial sources are treated mechanically. Electrical precipitators, cyclones, and high temperature filters are used to control PM [2]. An electrical precipitators and cyclones in automotive applications is not practical. PM regeneration is one of the problems associated with cyclones. Electrical precipitator needs high voltage to operate, around 30kV [2]. This voltage is not practical in automotive applications. Filter failure due to thermal stresses, and filter clogging are some of the problems associated with using filters in diesel engines.

Location selection is used to minimize human and wildlife exposure to emissions from industrial complexes. For example, industrial facilities are built in rural areas and release emissions from high stacks.

In contrast, automobiles and trucks are mostly used in cities and their emissions are close to ground level.

In summary, automotive sources have more effect on humans, animals and crops due to the direct exposure and some limitations in exhaust after treatment technology.

1.3 Diesel and Petrol Engine Emissions

The objective of this section is to compare fuel economy and emission from gasoline and diesel engines. In general, diesel engines are more fuel efficient and produce less carbon monoxide and unburnt hydrocarbon, but produce excessive amounts of nitrogen oxidizes and PM.

Charbonnier et al. [3], conducted a comparison between gasoline and diesel passenger cars, with the same engine size and operating at the same conditions. The comparison was based on fuel economy and emission. Diesel vehicles were 23-39 % less in fuel consumption. CO, HC and CO_2 emissions from diesel vehicles were respectively 60%, 40% and 16% less than for gasoline vehicles. On the other hand, gasoline vehicles emitted 32% less NOx and emitted only from 1-5% of the PM emissions compared to diesel vehicles. The dramatic emissions difference is due to mixture strength. Gasoline engines usually operate near a stoichiometric air fuel ratio, while diesel engines operate on lean mixtures.

For the same amount of air consumption, gasoline engines consume more fuel to operate near stoichiometric conditions. In contrast, diesel engines consume less fuel because they run lean. Lean mixtures lead to better fuel consumption and generally lower emission but very high NOx emission due to the excess air and high temperature associated with the high compression ratio in diesel engines. Diesel engines emit more PM than gasoline engines due to the domination of diffusion combustion.

1.4 NOx Formation Mechanisms

The purpose of this section is to discuss NOx formation mechanisms. Although, NOx formation mechanisms include thermal, fuel, prompt, and the intermediate mechanism, this section covers only the thermal mechanism and the fuel mechanism. The thermal mechanism dominates NOx in diesel engines, while fuel mechanism slightly contributes to the overall NOx formation from diesel engines. The propmt mechanism is important for hydrocarbon-rich mixtures in burners. The N_2O intermediate mechanism is important for lean mixtures in gas turbines. For more information, different NOx mechanisms are discussed by Bowman et al. [4].

1.4.1 Thermal Mechanism (Extended Zeldovich Mechanism)

In the combustion of clean fuels containing no nitrogen, NO is formed from oxidation of atmospheric nitrogen. The oxidation of atmospheric nitrogen requires high temperatures, usually above 1800 K [4]. This process is known as the thermal mechanism. According to Bowman et al. [4], this mechanism dominates NO formation in engines because the combustion products are usually higher than 1800K during combustion.

The following reactions illustrate the Thermal Mechanism or the extended Zeldovich Mechanism.

$$O + N_2 \longleftrightarrow NO + N \qquad 1.1$$

$$N + O_2 \longleftrightarrow NO + O \qquad 1.2$$

$$N + OH \longleftrightarrow NO + H \qquad 1.3$$

In modeling, the rate of formation of NO can be calculated based on two assumptions. The first assumption is the existence of equilibrium temperature and concentration of O_2, N_2, O and OH. The second assumption is that the NO concentrations are less than their equilibrium values. Therefore, the reverse reactions can be neglected and NO concentration can be calculated from reaction 1.1 by:

$$d\,[NO]/dt = 2K\,[O]\,[N2] \qquad 1.4$$

Where K is the forward reaction rate coefficient for reaction 1.1.

$K = A\ Exp[-E/RT]$

E	: Activation Energy (J/kmol)
R	: Universal gas constant (kJ/kmol.k)
T	: Temperature (k)
A	: Empirical constant (pre-exponential factor, various units)

Integrating equation 1.4, NO concentration can be determined as a function of time. From the above, higher temperature leads to higher formation rates of NO. NO formation is only significant at 1800 K, or higher.

Factors affecting NOx formation are time, temperature and the concentration of O_2, N_2, O and OH. From equation 1.4, NOx formation rate is highly dependent on time, temperature and air concentration.

1.4.2 Fuel-N Mechanism

In this mechanism, NO is formed by the oxidation of the nitrogen contained in the fuel bond. It is a very important mechanism for coal and coal derivative fuels. A typical nitrogen content is 0.5-4% by weight for these types of fuels. As a result, a considerable amount of NO is emitted due to oxidation of nitrogen content in the fuel. In diesel fuels nitrogen content is approximately 200 ppm. The contribution of fuel-N mechanism is generally around 10% of the total NO emissions provided the nitrogen content in the fuel.

1.5 PM Formation and Fuel properties

This section discusses the formation mechanism of PM. Then, PM formation in diesel engines is discussed followed by the effect of diesel fuel properties on PM emission from diesel engines.

1.5.1 Formation Mechanism of PM

According to Glassman [6,7], PM formation mechanism is the same for all fuels and can be described as in Figure 1.1

Figure 1.1: Formation Mechanism of PM

Nucleation > Surface Growth > Agglomeration

Nucleation

Diesel fuels are dominated by hydrocarbon molecules with 12 to 22 carbon atoms and a hydrogen/carbon ratio about 2. In the fuel-rich zone of a fuel spray flame, the fuel starts to dehydrogenate or lose hydrogen leading to formation of numerous soot particles. The nucleation process begins as soot particles form with about 10^5 carbon atoms and H/C ratio of 0.1.

Surface Growth

The nucleation process produces a large number of very small soot particles with a diameter from 0.02 to 0.03 microns (20 to 30 nm). Gasified compounds in the combustion chamber start to deposit on those small particles, forming lager particles.

Agglomeration

In this stage, colliding soot particles start to agglomerate with one another to create large size particles, forming what is known by PM.

1.5.2 Factors Affecting PM Formation

PM formation from combustion processes depends upon more than one factor. Therefore, it is difficult to estimate the exact amount of PM produced per unit weight of fuel [6]. The tendency of sooting will be studied instead. Equivalence ratio and carbon bond structure are the most dominating factors in PM formation [6,7].

Equivalence Ratio

Rich mixtures have more sooting tendency because there is not enough oxygen to burn the soot formed from heated fuel. Diffusion flames have more sooting tendency than premixed flames because they have fuel-rich regions where fuel is heated.

Carbon Bond Structure

Paraffins, or alkanes, have the least sooting tendency because they have single-bonded open chain saturated hydrocarbon. The general symbol of Paraffins is (C_nH_{2n+2}). Methane (CH_4), ethane (C_2H_6) and propane (C_3H_8) are single-bonded hydrocarbons. Although they are from the same family, methane has the least sooting tendency because it has one carbon, followed by ethane then propane.

Olefins, or alkenes, have more sooting tendency because they have a double bond, which is more stable than single bond. The general symbol of olefins is (C_nH_{2n}).

Acetylenes, or alkynes, have higher sooting tendency because they have one carbon-carbon triple bond, which is more stable than a double bond. The general symbol of acetylenes is (C_nH_{2n-2}).

Aromatics have the highest sooting tendency because their ring structure is very stable. The general symbol of Aromatics is (C_nH_{2n-6}). Aromatic content in diesel fuel has a significant effect on PM emissions from diesel engines. Refineries aim to produce the least amount of aromatics to control PM emissions from diesel engines.

1.5.3 PM Formation in Diesel Engines

The boiling points of diesel fuels range from 130 -350 °C [8]. On injecting the diesel fuel into the combustion chamber, the low boiling point hydrocarbons will evaporate immediately. Once the low boiling compounds evaporate they will react with the oxygen in the combustion chamber. The reaction takes place at the molecular level and forms CO_2 and H_2O at high temperatures or yields partial oxidized products at medium temperatures [8]. The partial oxidized products will be carbonized (deghydrogenized) forming low molecular weight soot [8].

1.5.4 The Effect of Fuel Properties on PM Formation

The main factors that dominate PM formation in diesel engines are the evaporation and mixing rate of the fuel injected into the combustion chamber. Therefore, the chemical and physical properties of diesel fuels have a significant effect on soot tendencies. The chemical properties are H/C ratio , aromatic content, sulfur content and cetane number, while the physical properties include specific gravity, viscosity and distillation temperature [8].

H/C ratio

The H/C ratios are indeces of thermal stability and lower H/C ratio means more carbon in the fuel. Therefore, high H/C ratio fuels have lower sooting tendency.

Aromatic Content

Aromatic hydrocarbons have high boiling points and they are very stable. As a result, high aromatic content leads to higher boiling point of the fuel and consequently high sooting tendency.

Sulfur Content

The combustion of sulfur leads to more sulfate compounds in the combustion chamber. Sulfate compounds will deposit on soot particles producing more soot and preventing soot oxidization.

Cetane Number

Cetane number is the measure for diesel fuel ignition quality. High cetane numbers are indeces for easier and faster ignition in diesel fuels. Low ignition time reduces the possibility of PM formation.

Specific Gravity

The higher the specific gravity the higher the sooting tendency. High specific gravity is an indication for a lower H/C ratio. As discussed above, low H/C ratio is associated with higher sooting tendency.

Viscosity

Lower viscosity yields smaller droplet size. Smaller droplets are easier to evaporate and burn. Consequently, low viscosity is associated with lower sooting tendency.

Distillation Temperature

T90 is the temperature at which 90% of the diesel fuel will evaporate. Low boiling points lead to less sooting tendency.

1.6 Emission Test Cycles

The objective of this section is to introduce emission test cycles. The advantages and disadvantages of transient and steady-state emission test cycles are discussed. Further information can be found in [9,10,11].

As discussed in section 1.2, stationary sources are easier than mobile sources to apply emission control technology. It is also easier to control emission from stationary sources. Typically, industrial facilities have a maximum ground level concentration to meet within a given area around the plants for each pollutant. The plant has to meet these regulations by any means of their preference, for example, exhaust after treatment, using another combustion system that has better efficiency or even reducing production.

In the case of automotive sources, emissions are dramatically affected by vehicles/engines operating mode. Every country has its own driving patterns. Therefore, various test emission test cycles were established to model the driving pattern in each country and provide a fixed condition for emission testing. There are also emission test cycles for both highway and urban driving. Generally, emission test cycles are divided to transient and multimode tests.

1.6.1 Transient Tests

The exhaust emission tests for passenger cars and light duty trucks are performed on a chassis dynamometer. The vehicle is driven according to a prescribed speed and time pattern. Exhaust is collected in bags for analysis. Typically, two tests are conducted, one for the urban and the other for the highway. In the US EPA system, those tests are averaged with a 55% weighting factor for the urban test and 45% for the highway test.

The advantage of transient tests is the accurate result for emission due to the good simulation of driving patterns. The disadvantages of transient tests are that they are very expensive to conduct and do not give mode by mode results.

1.6.2 Multi-Mode Tests

Chassis dynamometers are not good candidates for testing heavy duty engines. Heavy duty engines are used in different applications, including trucks, tractors and heavy equipment. Multimode tests based on an engine dynamometer were introduced to overcome the variety of these applications by testing only the engine.

Multimode tests are a set of modes, each of which has a speed and torque value defined based on the rated speed and torque. Exhaust gas emissions are analyzed by real time instruments. Each mode has a weighting factor that contributes to the overall emission test result.

The advantages of this type of test are:

- less expensive than transient tests
- real time results can be obtained
- mode by mode result is suitable in the research phase for comparison between emissions from fuels and exhaust after treatment techniques.

The disadvantage is that it does not simulate the real driving conditions, especially transient operation.

1.7 Diesel Engine Emission Regulations

Regulations related to emissions and air quality may be divided into two classes:

- Ambient air quality standards.
- Tailpipe emission regulations.

For more information on ambient air quality standards, readers may refer to Dhaliwal [9].

1.7.1 Ambient Air Quality Standards

All diesel engines for highway applications and some for off-road use are subject to the "tailpipe"emission regulations. These regulations specify the maximum amounts of pollutant allowed in exhaust gases from diesel engines. The emissions are measured over an engine test cycle which is also specified in the regulations. The duty to comply with such a regulation belongs to the equipment (engine) manufacturers. All equipment must be emission certified before they can be released to the market. The authorities regulating engine tailpipe emissions include Transport Canada, the US EPA (Environmental Protection Agency) and California ARB (Air Resources Board). An example of this class of regulations is the EPA requirement that diesel particulate matter emissions from all heavy-duty diesel engines for highway use are below 0.1 g/bhp-hr.

Diesel engines are often used in confined spaces. In these cases, the emissions are regulated through ambient air quality standards rather than by tailpipe regulations. The ambient air quality standards specify the maximum concentrations of air contaminants which are allowed in the workplace. These regulations are set and enforced by occupational health and safety authorities such as OSHA (Occupational Health and Safety Administration) or MSHA (Mining Safety and Health Administration). The duty to comply with such a regulation is on the end-user (mine and warehouse owners, etc.).

1.7.2 Tailpipe Emission Regulations

Current Diesel Engines Regulations

The first US emission control for diesel engine smoke was implemented in 1970, while NOx, CO and HC from diesel engines were regulated by the Clean Air Act in 1977. Readers may refer to Walsh [12] for more detailed historical background on PM regulation.

All 1970 models were required to pass an opacity test. The new opacity procedure number is SAE 1667 standard [refer to SAE Handbook]. An opacity test is a direct measurement of the smoke from an engine exhaust. It is expressed by a percentage of light that can be blocked by the smoke from diesel engines. From 1970 to 1973, the standard opacity was 40% during acceleration and 20% during lugging. In 1974, the opacity standard was set to more stringent levels: 20% during acceleration, 15% during lugging and 50% at maximum loads.

The first particulate matter (PM) emission rate standard was set by the US EPA in the USA in 1980. It was 0.6 g/mile for cars and light trucks. In 1982 it dropped to 0.2 g/mile for cars and 0.26 g/mile for light trucks. In March 1985, US EPA established a new PM standard. It was 0.6 grams per brake hour power hour (0.6 g/bhp-hr) or (0.8 g/kW-hr). This standard was effective until 1988. From 1988 to 1990, it was (0.25 g/bhp-hr) or (0.34 g/kW-hr) then, from 1991 to 1993 it was (0.18 g/bhp-hr) or (0.13 g/kW-hr).

From 1974 to 1988 the NOx standard for heavy duty engines was higher than (11 g/bhp-h). Starting from 1988, NOx emission was (10.7 g/bhp-h). In 1990 NOx standards was reduced to (6 g/bhp-h). Table 1.1 and provide EPA diesel engines emission standard starting from 1990. These regulations are in effect untill 2003 [9].

Table 1.1: EPA Emission Standards for Heavy-Duty Diesel Engines, g/bhp-hr

Year	HC	CO	NOx	PM
Heavy-Duty Diesel Truck Engines				
1990	1.3	15.5	6.0	0.60
1991	1.3	15.5	5.0	0.25
1994	1.3	15.5	5.0	0.10
1998	1.3	15.5	4.0	0.10
Urban Bus Engines				
1991	1.3	15.5	5.0	0.25
1993	1.3	15.5	5.0	0.10
1994	1.3	15.5	5.0	0.07
1996	1.3	15.5	5.0	0.05*
1998	1.3	15.5	4.0	0.05*

* - in-use PM standard 0.07

Future Diesel Engine Regulations

In October 1997, the EPA adopted new emission standards for model year 2004 and later heavy-duty diesel truck and bus engines [9]. Manufacturers have the flexibility to certify their engines to one of the two options shown in Table 1.2.

Table 1.2: EPA Emission Standards for Year 2004 and Later HD Diesel Engines, g/bhp-hr

Option	NMHC + NOx	NMHC
1	2.4	n/a
2	2.5	0.5

In December 21, 2000, the EPA signed emission standards for model year 2007 and later heavy-duty highway engines (the California ARB adopted virtually identical 2007 heavy-duty engine standards in October 2001).

The first component of the regulation introduces new, very stringent emission standards[1], as follows:

- PM - 0.01 g/bhp-hr
- NOx - 0.20 g/bhp-hr
- NMHC - 0.14 g/bhp-hr

---

[1] http://www.dieselnet.com/standards/us/hd.html

1.8 Diesel Engine Emission Control

Meeting the stringent diesel engine emission standards is a challenge for engine manufacturers around the world. Diesel engine emission control techniques include:

- engine technology
- fuel technology
- exhaust after treatment

1.8.1 Engine Technology

Engine technology includes high pressure fuel injection, exhaust gas recirculation (EGR), electronic fuel control, injection timing, split injection and high compression ratios [13]. According to Lee et al. [13], the previous factors have been investigated to achieve optimization between NOx and PM emission from diesel engines. For example, NOx emissions have been reduced by 63% and PM by 73% due to engine technologies.

1.8.2 Fuel Technology

Fuel technology includes alternative fuels and the development of the existing fuel properties for low emission, such as low sulfur fuels and low aromatic content. Alternative (non-hydrocarbon) fuels are beyond the interest of this research.

There is a European program called "A European Program on Emissions, Fuels and Engine Technologies (EPEFE)". It focuses on the development of diesel and gasoline fuels for emission reductions [14,15,16].

According to Lee et al. [13], the most important diesel fuel properties are density, boiling point T90%, aromatic content and sulfur content [16]. PM has been reduced by 10% due to lowering diesel fuel sulfur content from 0.3% to 0.05%,

1.8.3 Exhaust After Treatment

Exhaust after treatment was introduced because engine and fuel technology alone have not been able to meet the proposed diesel engine emission standard.

A summary of exhaust after treatment was introduced in Lee et al. [13]. Exhaust after treatment for NOx includes selective catalytic reduction (SCR) and nonthermal plasma. Both are in the research phase due to the cost associated and the sophisticated operation.

Exhaust after treatment for PM includes diesel particulate filters (DPF) and oxidizing catalytic converters (DOC). DPF has higher efficiency than oxidizing catalytic converters but DPF has regeneration problems. Regeneration is the process of cleaning the filter after it has become partially plugged with PM. This involves burning the PM and the problems include difficulty in getting reliable PM ignition as well as the PM does not burn.

DOC are effectively used to control CO, HC and PM from diesel engines. DOC use the excess air of the diesel engine exhaust to oxidize the organic part of PM and HC to CO_2 and water, while they oxidize CO to CO_2. DOC effects on NOx are rarely discussed in the literature. In general, some studies showed DOC has a slight effect on NOx emissions. As discussed in the following chapters some studies showed that DOC increased NOx emission while other showed that it be decreased.

1.8.4 The PM-NOx Tradeoff

The heterogeneous combustion of diesel fuel is a complex process dominated by air/fuel mixing. Diesel fuel combustion occurs in three phases, namely, ignition delay period, premixed combustion and diffusion combustion.

Delay Period

Delay period is the time between the start of injection and the beginning of combustion. Short delay period is achieved by high temperature and high pressure of combustion chamber.

Premixed Combustion

A rapid pressure rise takes place due to fuel combustion in the delay period. In this stage most of NOx is formed, and reducing the temperature and the pressure of combustion process leads to NOx reductions.

Diffusion Combustion

The remaining fuel or the injected fuel will burn as soon it finds oxygen. It is a slow combustion and most of the PM is formed in this stage.

PM formation is reduced by high injection pressure and good air fuel mixing. These are the same conditions that increase NOx emission via the thermal mechanism.

1.9 Conclusion

Diesel engines are reliable and efficient sources of power but they emit excessive amounts of NOx and PM. The effects of NOx and PM on humans and the environment have prompted governmental and regulatory agencies to set and enforce stringent NOx and PM standards. The current NOx and PM standards are mostly met by engine technologies [16]. However, the proposed NOx and PM standards will require enhancement beyond the current technology.

PM-NOx tradeoff makes it hard to control both using the same control method. Therefore, the low sulfur/aromatic diesel is the proposed method to PM control. DOC have been successfully applied to control PM, CO and HC. The effect of DOC on NOx emissions is a concern due to the excess oxygen in diesel exhausts which may lead to more NOx emissions.

The objectives of this thesis are to investigate the effects of:

- low sulfur/aromatic diesel on PM emissions, and
- DOC effect on NOx emissions from diesel engines.

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Chapter 2

Fuel Properties Effect on PM Emissions from Diesel Engines

A paper based on this chapter will be submitted to the Petroleum Socity for publication.

Chapter 2

Fuel Properties Effect on PM Emissions from Diesel Engines

Abstract

Currently, diesel engines meet air pollution regulations mostly with the advances in engine technology and enhanced fuel properties. A new regulation for North America has been proposed for the year 2004. To meet the new stringent regulations, low sulfur/aromatic diesel fuels are favoured over exhaust after treatment due to the cost associated with exhaust after treatment. The effect of low sulfur/aromatic fuel is not clearly addressed in the literature. Some studies have shown that low sulfur/aromatic fuel reduces PM emission from diesel engines, while other studies have shown that it did not affect on PM emissions. The objective of this study was to experientially investigate the effect of low sulfur/aromatic fuel on PM emission from diesel engines.

The study included a literature review on the effect of engine technology, enhanced fuel properties and exhaust after treatment on PM emissions from diesel engines. For the experimental study, four heavy-duty engines, one medium-duty and one light-duty engine were tested using the Japanese 6-mode test. Three of the tested engines were not affected by the difference in sulfur content of the fuel, while the other three showed PM reductions of 70%, 15% and 8% compared with the high sulfur/aromatic content fuel.

2.1 Background

The efficiency and the durability of diesel engines make them the best candidate for most industrial and automotive applications [1,2]. However, because of the diffusion flame combustion in diesel engines, they emit excessive amounts of particulate matter (PM). PM is acknowledged as a health hazard, especially for particles with diameters less than 2 microns (PM_2) [3]. Most of the particles emitted by diesel engines are in the range of 2 micron or less [4].

Engine manufacturers focus on three main areas of research to meet exhaust emission regulations. These areas are engine technology, exhaust after treatment and alternative fuels.

Engine technology, commonly referred to as in cylinder emission control, includes applying EGR, combustion chamber design and high pressure electronically controlled fuel injection systems. Exhaust after treatment includes PM traps and catalytic converters. Some of the alternative fuel technologies for diesel engines, are dual fuel engines, dimethylether engines and reformulated diesel fuels for conventional engines. Reformulated fuels generally contain less sulfur and less polycyclic aromatic hydrocarbon compounds (PAH) than conventional diesel fuels.

The main objective of this investigation was to study the effect of a reformulated low sulfur/aromatic diesel on PM emission as an alternative approach for PM emission control from diesel engines. This topic is extensively discussed in previous studies but some studies reported low sulfur/aromatic diesel fuels had no effect on PM emissions while other studies reported that it reduced PM emissions from diesel engines. Due to these inconclusive results, the objective of this research is to investigate the effect of low sulfur/aromatic fuel on PM emissions from diesel engines. Furthermore, it is also devoted to investigate emissions behavior of oil sands derived diesel fuels. Most of the previous studies used laboratory fuels, while this study used commercial diesel fuels, currently available in Alberta.

2.2 Literature Survey

2.2.1 Particulate Matter

By definition, PM is discrete solid or liquid particles suspended in the air. PM diameters range from 0.005 to 100 microns in aerodynamic diameters. An aerodynamic diameter is the diameter of a sphere having the density of water and a settling velocity equal to the measured particle. Particles smaller than 2.5 microns are considered fine particles, while those larger than 2.5 microns called coarse particles. Combustion produces fine particles, while construction and mechanical wear produce coarse particles.

The effect of PM on human and animal health is dependent on PM size. The filtration mechanism of the human body tends to prevent PM with 10 micron diameter or larger from entering the lungs. Therefore, PM larger than 10 microns in aerodynamic diameter is less of a health hazard. If the breathing is done though the nose, only PM_1 are capable of entering the thoracic region [1]. PM_1, or smaller, can reach the lungs causing inflamation and blocking of the areas where oxygen transfer occurs. In tests on animals, it has been shown that exposer to inert particulates increases cancer in rats [2]. The smaller the PM, the more dangerous the effect. Therefore, the regulated values of concentration and exposure time for $PM_{2.5}$ are more stringent than for PM_{10}. In general, ambient air monitoring and measurements are limited to PM_{10} or smaller.

Attention has been directed to measure PM size and distribution emitted from diesel engines [2,3,4,5]. Ahlivik et al. [2], reported that 96% of the PM was in the range of 0.01 to 1 micron and 4% was in the 1 to 10 micron range. Schraml et al. [3], reported a size range of 0.019-0.036 micron. A study by Hall [5], reported that 85% of the PM emission was smaller than 1 micron.

In brief, PM emissions from diesel engines are in the range of 1 micron or smaller which is acknowledged to be a heath hazard.

2.2.2 Diesel Engine Regulations

Because of their durability and fuel economy, there has been an increasing demand for diesel powered vehicles. Walsh [6] reported that the European sales of diesel powered vehicles have increased from 7.2% in 1980 to 22.1% in 1995. As a result, diesel fuel consumption as a ratio of total highway consumption has increased. The Japanese diesel fuel consumption ratio has increased from 39.3% in 1984 to 45.7% in 1994, while in the USA diesel fuel consumption has increased from 14.6% to 17.9% within the same period [6].

The rising demand for diesel powered vehicles and the increasing diesel fuel consumption have led to more PM emission from diesel engines. To counter this trend, regulatory agencies have set stringent standards for diesel engine PM emission to retard the arising problem of air pollution.

In the US EPA, the standard for heavy-duty diesel engines PM emission was 0.60 g/bhp-hr in 1991 and reduced to 0.10 g/bhp-hr in 1998. This represented approximately an 84 % reduction. In the USA by 2007, further 90% reduction is expected to 0.01 g/bhp.hr [6]. In Europe, the standard for heavy-duty diesel engine PM emission was 0.60 g/kW.hr in 1991 compared to 0.15 g/kW.hr in 1998. The reduction ratio represented approximately 75%. In Europe, it is expected to be 0.02 g/kW.hr by the year 2005 [6]. These strict regulations challenge future development of diesel engines.

Diesel engine manufacturers and oil companies are working on introducing new technologies to meet these regulations.

2.2.3 Diesel PM Control Methods

Methods to control PM emission of diesel engines can be classified in three broad areas:

- in-cylinder (engine technology)
- exhaust after treatment
- enhanced fuel properties (fuel technology)

In-cylinder PM Control

Combustion in diesel engines is governed by spray characteristics such as spray penetration, spray angle and spray droplet size. High injection pressures provide finer spray and faster tip penetration for the same combustion chamber geometry . As a result, a better air/fuel ratio and better mixing is obtained. These conditions lead to less PM emission but higher NOx emission and more combustion noise.

Su et al. [7], investigated the effect of high pressure injection on PM and NOx emission in diesel engines. The authors reported that increasing the injection pressure from 90 MP to 160 MP led to 76 % PM reduction but also found a 68% increase in NOx emission.

The PM-NOx tradeoff directed research engineers to exhaust after treatment as an alternative technology to reduce PM from diesel engines.

Exhaust After Treatment

Diesel particulate filters (DPF) have been successfully implemented in diesel engines as exhaust after treatment devices. The advantage of DPF is its high efficiency of particulate collection. DPF efficiency ranges from 60% to 95% [8,9]. The disadvantages of DPF are high engine back pressure, the need for soot regeneration and failure due to thermal stresses from the soot regeneration process.

Back-pressure from DPF reduces engine power and increases specific fuel consumption. The most challenging problem is oxidizing the collected soot, or in another words, filter regeneration. A typical soot oxidizing temperature is from 500 to 600 °C. In diesel engines application, this temperature is hardly achieved for enough time to self-regenerate the collected soot in the DPF. Consequently, passive and active PM regeneration techniques are implemented to prompt the PM regeneration process in DPF.

Passive regeneration processes include using fuel additives and catalytic coated surfaces. Fuel additives can lower PM ignition temperature to approximately 360 °C [10,11]. Catalytic coated surfaces lower PM burning temperature to approximately 400 °C [12].

Active regeneration processes include electric heaters, compressed air regeneration and reverse flow regeneration [13,14,15]. Active regeneration processes are more complicated than passive regeneration processes. Yet, both eventually lead to DPF failure. Soot burning temperature is approximately from 500 to 600 °C. The high burning soot temperature subjects DPF to severe thermal stresses that lead to failure. Ideal DPF materials should be thermally durable and should exert minimal back pressure on diesel engines to lower the low specific fuel consumption penalty [16,17].

Enhanced Fuel properties For PM Reductions

Enhancing diesel fuel properties is another route to control PM emission from diesel engines. Sulfur and aromatic content are key factors in PM reduction, for typical hydrocarbon diesel fuels.

The higher the sulfur content of fuel the higher the levels of sulfate compound formed from burning diesel fuels. Sulfate compounds are one of the major components forming PM in diesel engine exhaust. Therefore, lowering sulfur content in diesel fuels leads to lower PM emissions from diesel fuels. In 1993 the EPA set a maximum level of 500 ppm by mass of sulfur with a cetane index greater than 40 and a maximum limit on aromatic content of 35% by volume for diesel engine fuels. California had more stringent standards than the EPA for diesel engine fuels, namely, 10% to 20% aromatic content for small and large refineries respectively, and a minimum cetane number of 50.

After 1993, researchers began to investigate the effect of lower sulfur content on PM emissions from diesel engines. Kantola et al. [18] investigated the effect of two diesel fuels on PM emissions. One was with 0.05% (500 ppm) and the other one was 0.01% (100 ppm) sulfur content by weight. A Cummins diesel engine, model LTA 10-300, was used for the experiment operated at EPA steady-state modes 9 and 11. Both mode 9 and 11 were at the rated speed and at 75% and 25% of the rated torque, respectively. At the high load mode, low sulfur fuel produced 25% less PM than the high sulfur, while there was no significant change on the low mode.

Rao et al [19], investigated the effect of sulfur content on a Ford 1.8L Sierra turbo-diesel using the FTP75 emission test and Highway Fuel Economy Cycle. Number 2 diesel fuel with 0.2% (2000 ppm) sulfur content by weight was used as a baseline fuel. Two diesel fuels were used with 0.05% (500 ppm) and 0.001% (10 ppm) sulfur content by weight. The two low sulfur diesel fuels produced 15% and 20% less PM emissions than the baseline fuel respectively.

Rao et. al [20], repeated the same experiment but with a catalyst, and reported a 10% and 20% less PM emissions over the baseline fuel. The reduction was based on PM emission upstream of the catalytic converter.

In another study, diesel fuel sulfur content was investigated at high altitude using the EPA certification test [21]. Five diesel fuels were used with 5, 100, 200, 315 and 500 ppm sulfur content. The 5 ppm sulfur content fuel produced only 6% PM emission less than the 500 ppm fuel.

Over a range of different engines and different emissions test cycles used in these studies, the effect of low sulfur content fuel was generally a reduction in PM emission level.

Other studies showed the effect of aromatic content and sulfur content on PM emissions. Johansson et al [22], tested a combination of fuels with different sulfur of (253 ppm, 266 ppm, 2.1 ppm) and aromatic contents of (21.3%, 13.2%, 1.13%). The tested vehcile was VW Golf 1.6 L using FTP 75 as a test emission cycle. The author reported that the fuel with 253 ppm sulfur content and 21.3% aromatic content emitted 0.23 g/km of PM compared to 0.218 g/km from the fuel with 266 ppm sulfur content and 13.2% aromatic content. The difference in PM emission was due to the aromatic content difference, not the sulfur content.

Neill et al. [24], of National Research Council Canada (NRC) did a similar study to this research. The author compared the emissions of a single cylinder diesel engine, Ricardo Proteus, using eight fuels and an 8 mode AVL emission test. The fuels were divided into three sets. Each set has the same density but different aromatic and sulfur content. The aromatic content was from 14.3% to

39.0%, while sulfur content varied from 7 to 485 ppm. The study determined that PM emissions resulting from the difference between the fuels were insignificant. The PM emissions varied from 0.078 to 0.089 g/hp-hr.

Reynolds [25] tested two diesel engines and eight fuels on the ECE R49 test cycle. The sulfur content was 430 ppm, 423 ppm, 420 ppm and 97 ppm. The aromatic content varied from 14.9% to 24.2%. The tested engines' power were 186 kW at 2050 rpm and 298 kW at 1800 rpm. The author reported that PM reduction from engine 1 was insignificant but engine 2 produced 5% less PM emissions running on low sulfur diesel.

The most influential fuel properties were aromatic content, cetane number, sulfur content and some other physical properties such as density, viscosity and boiling points [25,26]. Lee et al. [23], highlighted that engine technology and fuel properties are a key factor in PM emission from diesel engines.

In summary, some studies reported that low sulfur/aromatic diesel had no effect on PM emission while other studies reported that it reduced PM emission from diesel engines. Some other studies reported that sulfur content is not the only factor that affects PM reduction from diesel engines. It was reported that engine technology and other fuel properties were important in PM emission from diesel engines.

This study was sponsored by Alberta Environment to investigate the different between oil sand fuels and conventional crude. Readers may refer to Alberta Environment report for more detailed information [27].

2.3 Experiment Setup

2.3.1 Fuel Properties

One high sulfur/aromatic and one low sulfur/aromatic fuel were used to perform emission testing. These fuels were typical commercially available from Esso, and Shell in the province of Alberta, Canada. The high sulfur/aromatic fuel was derived from conventional crude oil, while the low sulfur/aromatic, synthetic fuel, was derived from oil sands crude. Typically, the conventional fuel was expected to contain 500 ppm sulfur and the synthetic fuel was expected to contain 50 ppm sulfur. In both fuels, the sulfur content was higher than reported by supplies (114 ppm and 837 ppm compared with 50 ppm and 500 ppm the reported by the supplier). These values were confirmed by retesting a sample from both fuels in Alberta Research Council, Edmonton Alberta, for fuel properties analysis.

The two fuels were also significantly different in total aromatic content and polycyclic aromatic content. Table 2.1 lists the results of these tests.

Table 2.1: Fuels Properties List.

Standard	**Property**	**Esso #2 "conventional"**	**Shell CP 43 "Synthetic"**
ASTM D613	Cetane Number	40.9	40.2
ASTM D4052	Density at 15 C	846.6 kg/m^3	843.5 kg/m^3
ASTM D5453	Sulfur	837 ppm	114 ppm
ASTM D5291	Carbon	86.46 %	86.36
	Hydrogen	12.99 %	13.45
ASTM D4629	Nitrogen	177 ppm	59.2 ppm
CAN/CGB 3.0#15.0 Supercritical Fluid Chromatography	Polyaromatics	2.1 %	0.4 %
	Diaromatics	10.4 %	4.0 %
	Monoaromatics	21.6 %	19.4 %
	Total Aromatics	34.1 %	23.8 %
ASTM D86	Initial Boiling point	151.7 °C	156.8 °C
	5%	168.6 °C	172.3 °C
	10%	177.2 °C	181.3 °C
	20%	192.3 °C	195.5 °C
	30%	209.0 °C	210.4 °C
	40%	227.2 °C	226.3 °C
	50%	244.7 °C	243.2 °C
	60%	260.8 °C	259.8 °C
	70%	277.9 °C	276.3 °C
	80%	297.5 °C	292.9 °C
	90%	324.2 °C	312.9 °C
	End Point	355.5 °C	345.9 °C
	Residue	1.0%	1.0%
	Loss	0.8%	0.5%

2.3.2 Test Vehicles/Engines

Four heavy-duty diesel engines, one medium duty and one light duty engine were used for testing. Table 2.2 provides a list of the tested engines. These vehicles/engines represent the majority of the Province of Alberta fleet. In addition, they cover different ages and different engine manufacturers for technology diversity.

Table 2.2: Test Vehicles/Engines List.

	Vehicle Type	**Engine Model**	**Engine Rating (hp/rpm)**	**Aspiration**	**Odometer km**	**Test Date**
1	2000 Kenworth T800B	Cummins N 460E	460/2100	Turbo charged intercooled	151200	Feb. 21 2001
2	Kenworth T700	Detroit Diesel Series 60	425/2100	Turbo charged intercooled	143000	Feb. 26 2001
3	1988 Kenworth T600A	Caterpillar 3406	400/1800	Turbo charged intercooled	946400	Feb. 27 2001
4	1993 Kenworth	Detroit Diesel Series 60	430/2100	Turbo charged intercooled	931200	March 1 2001
5	1993 Dodge Ram 250	Cummins LT10	200/2500	Turbo charged intercooled	235100	March 15 2001
6	1993 Isuzu ELF 250	Isuzu 4BE1	130/3500	Naturally Aspirated	N/A	March 21 2001

2.3.3 Emission Test Cycle

A modified Japanese 6-mode test cycle was used to evaluate exhaust emission for the two fuels. The Japanese 6-mode test was a certification test standard for Japan. Although it is no longer used for certification, it is a good comparison tool of emissions from different engines and different fuels as well as performance investigation of exhaust after-treatment devices. Table 2.3 and Fig 2.1 provide a description of the Japanese 6-mode test. Each mode of the test represents an operation mode in a typical driving pattern in a Japanese city. The weighting factors represent each mode contribution to the final test result.

Table 2.3: The Japanese 6-mode Test

Mode Number	**Speed (% of Rated Speed)**	**Torque (% of Max Torque)**	**Weighting Factor**
1	idle	idle	0.355
2	40%	100%	0.071
3	40%	25%	0.059
4	60%	100%	0.107
5	60%	25%	0.122
6	80%	75%	0.286

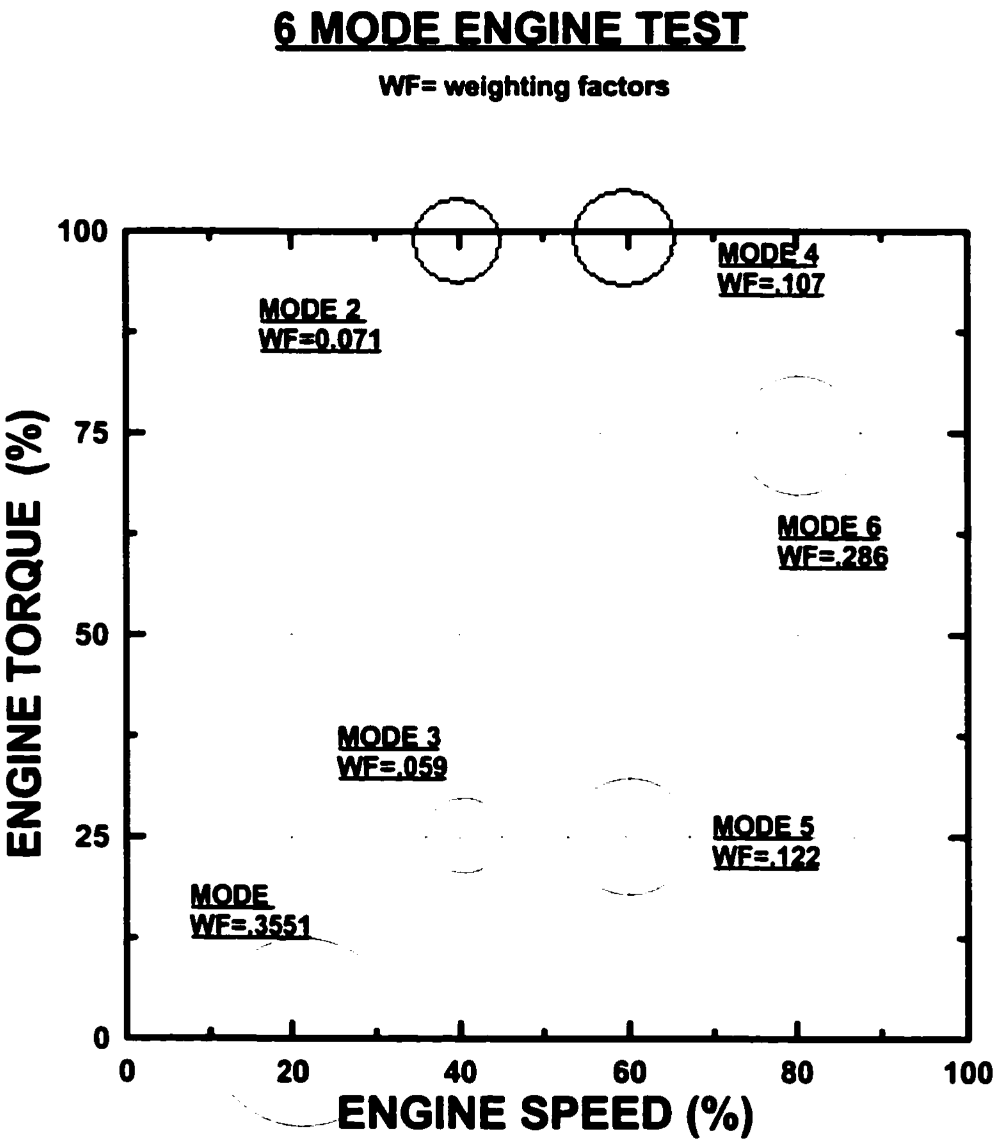

Figure 2.1: 6-Mode Test

The six modes would represent the following:

1. Idle : stop in a traffic signal or during pickup/delivery, (35.5%).
2. Mode 2: lugging, high torque low speed, (7.1%).
3. Mode 3: low speed cruise. low speed low torque, (5.9%).
4. Mode 4: acceleration, max load medium speed, (10.7%).
5. Mode 5: high speed cruise, low load medium speed, (12.2%).
6. Mode 6: hill climbing or full load highway, full load at high speed, (28.6%).

The summation of the weighting factors is 100%, hence, the weighted parameter would be calculated as in Equation (2.1):

$$Y_{total} = 0.355*Y_1 + 0.071*Y_2 + 0.059*Y_3 + 0.107*Y_4 + 0.122*Y_5 + 0.285*Y_6 \qquad 2.1$$

where Y is the measured parameter and the subscripts indicate values for each mode.

2.3.4 Measurement Equipment

The measured engine parameters were speed, torque, air consumption, fuel consumption, exhaust gas composition and PM emission concentrations. Table 2.4 provides a list of the measurement equipment.

Table 2.4: Measurement Equipment

Parameters	**Equipment**	**Range**	**Resolution**
Engine Torque	Eddy-Current MidWest Dynamometer Model 1014A	0 to 1000 Nm	1 Nm
Engine Speed		0 to 10000 rpm	1 rpm
Air consumption	SAE J244	0 to 1380 Pa	0.5 %
Fuel consumption	Pacific scale Model 550	0 to 60 Kg	5 g
Exhaust Temperature	K-Type thermocouple	0 to 1260 °C	0.9 °C
Other Temperature	T-Type thermocouple	-59 to 93 °C	0.9 °C
PM (darkness filter method)	AVL 415 smoke meter	0 - 31999 mg/m^3	1 mg/m^3
PM scale (filter weight method)	A&D model Gr-202	42 g	0.01 mg

Dynamometers

Three dynamometers were used to cover this range of vehicles/engines. Vehicles 1 to 4 were tested using a chassis dynamometer for heavy duty trucks at Waterous Detroit Diesel engine in Edmonton. Vehicle number 5 was tested using a light-duty chassis dynamometer at the University of Alberta. Test number 6 was conducted at University of Alberta using an engine dynamometer.

Air Measurement

A standard ASME nozzle and two Siemens air mass flow meters were used to measure engine air consumption. The ASME standard nozzle uses a 220 litre air drum with two nozzles. The diameters of the nozzles were 73.60 mm and 63.59 mm respectively. The pressure difference between the air drum and the ambient pressure was measured by a Validyne type CD 75 pressure transducer with 1380 Pa range. The air consumption was calculated directly from the pressure difference according to SAE Recommended Practice J244. The calculation procedures followed those of Nowak [29]. The 220 L drum was used to measure air consumption for test number 6.

The Siemens mass air flow sensor uses the principle of temperature compensated hot film anemometer. The two Siemens sensors were calibrated against the ASME nozzle.

The two Siemens sensors were used in parallel for measuring air mass flow rate consumed by vehicles 1 to 4, while one Siemens sensor was used for vehicle number 5.

Fuel Consumption

The fuel mass consumption was measured by a Pacific Scale Model 550 and a stop watch. Scale specifications are provided in Table 2.4. One reading was taken at the beginning of each mode. A second reading was taken after 3 to 5 minutes. The net mass consumption is the difference between the two readings. The accuracy of mass flow is highly dependent on the duration of each mode. The mass flow rate was calculated by dividing the net mass consumption by the duration of each mode.

Two separate drums were used as fuel tanks for the vehicles/engines to eliminate fuel contamination. On switching from one fuel to the other the vehicles/engines were run for 10 minutes to purge the fuel system by burning the remaining fuel in the lines. Three feed pumps were used to deliver fuel to the vehicles fuel system, as shown in Figure 2.1. The three feed pumps were connected to suction and delivery manifolds. Diesel fuel was pumped from the tank to the delivery manifold then into a primary filter in the engine fuel circuit. The return line from the vehicles was cooled using a water cooled copper coil, then delivered to the returned to the suction manifold.

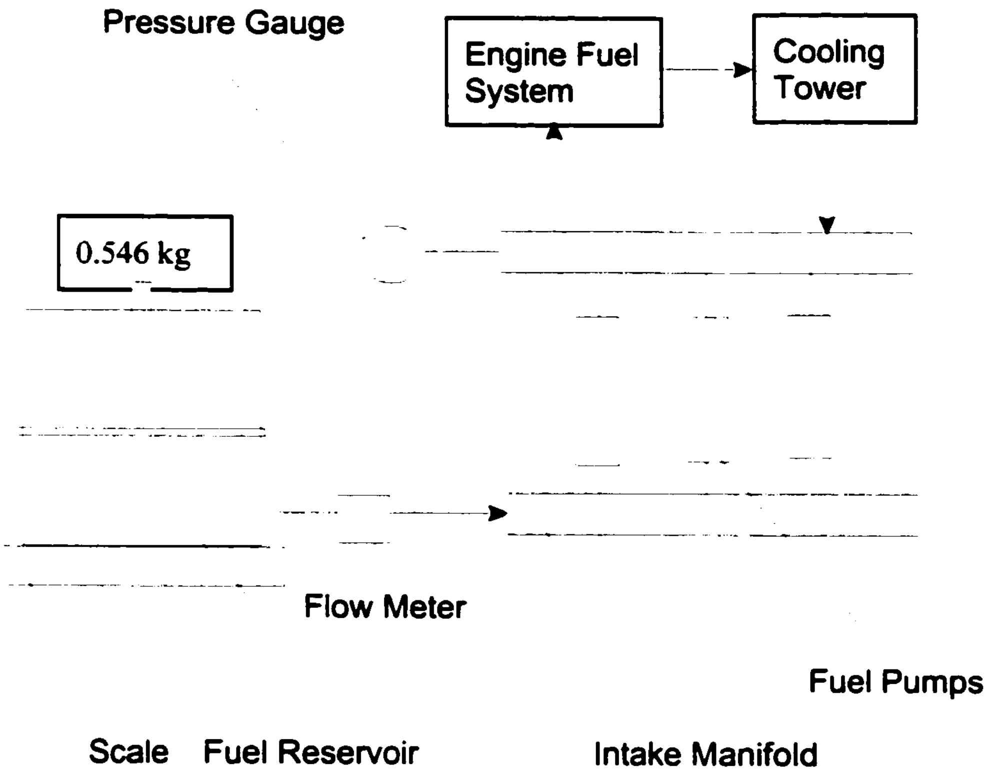

Figure 2.1: Fuel Flow Measurement Circuit

PM Measurement

PM emission rate was measured using two techniques: a filter mass measurement and an AVL 415 smoke meter. Specification of PM scale and AVL are provided in Table 2.4. The first technique measures the PM collected from an exhaust sample on a fibrous filter by weighing the filter before and after the experiment, while the second measures the opacity of a paper filter after a specific volume of exhaust was passed through. The opacity is then calibrated to provide PM weight. The filter mass measurement was used because filter mass measurement is a direct measurement of the particulate mass, while the other method is indirect.

a) Mass filter measurement

The filters used in the test were pre-conditioned in an environmental chamber prior to and after the test. The purpose of this chamber is to maintain the filters at a certain temperature and humidity before and after the sample process for accurate measurement. For example, the humidity absorbed by the filter will not add weight to the collected PM.

An exhaust sample and filtered dilution air were drawn through stainless steel and Teflon tubing using a vacuum pump. The sampling process was run for 3 minutes in the smokier modes, high load, and for 5 minutes in relatively clean modes. Dilution air was used to cool down the sample to simulate the dispersion of exhaust in the atmosphere. The dilution ratio varied from 1.5:1 to 14:1. Both the total sample and the dilution flow rates were measured by mass flow meters. The combined sample was passed through the fibrous filters, as shown in Figure 2.2. The fibrous filters were pre-conditioned, again, before weighing to determine the net weight of PM collected from this sample within the sampling time.

At the University of Alberta a dilution tunnel was used instead of the dilution pump, as shown in Figure 2.3. The dilution ratio varied from 2:1 to 10:1 because the fan delivers a constant air flow while the discharged exhaust varies according to engine rpm. The dilution ratio is determined by dividing the concentration of CO_2 without dilution by the diluted value.

b) AVL Smoke Meter

AVL model 415 smoke meter was used to measure the PM concentration in the exhaust. The smoke meter draws a known volume of exhaust through a Teflon line through a white paper filter. The change of light reflectivity is proportional to the amount of PM collected on the filter surface. It is then correlated to a mass of PM per volume of exhaust in g/m^3.

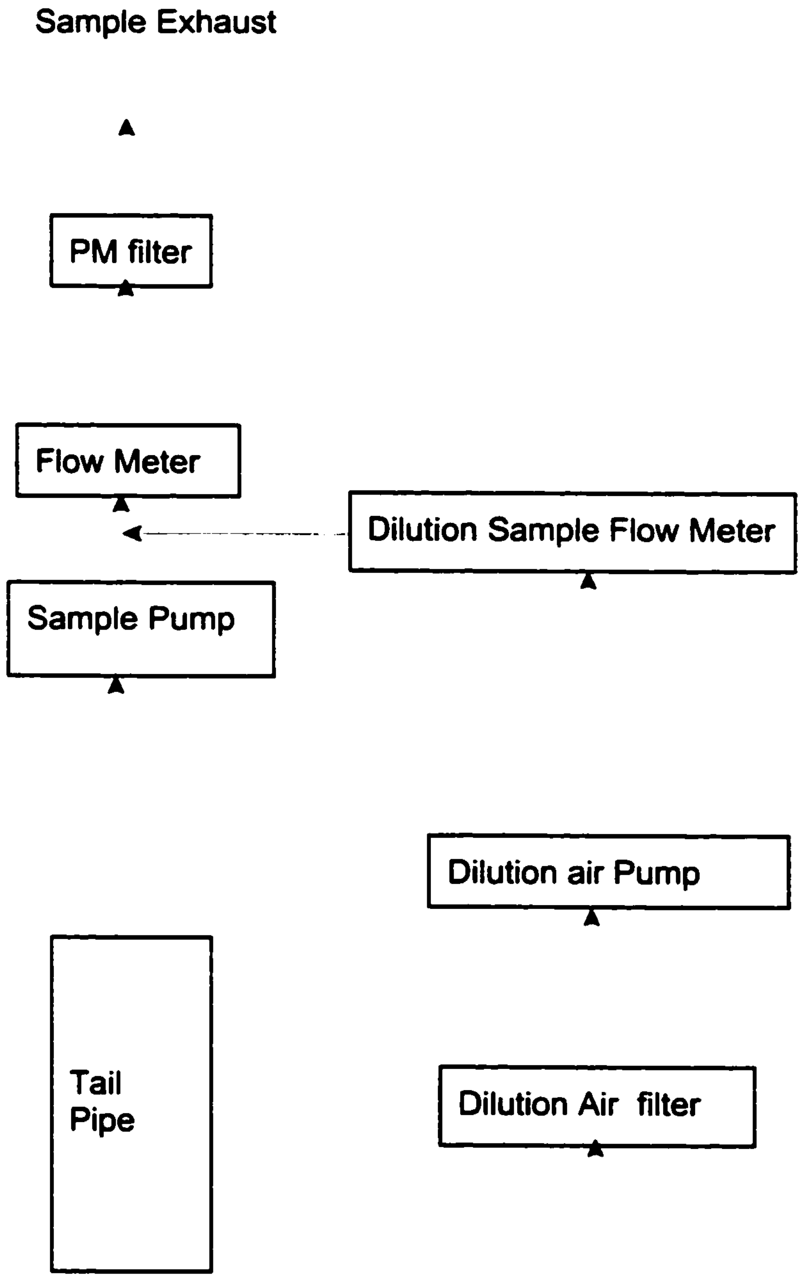

Figure 2.2: PM Sampling System

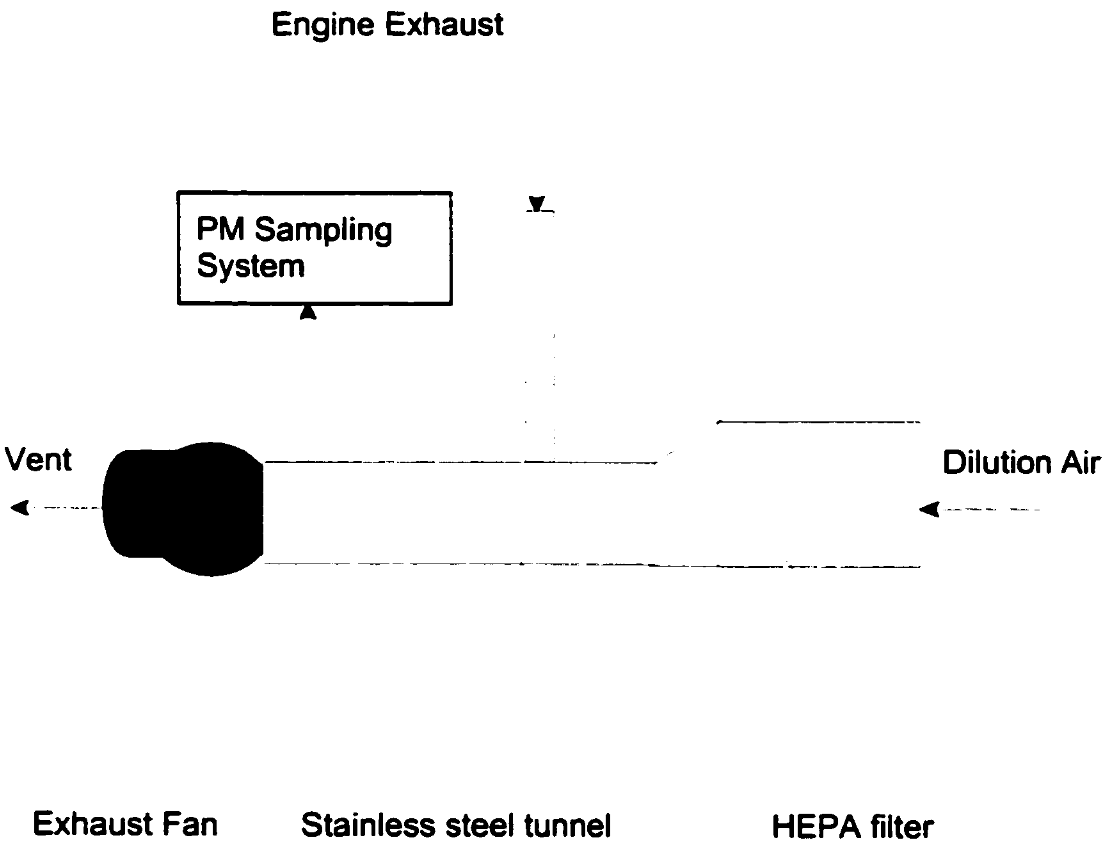

Figure 2.3: Schematic of Dilution Tunnel at University of Alberta

Exhaust Composition measurement

A Vetronix 5 gas analyzer and a set of California Analytical gas analyzers were used to measure the exhaust gas compositions. The Vetronix 5 gas analyzer was used at Waterous, for vehicles/engines 1 to 4, while both analyzers were used at University of Alberta for vehicles/engines 5 and 6. The specifications for the analyzers are shown in Table 2.5 and 2.6. Both were calibrated using calibration gases. The sampling circuits are shown in Figure 2.4 and 2.5.

Table 2.5: Vetronix Specifications (Model 1100)

Gas	**Rang**	**Resolution**
NOx	0-4000 ppm	1 ppm
HC	0 - 20,000 ppm	1 ppm
CO_2	0 - 20%	0.1 %
CO	0 - 10 %	0.01 %
O_2	0 - 25 %	0.01 %

Table 2.6: California Analytical Gas Analyzer Specifications

Instrument	Gas	Principle	Range	Calibration
California Analytical 300 CLD	NOx	CLD	0 to 3000 ppm NOx	Zero = N_2 Span = 2850 ppm
California Analytical 300M- FID	HC	FID	0 to 30,000 ppm CH_4	Zero = N_2 Span = 5140 ppm
California Analytical 300M- HFID	CH_4	FID	0 to 30,000 ppm CH_4	Zero = N_2 Span = 485 ppm CH_4
California Analytical 300	CO_2, high CO low CO	NDIR	0 to 20% CO_2 0 to 25,000 ppm CO 0 to 1,000 ppm CO	Zero = N_2 span =11.98% CO_2 Span = 5140 ppm CO Span = 485 ppm CO
California Analytical 100 P	O_2	P	0 to 30,000 ppm	Zero = N_2 span = 20.9% air

Chemiluminescent (CL)
Flame Ionization (FID)
Nondestructive Infra-Red (NDIR)
Paramagnetic (P)

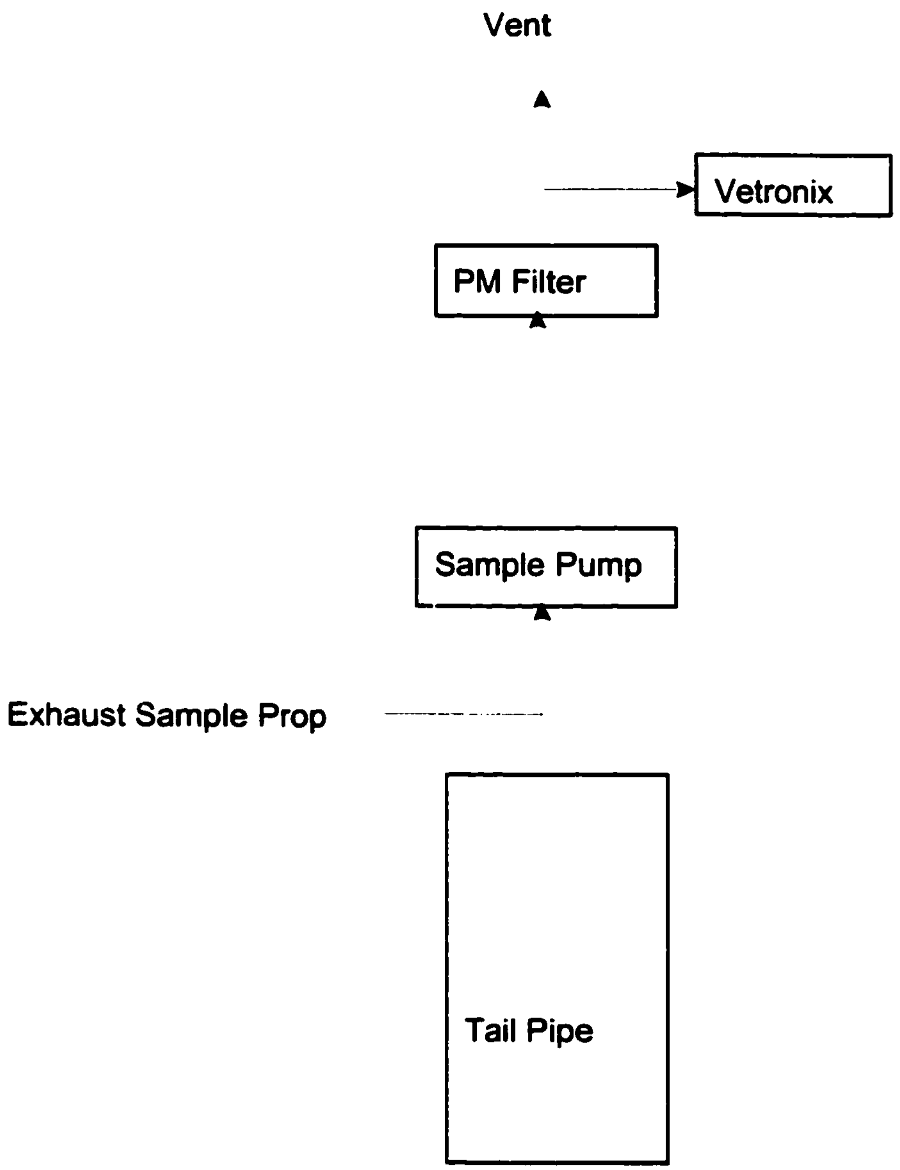

Figure 2.4: Emission Sampling Circuit (Waterous)

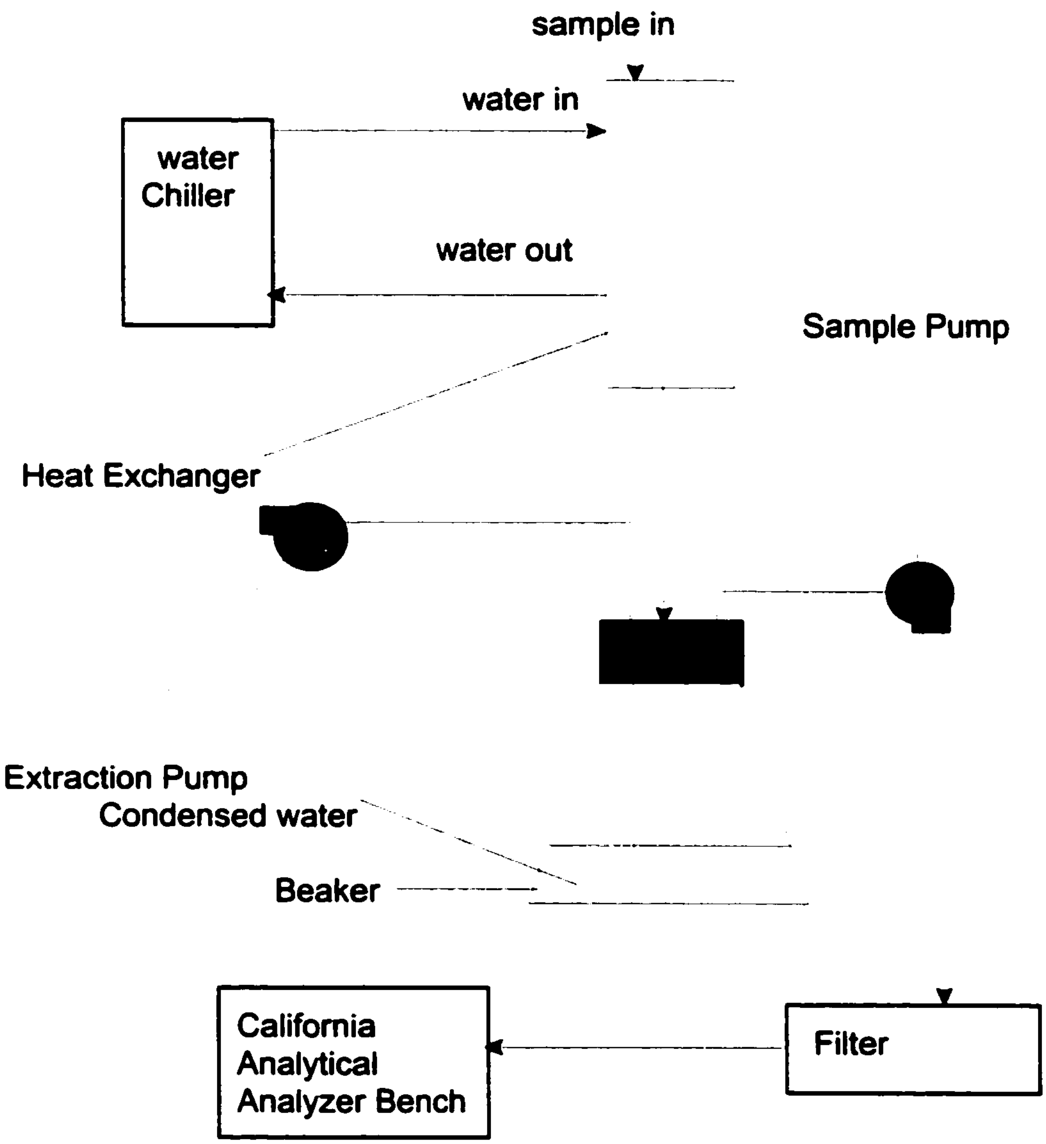

Figure 2.5: Exhaust sampling system (University of Alberta)

2.3.5 Test Conditions

The purpose of describing test conditions is to identify some the periodic problems that the test crew encountered. These problems are a potential source of error for the test results.

Weather Conditions

The first three trucks were tested in February. The temperature during this time of the year in Edmonton varied from -20 to 10 °C. The low temperature froze the sampling lines that led to missing gas analysis values for some of the modes. The AVL model 415 is designed to operate at room temperature and failed to give reading for the first vehicle test.

Experiment Setup

In waterous tests, very long sample lines were used for both AVL and scale method for PM measurement. The long sample lines froze-up and water bubbling problems that may affect the accuracy of the measurement.

2.4 Result and Discussion

2.4.1 Diesel Fuels

The two fuels were similar in most of their chemical and physical properties, as shown in Table 2.1. However, there was a significant difference in sulfur content, aromatic content, distillation range and slight difference in nitrogen content. Higher sulfur content, aromatic content and distillation range are generally associated with higher PM emissions [18,21,22,23]. The higher nitrogen content in fuel slightly increases NOx emissions.

Both fuels did not meet the manufacture specifications for sulfur content. The manufacture specifications for the synthetic fuel was 50 ppm and 500 ppm for the conventional fuel. The composition analysis results from Alberta Research Council found 114 ppm and 837 ppm sulfur content for the synaesthetic and conventional diesel fuel, respectively. These values were confirmed by reported testing.

The two fuels are significantly different in total aromatic, monoaromatics and diaromatics. For example, total aromatic was 23.8% for the synthetic fuel and 34.1% for the conventional fuel. The synthetic fuel had lower monoaromatics and diaromatics 19.4% & 4% compared to 21.6% & 10.4% for the conventional fuel.

Aromatics have the highest sooting tendencies among fuels because they contain double carbon-carbon bonds. High aromatic content is generally associated with PM emissions [24, 25].

Distillation range or boiling point range is an indication to fuel volatility. Higher volatile fuels are more reactive and produce less PM and unburnt hydrocarbon emissions [22, 23].

The nitrogen content was 177 ppm in the conventional fuel compared to 59 ppm in the synthetic fuel. This ratio is approximately 3:1. NOx emissions from the conventional fuel were slightly higher than the synthetic fuel because the major NOx formation mechanism was due to the thermal mechanism. As shown in Table 2.7, the average NOx emissions was 21.7 and 21.9 g/kg fuel from the synesthetic and conventional fuel respectively. The difference between NO from both fuel was 0.2 g/kg fuel. As per the calculations in appendix C, the conventional fuel emitted 0.252 g/kg fuel of NO more than the synthetic fuel due to the difference in nitrogen content in the fuel. The calculated number agreed with the experiment result. The calculations were done provided that all the nitrogen in the fuel would form NO.

Table 2.7: Weighted NOx Emissions

	NOx Emission in g/sec		**NOx Emission in g/kg fuel**		**NOx Emission in g/kW.hr**	
	Shell	Esso	Shell	Esso	Shell	Esso
Cummins N14 460 (1)	0.23	0.24	21.1	23.1	6.18	7.1
GM series 60 (1999) (2)	0.075	0.074	10.7	10.7	3.1	3.02
Caterpillar 3406 (3)	0.12	0.14	19.3	21	5.8	6.69
GM series 60 (1993) (4)	0.2	0.21	33	35.2	9.93	11.8
Cummins Pick up (5)	0.04	0.03	18.2	13.5	4.82	3.77
Isuzu 4BE1 (6)	0.58	0.84	27.8	27.8	7.78	8
Average	**0.21**	**0.25**	**21.7**	**21.9**	**6.3**	**6.73**

2.4.2 PM Emissions

The filter mass measurement was used because filter mass measurement is a direct measurement of the particulate mass, while the other method is indirect. Appendix C provides uncertainty calculations due to the resolution of the equipment used in the experiment. The calculated uncertainty was approximately ±3% for a single measurements and 1.2% for 6-mode average.

The average mode by mode emission results for all the engines were calculated and summarized in Table 2.8. Looking at data on a mode by mode basis demonstrates the relationship between operating condition and emission levels. It can be used as an optimization tool for air pollution control. For example, mode 2 (low engine speed high torque) produced 1.18 g/kW.hr soot while mode 6 (a similar power level at high speed) produced only 0.54 g/kW.hr on average.

For both the tested fuels, mode 2 (high torque and low speed) yielded 47 g/s the highest PM emission rates on average. Surprisingly, mode 1, idle, emitted the highest PM emissions, 5.78 g/kg fuel, followed by mode 2 emitted 4.48 g/kg fuel. At low speed modes the high torque associates with high PM emission.

For example, mode 2 emitted 4.48 g/kg fuel of PM and mode 3 emitted 2.74 g/kg fuel of PM on average. On the other hand, at medium speed modes, high torque associates with low PM emissions.

For example, mode 4 emitted 1.24 g/kg fuel of PM and mode 5 emits 2.77 g/kg fuel of PM on average.

Table 2.8: Average Mode by Mode Soot Emission Results

	Soot Emission in g/sec		Soot Emission in g/kg fuel		Soot Emission in g/kW.hr	
	Shell	Esso	Shell	Esso	Shell	Esso
A (1)	1.96	2.34	5.44	6.12	-	-
B (2)	45	49.8	4.45	4.52	1.13	1.22
C (3)	11.2	10.7	2.85	2.63	0.96	0.91
D (4)	14.9	16.5	1.22	1.26	0.30	0.32
E (5)	13.9	12.7	2.81	2.73	1.10	1.16
F (6)	9.32	19.6	0.97	2.11	0.31	0.76

Three engines demonstrated PM reduction by using the synthetic diesel fuel, while PM from the other three engines did not change.

The reduction was 70%,15% and 8% for engines/vehicles number 2, 4 and 6 receptively. Truck 2 had the highest PM emission 1.22 g/kW.hr and the highest reduction rate 70%, which it seemed very high compared to the reported reduction in the literature. From the literature, using low sulfur fuels led up to 25% reduction of PM emissions [18-21]. Clark et al. [30] reported in their literature review that 40% PM reduction was obtained due to using low sulfur fuel (0.005%) by weight. The weighted average of PM emissions for the six vehicles/engines were 0.744 g/kW.hr for the conventional fuel and

0.57 g/kW.hr for the synthetic fuel, as shown in Table 2.9. The reduction was approximately 24%. By excluding vehicle 2, they were 0.651 g/kW.hr and 0.613 g/kW.hr respectively. The reduction was approximately 6%.

The other engines/vehicles that did not exhibit any PM reduction were engines/vehicles number 1, 3 and 5, and these results agree also with the literature [22-24].

The average PM emission is 2 g/kg fuel and generally more than 50% PM is soot. According to the calculations in appendix C, if all the sulfur in the fuel is oxidized, it would produce 2.51 g/kg fuel. It can be concluded that not all the sulfur was converted to sulfate and most of the sulfur will be emitted in another form, for example SO_2. Therefore, using low sulfur diesel does not necessary reduce PM emissions. The amount of sulfate condensed on soot particles depends upon the conditions inside the combustion chamber and exhaust system of engines. A certain amount of sulfate was condensed on soot particles due to residence time, temperature constraints and engine technology. Therefore, reducing sulfur content will not always lead to PM reductions, as shown in Table 2.9.

In brief, from this investigation the average PM reduction due to low sulfur/aromatic diesel fuel was 24% including vehicle 2 and 6% excluding the same vehicle. Vehicle number 2 were excluded because PM reduction was higher than reported in the literature. This is similar to some of the previous studies, as shown in the literature review.

Table 2.9: Weighted Average PM Emissions

	Soot Emission g/sec		**Soot Emission g/k fuel**		**Soot Emission g/kW.hr**	
	Shell	Esso	Shell	Esso	Shell	Esso
Cummins N14 460 (1)	14.6	13	1.39	1.24	0.389	0.382
*GM series 60 (1999) (2)	8.5	30.3	1.28	4.23	0.35	1.21
Caterpillar 3406 (3)	14.6	14.7	2.34	2.29	0.702	0.701
GM series 60 (1993) (4)	19.2	19.8	3.11	3.31	0.950	1.11
Cummins Pick up (5)	4.41	4.39	2	1.98	0.667	0.669
Isuzu 4BE1 (6)	1.85	1.97	1.39	1.49	0.360	0.394
Average	10.6	14	1.92	2.42	0.570	0.744
Average*	**10.9**	**10.8**	**2.05**	**2.06**	**0.613**	**0.65**

* the calculated average excludes vehicle 2.

2.5 Literature Review Summary

Particulate matters with 10 microns in aerodynamic diameters (PM10), or higher, are less of a health hazard. $PM_{2.5}$ or less reach the lungs causing lung inflamation, blocking the area where the oxygen transfer occurs and causing cancer in animals.

96% of the PM emission from diesel engines is in the range of $PM_{2.5.}$ High injection pressure of diesel fuel reduces PM mass emission significantly but increases the NOx emission from diesel engines.

PM traps are used as exhaust after treatment devices but they remain under investigation because of associated problems with the regeneration process. Some fuel additives are used to control the PM emission from diesel engines, however the high cost and the difficulties associated with commercialized usage limits their practicality.

Advances in oil refineries allow the control of diesel fuel properties for less PM emission from diesel engines. The effect of low sulfur/aromatic fuels varies from no effect to 40% less PM than high sulfur/aromatic fuels.

2.6 Conclusion

The purpose of this study was to investigate the effect of low sulfur/aromatic fuel on PM emission from diesel engines. Six vehicles/engines were used to cover different ages and different engine manufacturers for technology diversity. One high sulfur/aromatic and one low sulfur/aromatic diesel fuel were used. A modified Japanese 6-mode test cycle was employed to evaluate exhaust emissions for the two fuels.

Using low sulfur/aromatic fuel leads to a reduction of PM emissions from 3 vehicles/engines but the other 3 had no effect. The PM emissions reduction was 70%, 15% and 8%. Since 70% PM emissions reduction is very high compared to the reported in the literature, the average PM reductions were calculated including and excluding that value. The average PM reduction was approximately 24% and 6%, respectively. Both figures match data reported in the literature.

Using low sulfur/aromatic diesel does not definitely decrease PM emissions but it definitely does not increase PM emissions.

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Chapter 3

DOC Effect on NOx Emission from a Heavy Duty Diesel Engine

This chapter will form the basis of a paper to be submitted to SAE for publication.

Chapter 3

DOC Effect on NOx Emission from a Heavy Duty Diesel Engine

Abstract

Currently, diesel engines meet air pollution regulations mostly with the advances in engine technology and enhanced fuel properties. A new regulation for North America has been proposed for the year 2004. Due to the PM-NOx tradeoff and the limited effect of fuel properties on NOx emissions, exhaust after treatment is proposed to meet the future regulation. Diesel oxidizing catalysts (DOC), which are one of the exhaust after treatment technologies, have been successfully employed in diesel engines to control CO, HC and PM emissions. However, the DOC effect on NOx emission from diesel engines is not certain. The objective of this study is to experientially investigate the effect of DOC on NOx emission from diesel engines.

This study provides a literature review on the effect of engine technology, enhanced fuel properties and exhaust after treatment on NOx emission from diesel engines. This study shows that DOC increases NOx from the tested engine. The experiment was done twice and there was good agreement between the results. The Japanese 13-mode test was employed as the emission test cycle.

The weighted DOC effectiveness was -2.65% showing that on average NOx was increased by 2.65%. On low load modes DOC effectiveness dropped to -8.6% showing that significant increases in NOx emissions are possible.

3.1 Introduction

Diesel engines are reliable and efficient sources of power. However, they produce excessive amounts of NOx that contribute to the formation of acid rain and the production of ground level ozone and smog [1,2].

Diesel oxidizing catalysts have been effectively used to control CO, HC and PM. Most the studies done were to investigate the effect of DOC on CO, HC and PM but DOC effects on NOx were unobserved. A few studies reported the effects of DOC on NOx emissions from diesel engines. The reported DOC effectiveness varied from approximately -2% to 7%. Due to these inconclusive results, the purpose of this research was to investigate the effect of diesel oxidizing catalyst (DOC) on NOx diesel engine emissions.

3.2 Literature Review

3.2.1 Diesel Fuels

Takei et al. [3] investigated fuel properties effect on diesel engine emissions. Test fuels were prepared by blending and additive treatment. The tested vehicle was TOYOTA COROLLA with a naturally aspirated 2.0 liter diesel engine. The Japanese 10-15 and ECE+EUDC test cycles were employed [3]. The ECE+EUDC test cycle found that NOx emissions were 29% to 32% higher than the Japanese test cycle. PM emissions were 38% to 53% higher on the same cycles. NOx emission was slightly reduced using low aromatic content diesel fuel. NOx emission was not affected by any other properties.

Clark et al. [4] investigated the effect of aromatic content on NOx emissions using six diesel fuels and a Navistar V8 7.3 liter diesel engine model T444. The FTP transient federal test was employed [4]. The lowest NOx emission was 4.607 g/kW.h and was obtained from diesel fuel with 0.1 % aromatic content. The highest NOx emission level was 5.552 g/kW.h and was obtained from diesel fuel with 29% aromatic content. The reduction due to lower aromatic fuel was approximately 18%.

Neill et al. [5] of the National Research Council of Canada (NRC) studied the effect of aromatic content on NOx emission. The authors compared the emissions of eight fuels using one cylinder diesel engine model Ricardo Proteus on 8 modes AVL emission test cycle. The fuels were divided into three sets. Each set had the same density but different aromatic content and sulfur content. The study determined that the maximum NOx reduction due to using low aromatic content fuel was 6%. The rest of results were not significantly different with 95% level of confidence.

Reynold [6] tested two diesel engines: a turbo charged and a water cooled engine, using ECE R49 13 mode steady state and eight fuels. The lowest aromatic content was 15% and the highest was 28.7% by volume. NOx emissions from both engines were not affect by the difference in aromatic content. In brief, aromatic content in diesel fuel does not significantly affect NOx emissions.

3.2.2 Engine Technology

Engine technology, commonly referred to as in-cylinder technology, focuses on controling engine emissions within the combustion chamber. It can be achieved by reducing combustion chamber pressures, temperatures and the dilution of air fuel mixtures. Reducing combustion chamber temperatures and the dilution of air fuel mixtures suppresses NOx formation via the Thermal Mechanism. The following are some of the engine technology methods used to control NOx emissions from diesel engines.

Injection Timing

Injection Timing significantly affects diesel engine performance and emissions. It is also responsible for the maximum pressure and temperature of combustion. Advanced injection timing leads to higher combustion temperature. High temperatures lead to high NOx but low PM emissions. Retarded injection timing lowers the combustion temperature and reduces NOx but increases PM emission. Timing can be optimised for power, emission and fuel combustion [7,8].

Injection Pressure

Injection pressure and droplet size effects on exhaust emission have been investigated [8,9,10]. Injection pressure, droplet size and spray patterns are the factors that mostly affect exhaust emission the most. High injection pressure and small droplet size improve air/fuel mixing and reduce PM emission but increase NOx emission. Spray patterns includes injection angle and spray covering area. A good spray pattern improves air/fuel mixing and reduces ignition delay. Generally, any parameter that improves air/fuel mixing or increases combustion chamber temperature decreases PM but increases NOx emission.

The most effective way to control NOx without increasing PM emission is using split or pilot injection [11,12]. At first, a small amount of fuel is injected then the reminder is injected. The polite quantity ignites first with a limited heat release compared to the full amount of fuel. When the rest of the charge is injected it will ignite due to the high temperature in the combustion chamber but with a limited pressure rise. Another advantage of split injection is reducing the delay period. Split injection provides improved conditions for PM-NOx takeoff but neither NOx nor PM reduction is enough to meet the proposed emission for diesel engines.

EGR

Exhaust gas recirculation (EGR) is the most effective technique among engine technologies for NOx reduction [13,14]. The fresh air charge is diluted with exhaust to reduce the amount of oxygen in a combustion chamber. The advantage of EGR is the significant NOx reduction with minimal effect on specific fuel consumption. It was found that the optimum EGR to fresh air charge ratio is from 15% to 30% [13,14]. Generally, EGR increases initial charge temperature due to high exhaust temperature.

To overcome the increasing charge temperatures cooled EGR was proposed. Mattarelli et al. [13] reported that using cooled EGR NOx emission was reduced by 64% compared with 55% without cooling.

According to Yoshikawa et al. [15], the disadvantages of EGR include:

- Excessive EGR leads to high PM and HC emission.
- Soot buildups on intake manifold reduce intake air pressure. As a result, less power is generated.
- Soot carried in the blow-by gases deteriorates the lubricating properties of oil.

The author also investigated a filtered EGR to overcome soot buildup.

In brief, the negative effects of EGR led to using water/steam injection to reduce NOx emission.

Water/Steam Injection

Water/steam injection is applied to control NOx emissions from diesel engines. Manifold fumigation and stratified water-fuel injection are two methods of implementing this technique. Manifold fumigation is done by injecting water into the intake manifold. Stratified water-fuel is done by injecting water into the combustion chamber. Water injection reduces O molecules that produce OH radicals. OH radicals react with N_2 to form ON from the thermal mechanism. The evaporation of the injected water limits combustion chamber temperature.

It was reported that water injection led to 50% decrease of NOx emissions in diesel engines [16,17]. The advantage of water injection is it does not prompt PM emissions as EGR does. The disadvantage of water injection is that high specific fuel consumption.

Briefly, both fuel and engine technologies have limitations in meeting targeted NOx reductions. Therefore, exhaust after treatment will be considered.

3.2.3 Exhaust After Treatment

Plasma Treatment

the effect of plasma on NOx reduction was investigated [18.19]. NOx treatment can be achieved by chemical oxidation of NO to NO_2 or by chemical reduction via dissociation of NO to N_2 and O_2 [18]. The chemical reduction of NO is hard to achieve in mobile applications because it requires very high electrical energy to dissociate NO. Nonthermal plasma requires less power than thermal plasma but it oxidizes NO to NO_2 [18]. The conversion of NO to NO_2 requires additional NO_2 treatment. In power plant application NO_2 is controlled by scrubbing.

Penetrante et al. [19] applied plasma along with a catalytic converter to control NO_2. The author pointed out that using plasma might lead to more NO formation. The dissociation energy of O_2 is smaller than N_2. Hence, N and O radicals will be generated. Both radical will react to form more NO.

Catalytic Converter

There are three types of diesel engines Catalytic converters

- Diesel Oxidizing Catalyst (DOC)
- Selective Catalyst Reduction (SCR)
- Absorption Catalyst

Oxidizing Catalyst

Most of the studies done on diesel catalysis did not address catalyst effect on NOx emissions. They generally focused on CO and HC [20,21]. Oxidizing catalysts use the excess air in diesel engine exhaust to oxidize CO, HC, Poly aromatic hydrocarbons (PAH), and aldehydes as following [1]:

$$CO + O_2 \longrightarrow CO_2 \qquad 3.1$$

$$HC + O_2 \longrightarrow CO_2 + H_2O \qquad 3.2$$

$$PAH + O_2 \longrightarrow CO_2 + H_2O \qquad 3.3$$

$$\text{Aldehydes} + O_2 \longrightarrow CO_2 + H_2O \qquad 3.4$$

The other concern, from studying oxidizing catalysts was PM reduction. Oxidizing catalysts oxidize Soluble Organic Fraction (SOF) to reduce PM emissions from diesel engines. Studies have reported that some catalysts increased PM emissions by oxidizing SO_2 to sulfate; sulfate is a PM constituent in addition to soot and SOF. Sulfate will react with water to form sulfuric acid. Sulfuric acid causes catalyst poisoning. It was reported that

Platinum-based catalysts form sulfate at lower temperatures than Palladium-based catalysts [22,23,24].

Hansen et al. [24] reported 1% effectiveness for NOx by using DOC. A steady state 5 modes test was employed using a 200 kW bus engine. The purpose of the study was to examine the effect of exhaust after treatment technology on emissions from construction equipment [25]. DOC was used in a dump truck, powered by 210 hp IH engine model DT 466 and IH bulldozer model TD 25 G, powered by 450 hp Cummins' engine. The DOC effectiveness was -2% for the bulldozer, and no effect for the dump truck was reported. Both catalysts were platinum based.

The effect of DOC on NOx emission from a light duty and heavy duty diesel engine was investigated [26]. A diesel passenger car model V W Golf and Volvo diesel engine and three different fuels were used for the test. The emission driving cycles were A13 for the passenger cars and steady state ECE R49 test for the diesel engine. A13 is similar to FTP 75. The same catalyst was used for both applications. The DOC NOx effectiveness for the passenger car was 3% using the reference fuel, while there was no effect using the other two fuels. The DOC NOx effectiveness for the heavy duty engine was 7% and 17% using the second and third fuel, while there was no effect using the reference fuel. The tested fuels had different sulfur content and aromatic content.

Ainslie et al. [25], in his literature review, reported that the maximum DOC efficiency was 15% using the new European driving cycle. Other studies reported that DOC has no effect on NOx reduction [27,28].

In conclusion, oxidizing catalysts did not show reliable NOx reduction efficiencies.

Selective Catalyst Reduction (SCR)

Ainslie et al. [25], in his literature review, summarized the advantages and limitations of SCR technology. Since diesel engine exhaust has excess air, a reducing agent is needed to react with NO. A chemical reaction takes place between NO and that agent causing NO decomposition. The agents used were Urea, Ammonia, diesel fuel or hydrocarbon additives. The reported NOx conversion efficiency was approximately 65% for both urea and ammonia, while it was approximately 30% for hydrocarbon SCR [25]. The limitations of urea and ammonia are that extra storage tanks are needed. Furthermore, the ratio between NOx emission and Urea or Ammonia is crucial. An incorrect ratio will lead to catalyst poisoning and Ammonia Slip. The limitations of using diesel fuel as a reducing agent are low efficiency and more specific fuel consumption.

Absorption Catalysts

Absorption Catalysts are an emerging technology used in gasoline engines [25]. In gasoline engines NOx reduction is achieved due to the reaction between CO and HC. Unlike diesel engines, gasoline engines run on an equivalence ratio between [0.9 to 1.1], while diesel engines always run lean. This technology relies on the chemical absorption of NOx in lean mixture and a periodic regeneration in rich mixture. Since diesel engines run lean, the rich conditions are hardly achieved. Furthermore, rich conditions are associated with excessive smoke. Therefore, this technology remains under investigation.

Generally, the advantages and the disadvantages of exhaust after treatment techniques were covered in the literature except for DOC. The objective of this study to highlight the effect of DOC on NOx emission as a possible drawback.

3.3. Experimental setup and Measurement

3.3.1 Test Cell

An Isuzu diesel engine, model 4BE1 1993, was used to examine NOx levels using DOC. The engine specifications are listed in Table 3.1

Table 3.1: Engine Specification

Engine Model	**ISUZU 4BE1**
Aspiration	Naturally aspirated
Number of Cylinder	4
Bore x Stroke	105 x 105 mm
Power kW	100 kW
Displacement Volume	3636 cm3
Compression Ratio	17.5
Compression Pressure	3 MPa
Fuel Injection Type	Direct Injection
Fuel Injection Order	1-3-4-2
Fuel Injection Timing	17 BTDC
Fuel Injection Nozzle Type	Hole type, four orifices
Fuel Injection Pressure	18 MPA
Engine Cooling System	Water Cooled

An eddy current dynamometer, Midwest model 1014A, was used to load the engine. Engine speed and torque were controlled using a digital dynamometer controller and a digital throttle controller. Initially, the engine speed was set using the dynamometer throttle then a controller was applied to control the specified torque. Exhaust, coolant and oil temperatures, fuel consumption, air consumption, torque and speed were the engine measured parameters. Table 3.2 contains the equipment used to perform the measurements.

Table 3.2: Measurement Equipment

Parameters	**Equipment**	**Range**	**Resolution**
Engine Torque	Eddy-Current MidWest Dynamometer Model 1014A	0 to 1000 Nm	1 Nm
Engine Speed		0 to 10000 rpm	1 rpm
Air consumption	SAE practice j244	0 to 1380	0.5 %
Fuel consumption	Pacific scale Model 550	0 to 60 Kg	5 g
Exhaust Temperature	K-Type thermocouple	0 to 1260 °C	0.9 °C
Other Temperature	T-Type thermocouple	-59 to 93 °C	0.9 °C

Air consumption was measured by a 220-liter air drum with two ASME nozzles. The diameters of the nozzles were 73.6 mm and 63.59 mm respectively. The pressure difference between the air drum and the ambient pressure was measured by a Validyne type CD 75 pressure transducer with 1380 Pa range. The air consumption was calculated directly from the pressure difference according to SAE Recommended Practice J244. The calculation procedure is as shown by Nowak (1994) [29].

The engine exhaust temperature was measured using a Chromel-Alumel thermocouple, while the engine oil, coolant, wet and dry temperatures were measured using a Copper-Constantan thermocouple, as shown in Liu (2000) [30]. Fuel consumption was calculated using pacific scale. The fuel supply tank was instantaneously weighed by the scale. A voltage signal was sent to the data acquisition system. The volt signal corresponded to a specific fuel consumption, based on calibration equation. The calculated mass is divided by the sampling time to get the mass flow rate in grams per second. The fuel used in this experiment are Shell diesel fuel product number CP 43.

3.3.2 Emission Sampling Systems and Composition Measurements

The exhaust gas emission was cooled, filtered from PM and dried from moisture before the gas analysis process. At first, the sample was drawn to a cooling tower to cool the sample, as shown in Figure 3.1. the cooling tower is a stainless-steel coil with quarter inch tubing immersed in a four-gallon PVC container. The cooling fluid was an engine coolant. The cooling tower was connected to a refrigeration unit. The coolant temperature was maintained between 0 to 5 °C. The sample was expanded in a flask to allow the moisture to condensate. The condensated water was pumped out of the circuit, while the dry sample was pumped to a 5-micron filter for PM filtration. The sample was cooled, dried and filtered for more accurate measurements. The measured exhaust gas constituents were O_2, CO_2, CO, NOx, HC. Table 3.3 provides a detailed description of the instruments used for real time gas analysis of the tail pipe emissions.

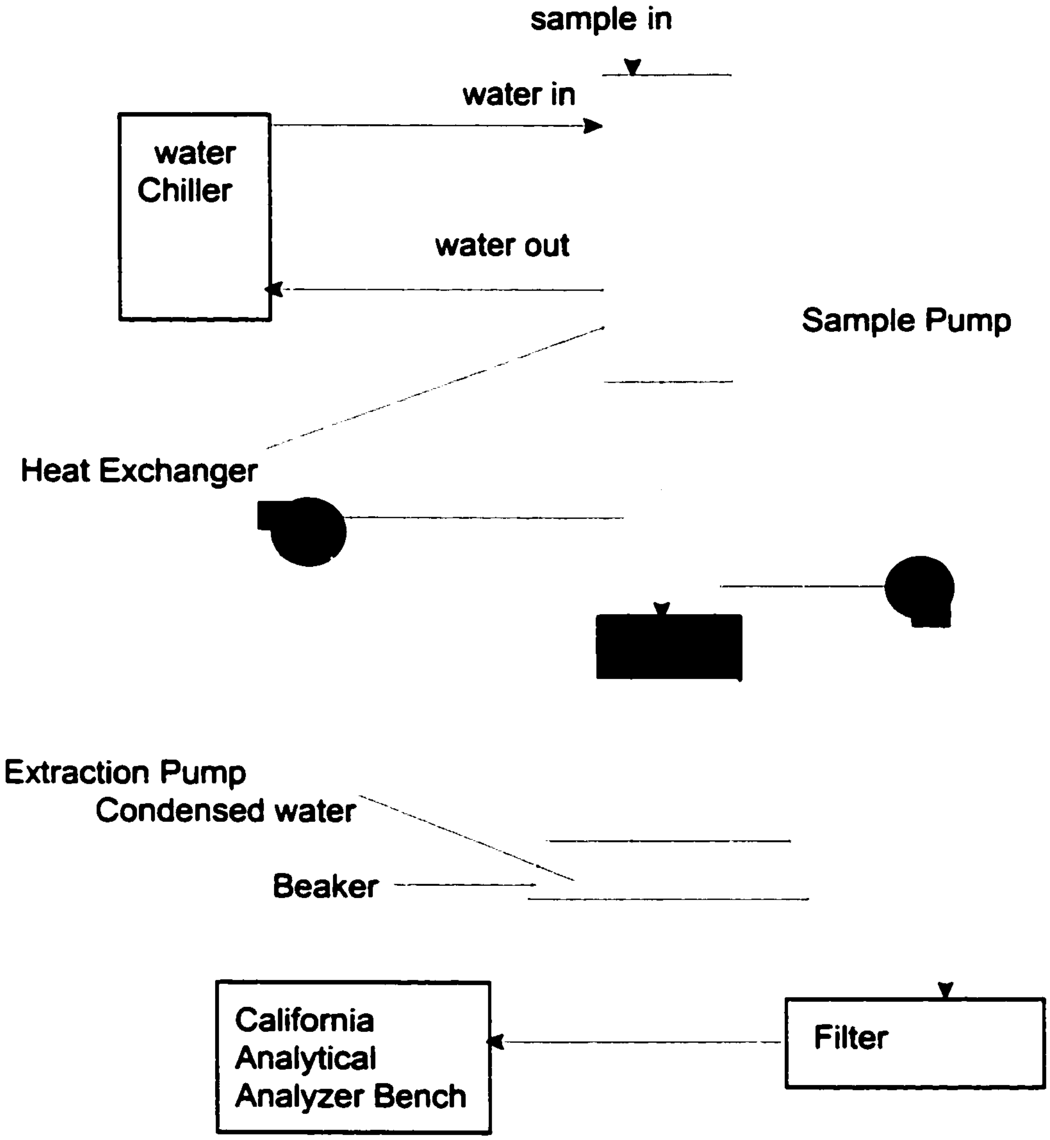

Figure 3.1: Emission Sampling Circuit

Table 3.3: Emission Equipment specification

Instrument	Gas	Dedication	Range	Calibration
California Analytical 300 CLD	NOx	CLD	0 to 3000 ppm NOx	Zero = N_2 Span = 2850 ppm
California Analytical 300M- FID	HC	FID	0 to 30,000 ppm CH_4	Zero = N_2 Span = 5140 ppm
California Analytical 300M- HFID	CH_4	FID	0 to 30,000 ppm CH_4	Zero = N_2 Span = 485 ppm
California Analytical 300	CO_2,	NDIR	0 to 20% CO_2	Zero = N_2 span =11.98% CO_2
	high CO		0 to 25,000 ppm CO	Span = 5140 ppm CO
	low CO		0 to 1,000 ppm CO	Span = 485 ppm CO
California Analytical 100 P	O_2	P	0 to 30,000 ppm	Zero = N_2 span = 20.9% air

Chemiluminescent (CL)
Flame Ionization (FID)
Nondestructive Infra-Red (NDIR)
Paramagnetic (P)

3.3.3 Emission Test Cycle

The Japanese 13-mode test is the official Japanese test cycle. Table 3.4 and Fig. 3.2 provide engine load and speed corresponding to each mode. From the table, the test consists of four load categories. Modes 11 and 12 represent the high load, modes 7, 8, 9 and 10 are medium-loads, modes 2, 3, 5, 6, 13 are low loads and modes 1 and 4 are idle. The weighting factor contribution is as follow:

Two idle modes constitute 41% of the weighing factor, 29.9% of the low load modes, 20.5 % of the medium loads then, 8.6% of the high load modes. It is obvious that low load modes have higher weighting factors than the high loading ones.

Table 3.4: Japanese 13-mode Test

Mode #	Load (%)	speed (%)	weighting factor %
1	0	Idle	20.5
2	20	40	3.7
3	40	40	2.7
4	0	Idle	20.5
5	20	60	2.9
6	40	60	6.4
7	40	80	4.1
8	60	80	3.2
9	60	60	7.7
10	60	80	5.5
11	95	60	4.9
12	80	80	3.7
13	5	60	14.2

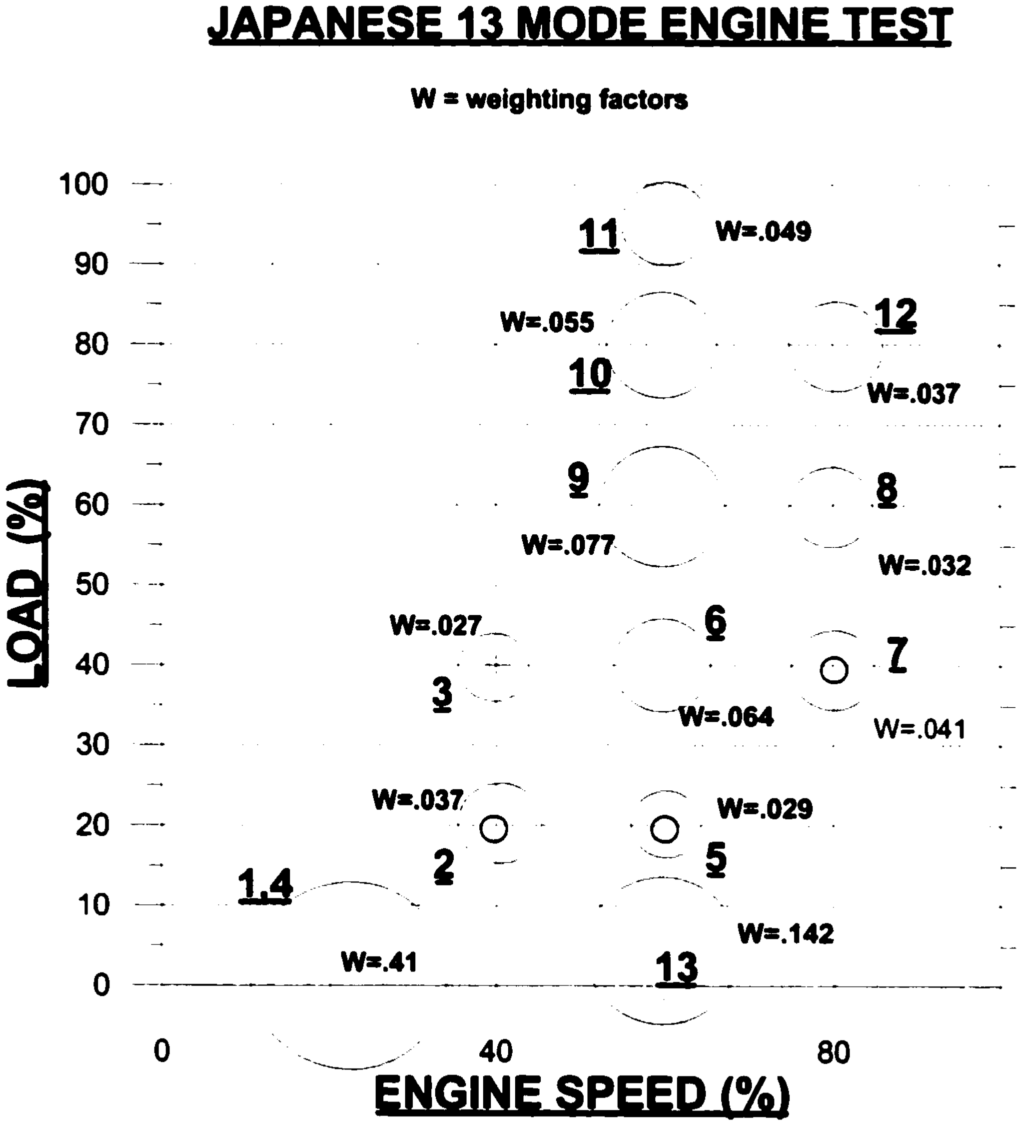

Figure 3.2: Japanese 13-mode Test

3.3.4 Catalytic Converter

In order to calculate catalytic converter effectiveness, upstream and downstream exhaust concentrations are needed. Upstream and downstream samples were drawn into the conditioning circuits as shown in figure 3.1. Then both sample lines, after conditioning, were connected to a 2-way solenoid valve. That valve directed only one sample to the analyser.

To assure stability, readings were recorded every five minutes for both upstream and downstream.

3.4 Results and Discussion

3.4.1 Diesel Fuel

The fuel used in this study is low sulfur diesel fuel, with 50 ppm sulfur content, derived form oil sands in northen Alberta, Canada. Low sulfur diesel is the standard in some European countries and the state California [30]. Furthermore, it is expected that low sulfur diesel fuels will be the standards for North America. The purpose of this study is to use a commercial fuel, not products in the research phase, to simulate the exact working operation conditions. The used engine was a 1993 model and the catalyst was an aged catalyst.

3.4.2 Test Cycle

The Japanese 13-mode test is the official Japanese test cycle and it is used in some of the Japanese studies [27,28]. The purpose of this study is to investigate the effect of DOC on NOx emission from diesel engines. The Japanese 13-mode test was chosen because it covers most of the engine operating conditions. The speed range is between 5 to 95% and the load is from 40 to 80%. These operation conditions will provide a good illustration for the catalytic performance at different loads and speeds. The Japanese 13-mode test replaced the Japanese 6-mode test. The main difference between the two, beside the number for modes, is that the idle weighting factor of the Japanese 13-mode test is higher than the 6-mode test. It is 0.41 for the 13-mode test compared with 0.355 for the 6-mode test.

The difference is attributed to the heavy traffic in most of the world capitals due to the rising number of diesel engines sales in the world. Two runs were conducted for experiment completion. Table 3.5 provides a summary for power and consumption.

Table 3.5: Power and Consumption on Japanese 13 mode Test Cycle

	Test 1	**Test 2**
Power (kW)	12.7	12.9
Fuel Consumption (g/sec)	1	1.03
Air Consumption (g/sec)	44.2	43.7

The maximum power recorded during the test was 43 kW, while the weighted power was 12.7 kW and 12.9 kW, respectively. Table 3.6 summarized test modes. The Japanese 13 mode test has two idle modes, each of which has 20.5% weighting factor. Idle modes are characterized with low exhaust temperate, low fuel consumption and insignificant power.

Table 3.6: 13-Mode Test Points

Mode Number	**Torque (N.m)**	**Speed (rpm)**	**Power (kW)**	**Weighting factor**
1	12.32	650 (idle)	~	20.5
2	46	1400	6.63	3.7
3	86	1400	12.8	2.7
4	11.2	650 (idle)	~	20.5
5	60	2100	13.6	2.9
6	74	2100	16.4	6.4
7	74	2800	22.1	4.1
8	108	2800	32	3.2
9	112	2100	24.9	7.7
10	150	2100	33.19	5.5
11	182	2100	40	4.9
12	145	2800	42.9	3.7
13	42	2100	9.2	14.2

3.4.3 DOC Effectiveness

The effect of DOC on the emissions from the 4 BE1 Isuzu diesel engine over 13-mode test was investigated. A low sulfur diesel fuel with 50 ppm sulfur content was used. The pollutants of interest were NOx, CO and HC. DOC increased NOx emission by 2.5% while it reduced CO and HC by 60% and 43% on average. Tables 2.7-2.9 provide a summary of the results. The uncertainty of 13-mode NOx emissions was approximately ±1.8%. Readers may refer to appendix C for detailed calculations.

Overall NOx Effectiveness

The calculated DOC effectiveness, for NOx reduction in this investigation, was -2.58 and -2.7%. From the literature, other studies reported -2%, 1%, 3% and 7 % [24,25,26].

Heywood [2], reported that no catalyst is available for NO decomposition to N_2 and O_2 at engine exhaust temperature. According to Heywood [2], NO reduction can be carried out under rich conditions where there is an excess of reducing species over oxidizing species. In case of low O_2 concentrations, the proposed reactions for NO reductions are:

$$NO + CO \longrightarrow CO_2 + N_2 \tag{3.5}$$

$$NO + C_nH_m \longrightarrow CO_2 + N_2 + H_2O \tag{3.6}$$

$$NO + H_2 \longrightarrow N_2 + H_2O + NH_3 \tag{3.7}$$

Table 3.7: 13-mode Test Results in g/sec

	Test 1			**Test 2**		
	U-stream	**D-stream**	**eff**	**U-stream**	**D-stream**	**eff**
CO	0.016	0.006	62.5	0.013	0.006	46
HC	0.005	0.003	40	0.004	0.003	25
NOx	0.03	0.031	-3.3	0.025	0.026	-4
CO_2	3.13			2.77		
O_2	8.33			7.46		

Table 3.8: 13-mode Test results in g/kg fuel

	Test 1			**Test 2**		
	U-stream	**D-stream**	**eff**	**U-stream**	**D-stream**	eff
CO	15.7	5.56	64.5	12.8	5.78	55
HC	4.89	2.53	48.3	4.23	2.76	34
NOx	28.9	29.7	-2.8	24.8	25.5	-3
CO_2	3041			2765		
O_2	8104			7449		

Table 3.9: 13-mode Test Results in g/kW.hr

	Test 1			**Test 2**		
	U-stream	**D-stream**	**eff**	**U-stream**	**D-stream**	eff
CO	4.48	1.59	64.5	3.64	1.63	55
HC	1.4	0.72	48.6	1.2	0.78	35
NOx	7.34	7.53	-2.6	7.01	7.2	-3
CO_2	871			781		
O_2	2321			2106		

Efficiency (eff)
Upstream (U-stream)
Downstream (D-stream)

Mode by Mode NOx Effectiveness

The DOC effectiveness on each mode was calculated. Tables 3.10-3.11, provide the values of DOC effectiveness for the two tests. In test 1, the minimum DOC effectiveness was -8.6%, while, in test 2, it was -7.6%. 2 and In general, low loads modes had the highest NOx formation.

The effect of DOC on NOx formation diminished on high load modes, as shown in Fig. 3.3. As previously discussed, NO reduction can be carried out under rich conditions where there is an excess of reducing species over oxidizing species. In high load modes, O_2 concentration, which is an oxidizing species, is less than low load modes. For example, comparing mode 2 and 3, both having the same speed, 1400 rpm, but different O_2 concentrations 16 and 13%. The high O_2 concentration, which is an oxidizing species, led to more NOx formation on mode 2 compared to mode 3, as shown in Fig 3.4.

The same result was obvious comparing modes 5 & 10. The O_2 concentration was 15% on mode 5 compared to 9.5% on mode 10. The high O_2 concentration led to more NOx formation on mode 2 compared to mode 3.

Yet, DOC had no effect on NOx decomposition due to the absence of reducing agents. As per 3.5 & 3.6, the reducing agents are CO or any hydrocarbon compound. As discussed in the literature, using an oxidizing catalyst for diesel engines requires reducing agents such as ammonia, urea and hydrocarbon for NOx reduction [25].

In summary, NOx reduction via DOC can not be achieved in diesel engine applications because the rich oxygen environment is not suitable for NOx decomposition [1,2]. Moreover, from the conducted test, using DOC led to more NOx emissions.

Table 3.10: DOC Negative Effectiveness on Japanese 13-mode Test Cycle (Test 1)

Mode Number	NOx Effectiveness	O_2 %	Speed (rpm)	Torque (N.m)
1	-5.5	17.7	650 (idle)	12
2	-8.6	16.2	1400	46
3	0.62	13.7	1400	86
4	-2.6	17.8	650 (idle)	11
5	-5.6	15.1	2100	60
6	-5.5	14.4	2100	74
7	-1.3	13.3	2800	74
8	-0.72	11.1	2800	108
9	-1.76	12.1	2100	112
10	-1.32	9.5	2100	150
11	2.8	7.2	2100	182
12	0.18	8.2	2800	145
13	-7.4	16.1	2100	42

Table 3.11: DOC Negative Effectiveness on Japanese 13-mode Test Cycle (Test 2)

Mode Number	**NOx Effectiveness**	O_2 %	**Speed (rpm)**	**Torque (N.m)**
1	-2.86	17.7	650 (idle)	12
2	-7.19	16.1	1400	46
3	-1.43	13.5	1400	86
4	-2.59	17.8	650 (idle)	11
5	-7.75	14.8	2100	60
6	-4.68	14.2	2100	74
7	-3.36	13.4	2800	74
8	1.4	10.9	2800	108
9	-3.5	12	2100	112
10	-0.73	9.9	2100	150
11	-2.69	7.84	2100	182
12	0.77	8.41	2800	145
13	-4.75	16.3	2100	42

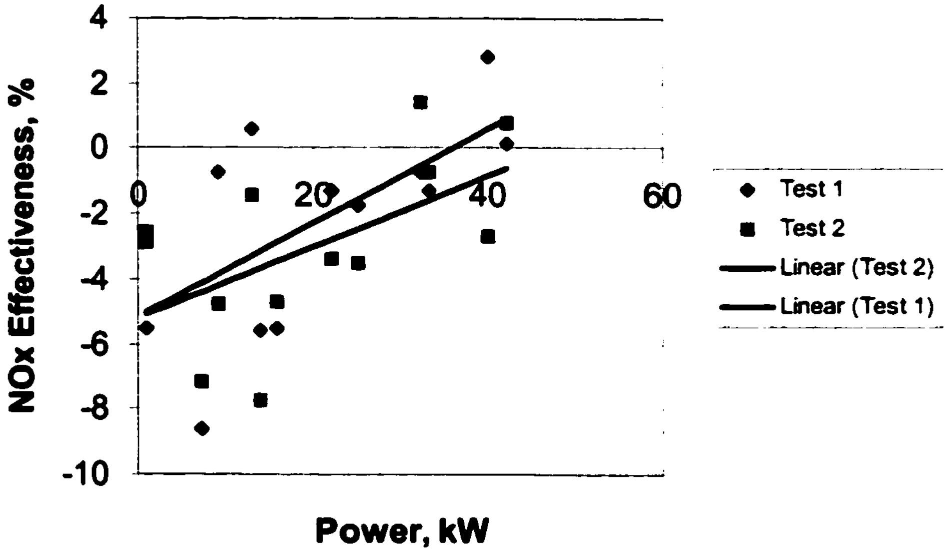

Figure 3.2: NOx Effectiveness Tends to be Negative at Low Engine Power

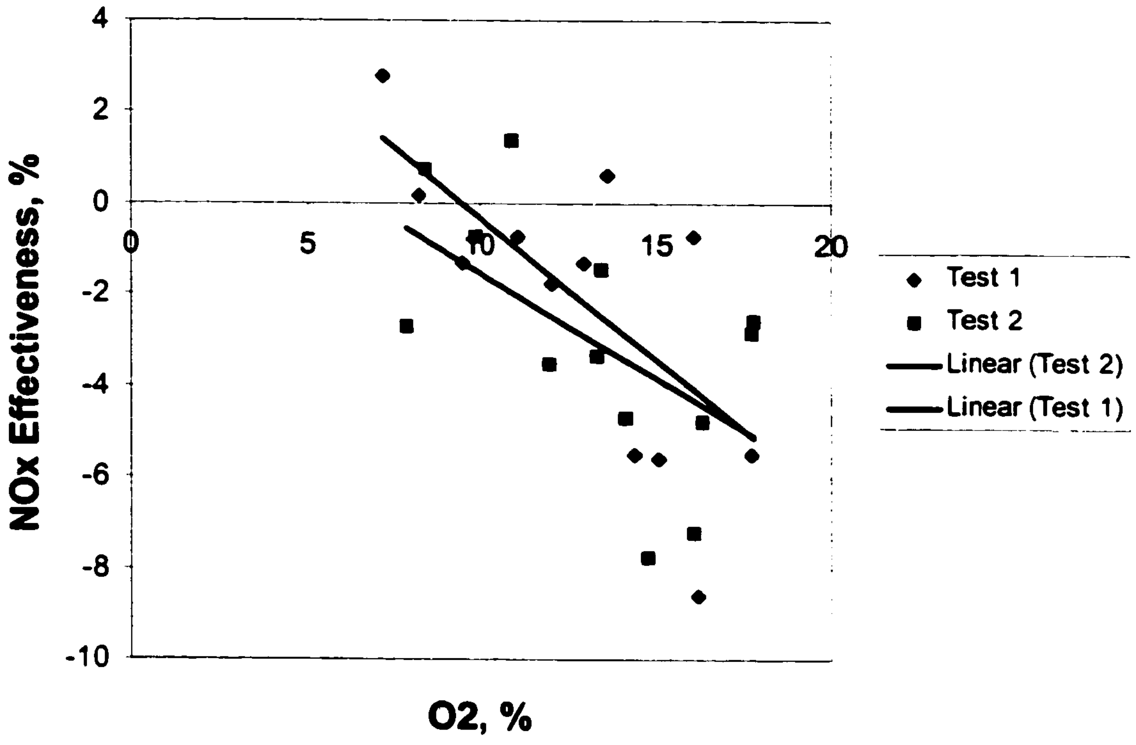

Figure 3.3: NOx Effectiveness Tends to be Negative with high Oxygen Concentrations

CO and HC Effectiveness

The average CO effectiveness was 60%, while the average HC was 42%. The calculated results agreed with the reported effectiveness from the literature [24,28]. It was also reported that for the same operating conditions that the effectiveness of CO is higher than HC. Moreover, DOC effectiveness is not high in diesel engine application because diesel engine exhaust temperature is low. According to Heywood [1], the higher the catalyst surfaces the higher the effectiveness. Low DOC effectiveness resulted from low weighted exhaust temperature (270 ^{o}C on average), as shown in Table 3.12.

Table 3.12: Low weighted Exhaust Temperature on Japanese 13-mode Test

Mode #	Exhaust Temp ^{o}C (test 1)	Exhaust Temp ^{o}C (test 2)
1	196	118
2	193	193
3	257	260
4	140	150
5	265	268
6	290	293
7	373	365
8	465	465
9	283	382
10	495	468
11	602	594
12	607	583
13	250	246
Weighted Temperature	**275**	**266**

3.5 Summary and Conclusion

3.5.1 Literature review Summary

Fuel properties effects on NOx emissions were investigated. NOx reduction gained from diesel fuel advances was approximately 18%, as reported in the literature. The only reported property that reduced NOx was aromatic content. Some studies reported that fuel properties have no effect on NOx reduction.

Engine technology, or in-cylinder technology, includes injection timing, high injection pressure, diesel fuel droplet size, spray pattern, water/steam injection and EGR. Engine technology reduces combustion chamber pressures, temperatures and dilutes air fuel mixtures. Research work done on engine technology was to optimize NOx and PM emission from diesel engines. For example, EGR can reduce NOx emissions from 50 to 60%. However, excessive EGR increases PM emission and deteriorates lubrication oil properties.

Exhaust after treatment has been introduced to meet the stringent air pollution regulations for diesel engines. Exhaust after treatment includes plasma treatment, selective catalyst reduction (SRC), absorption catalyst and diesel oxidizing catalytic (DOC). Plasma needs high electric power that is not available in mobile applications. Non-thermal plasma converts NO to NO_2 that requires additional treatment.

SCR is not suitable in mobile applications because it requires additional storage tanks for the reducing agent. Using diesel fuel as a reducing agent increases specific fuel consumption. Using ammonia as a reducing agent requires accurate ammonia injection or may lead to ammonia slips. Absorption catalysts are not suitable for diesel engines because rich conditions are hardly achieved in mobile applications.

Most of the studies done on DOC were done to investigate the effect of DOC on CO, HC and PM reduction from diesel engines. The reported NOx effectiveness using DOC was between -2% to 7%.

3.5.2 Conclusion

Isuzu engine model 4BE1 and low sulfur diesel was used to investigate the effect of DOC on NOx emissions. The Japanese 13-mode test, the official emission test in Japan, was used. Low sulfur diesel was the fuel of choice because it is expected to be the standard fuel for engines using DOC.

Exhaust gases were measured upstream and downstream to calculate DOC effectiveness. The experiment was done twice. The calculated DOC effectiveness for NOx was -2.6% and -2.7%, which means using DOC increased NOx emission from the tested engine.

There was good agreement between the two tests. DOC effectiveness was most negative on low load modes. For example, DOC effectiveness on mode number 2 was -8.6% and -7.19%. The higher O_2 concentration in the exhaust is associated with more negative DOC effectiveness.

The average CO and HC effectiveness of DOC was 60% and 42%, respectively. DOC effectiveness for both CO and HC is low because the weighted test temperature was low (270 °C on average).

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Chapter 4

SUMMARY AND CONCLUSION

CHAPTER 4: SUMMARY AND CONCLUSION

In response to the proposed diesel engine regulations in the year 2004, in North America, research engineers are investigating different emission control methods. Emission control methods include engine technology, exhaust after treatment devices and enhanced fuel properties. The objective of this study has been to investigate experimentally:

- The effect of low sulfur diesel fuels on PM emission from diesel engines.
- The effect of DOC on NOx emissions from diesel engines.

The experimental results show the following:

- Three of the tested engines produced 70%, 15% and 8% less PM emissions by using low sulfur/aromatic diesel fuel with 114 ppm, while the other three had no significant effect.
- DOC sightly increased NOx emissions by 2.65% on average from the tested engine.

4.1 Context of Diesel Emission Studies

The problem of air pollution from mobile sources has prompted governmental and regulatory agencies to set and enforce stringent air pollution regulations. The regulated emissions from diesel engines are carbon monoxide (CO), unburnt hydrocarbon (HC), nitrogen oxides (NOx) and particulate matter (PM). Diesel engines are reliable and efficient power sources but they emit excessive amounts of NOx and PM. NOx is toxic and contributes to smog and acid rain while PM is toxic and suspected of being carcinogenic.

Different exhaust emissions control strategies have been developed for diesel engines. This study is concerned with the effects of low sulfur diesel fuel on PM emissions and of diesel oxidizing catalyst (DOC) on NOx emissions. Low sulfur diesel fuel lies under enhanced fuel properties, while DOC lies under exhaust after treatment devices.

Although the effect of low sulfur/aromatic diesel on PM emissions has been investigated extensively, previous studies do not portray a clear picture. Some studies reported that low sulfur diesel has no effect on PM emission, while others reported that up to 40% PM reduction can be achieved due to low sulfur diesel.

Unlike low sulfur diesel, the effect of DOC on NOx emissions from diesel engines was rarely investigated. Of the few studies available, some reported that DOC has no effect on NOx emissions, while others reported NOx reductions can be achieved by applying DOC. The reported NOx effectiveness range is -2% to 7%. These conflicting results prompted the current study.

4.2 Effects of Low Fuel Properties on PM Emission from Diesel Engines

In this study, six vehicles/engines were tested to investigate the effect of sulfur content on PM emissions. Four heavy-duty engines, a medium-duty and a light-duty diesel engine were tested. Two commercial fuels were used and the Japanese 6-mode test was adapted to compare the PM emissions from both fuels on each engine.

Mode number 2 had the highest PM emission per second, while mode number one had the highest PM emission per k grams of fuels. Three engines emitted less PM using the low sulfur/aromatic diesel, while the other three had no significant effect.

Low sulfur/aromatic fuel is a potential factor for PM emission reductions but engine response is different from one to another. For example, PM reduction from using low sulfur/aromatic diesel was 70%, 15% and 8%. The average PM reduction was 24% due to low sulfur diesel.

The influence of aging on PM emission was evident from the significant difference between two identical engines but different model year. For example, vehicle 2 1999 model produced 70% less PM emissions but vehicle 4 1993 model showed no response to low sulfur fuel. Engine aging is one of the factors that may lead to different response to low sulfur diesel. However, the previous statement need more experimental data to confirm.

None of the new tested engines met the standard for PM emission for the year 1998 using the Japanese 6-mode test. It can be implied that different test cycles yield different emissions.

4.3 Effect of DOC on NOx Emissions from Diesel Engines

Isuzu engine model 4BE1, 3.6 L naturally aspirated producing 100 kW at 3500 rpm, and low sulfur diesel was used to investigate the effect of DOC on NOx emissions. The Japanese 13-mode test, the official emission test in Japan, was employed. Low sulfur diesel was the fuel of choice because it is expected to be the standard fuel for future engines using DOC. Exhaust gases were measured upstream and downstream to calculate DOC's effectiveness.

The experiment was done twice. The calculated DOC effectiveness for NOx was -2.6% and -2.7%, which means using DOC increased NOx emission from the tested engine. There was a good agreement between the two tests. DOC effectiveness was lower on low load modes, ie at low engine loads DOC increased NOx emission the most. For example, the DOC effectiveness was -8.6% on test 1 and -7.19% on test 2. In high load modes DOC had almost no effect on NOx emissions. The maximum effectiveness was 2.8% on mode 11, while, on test 2, was 1.4% on mode 8. Those figures are similar to what is reported in the literature. High O_2 concentration in the exhaust is associated with lower the NOx effectiveness. It can be implied that exhaust gas concentration has a significant effect on catalyst effectiveness.

The DOC was performing a reasonable job as an oxidizing catalyst. The average CO and HC effectiveness values were 60% and 43%, respectively.

These relatively low effectiveness values results from low catalyst temperature (270 °C on average).

4.4 Recommendations

The objective of this study was to investigate the effect of:

- Low sulfur diesel fuels on PM emission from diesel engines.
- DOC on NOx emission from diesel engines.

For a full coverage of the topics, the author would recommend further research. Test repeatability and results statistical analysis is recommended for any of the further research.

Using different test emission cycles and the same engine to evaluate the effect of different test cycles on DOC performance and PM emissions from different sulfur content fuels.

Chemical analysis of PM composition, specially sulfate compound, will resolve the role of low sulfur/aromatic fuels on PM reduction diesel engines. Furthermore, Measurements of NO and NOx upstream and downstream of the DOC to determine whether DOC forms NO or NOx.

Appendices

PARTICULATE MATTER EMISSION PROFILES OF ALBERTA HEAVY DUTY VEHICLES

March 2001

APPENDIX A

BASIC MEASUREMENT RESULTS

The basic power, consumption and exhaust data values are recorded in tables for six vehicle / engine tests:

In each section, there are six tables of basic test results:

- two tables of power, speed, fuel and air flow data (one for Shell, one for Esso)
- two tables of exhaust composition data (one for Shell, one for Esso)
- two tables of soot filter sampling data (one for Shell, one for Esso)

Notes below the tables identify test problems, missing data values and missing test modes. Where test modes or individual data values were not measured, these were generally replaced with the best-available estimate for calculating composite values. Normally, this was a value from the same engine and test mode using the other fuel.

Table A1.1.a Power and Consumption for Cummins N14 460 Engine on 6-Mode Test Using Shell Diesel (Waterous, 8:45 AM, Feb. 22, 2001).

Mode	Power	Speed	Fuel Flow (scale)	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	0	550	0.56	80
2	280	1200	20.2	498
3*	30	1200	3.22	182
4	306	1450	22.3	505
5*	30	1450	4.84	234
6	268	1700	19.9	506

*The Waterous dynamometer operator could not stabilize the system at the desired load (75 kW) so part-load power levels were relatively low for a 6-Mode test.

Table A1.1.b Power and Consumption for Cummins N14 460 Engine on 6-mode Test Using Essol Diesel (Waterous, 11:00 AM, Feb. 22, 2001).

Mode	Power	Speed	Fuel Flow (scale)	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	0	600	0.55	101
2	291	1200	20.35	465
3*	30	1200	4.11	195
4	306	1450	22.31	505
5*	30	1450	4.84	234
6	224	1700	19.71	506

*The Waterous dynamometer operator could not stabilize the system at the desired load (75 kW)

Table A1.1.c Exhaust Composition for Cummins N14 460 Engine on 6-Mode Test Using Shell Diesel (Waterous, 8:45 AM, Feb. 22, 2001).

Mode	CO	CO2	HC	NOx	02
	(%)	(%)	(ppm)	(ppm)	(%)
1	0.01	0.8	0	167	20.1
2	0	5.1	1	595	14.3
3	0.01	3.8	9	926	15.0
4	0	8.9	6	875	8.4
5	0	4.2	0	831	15.0
6	0	8.1	0	744	9.8

Table A1.1.d Exhaust Composition for Cummins N14 460 Engine on 6-Mode Test Using Esso Diesel (Waterous, 11:00 AM, Feb. 22, 2001).

Mode	CO	CO2	HC	NOx	02
	(%)	(%)	(ppm)	(ppm)	(%)
1	0.01	0.9	0	211	20.3
2	0	7.5	0	909	10.4
3	0.01	3.4	0	917	16.3
4[*]	*0*	*8.9*	*6*	*875*	*8.4*
5[*]	*0*	*4.2*	*0*	*831*	*15.0*
6	0	7.0	1	740	11.4

[*] Exhaust gas composition data are the same as Shell fuel data because the sampling line froze during Esso fuel tests.

Table A1.1.e Soot Sampling Data for Cummins N14 460 Engine on 6-Mode Test Using Shell Diesel (Waterous, 8:45 AM, Feb. 22, 2001).

Mode	Filter	Soot Mass	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y05	1.54	5	0.36	0.25
2	y02	2.43	5	0.38	0.25
3	y16	2.00	5	0.40	0.24
4	y06	1.30	5	0.43	0.27
5	y17	1.64	5	0.37	0.23
6	y03	2.72	5	0.41	0.23

Table A1.1.f Soot Sampling Data for Cummins N14 460 Engine on 6-Mode Test Using Esso Diesel (Waterous, 11:00 AM, Feb. 22, 2001).

Mode	Filter Number	Soot Weight	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y18	1.05	5	0.38	0.30
2	y15	2.17	5	0.38	0.24
3	y19	3.20	5	0.38	0.25
4**		1.30	5	0.43	0.27
5**		1.64	5	0.37	0.23
6	y20	2.21	5	0.40	0.22

** The engine was not stable in some modes during initial testing. As a result two filters were scrapped and only four filters remained for testing with Esso fuel. Modes 4 and 5 were not sampled.

Table A1.2.a Power and Consumption for newer Detroit Series 60 Engine on 6-mode Test Using Shell Diesel (Waterous, 3:30 PM, Feb. 26, 2001).

Mode	Power	Speed	Fuel Flow (scale)	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	0	600	0.58	64
2	178	1200	13.00	278
3	44	1275	4.45	168
4	223	1450	14.87	378
5	44	1450	4.89	193
6	149	1700	11.50	330

Table A1.2.b Power and Consumption for newer Detroit Series 60 Engine on 6-Mode Test Using Esso Diesel (Waterous, 4:50 PM, Feb. 26, 2001).

Mode	Power	Speed	Fuel Flow (scale)	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	0	600	0.63	62
2	179	1200	13.58	281
3	45	1220	4.52	158
4	231	1450	15.52	367
5	45	1479	4.91	196
6	149	1700	11.52	331

Table A1.2.c Exhaust Composition for newer Detroit Series 60 Engine on 6-Mode Test Using Shell Diesel (Waterous, 3:30 PM, Feb. 26, 2001).

Mode	CO	CO2	HC	NOx	O2	Opacity
	(%)	(%)	(ppm)	(ppm)	(%)	(%)
1	0.01	1.1	0	199	19.5	0
2	0.18	7	0	727	11.2	8.1
3	0	4.8	0	810	14.5	0
4	0.06	7.1	0	720	11.3	1.2
5	0	4.4	0	664	15	0.3
6**	*0.01*	*6.4*	*0*	*1204*	*11.8*	0

No Snap-idle test was done.

Table A1.2.d Exhaust Composition for newer Detroit Series 60 Engine on 6-Mode Test Using Esso Diesel (Waterous, 4:50 PM, Feb. 26, 2001).

Mode	CO	CO2	HC	NOx	O2	Opacity
	(%)	(%)	(ppm)	(ppm)	(%)	(%)
1	0.02	0.95	1	149	19.7	0
2	0.2	7.1	0	910	11.1	1.1
3	0	4.7	0	1094	14.6	0
4	0.06	6.8	0	686	11.8	1.6
5	0	4.7	0	489	14.6	1.1
6**	0.01	6.3	0	1255	11.9	2.1

Snap-idle test result was 10.2% Opacity.

** Emissions data were not available for Mode 6 in both fuels because the sampling line froze. Composites used mode 6 values from the other Detroit Diesel Series 60 Engine (March 1)

Table A1.2.e Soot Sampling Data for newer Detroit Series 60 Engine on 6-Mode Test Using Shell Diesel (Waterous, 3 :30 PM, Feb. 26, 2001).

Mode	Filter Numbe	Soot Weight	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y24	1.49	5	0.41	0.27
2	y28	4.00	5	0.40	0.27
3	y29	4.96	5	0.41	0.26
4	y23	1.73	5	0.41	0.25
5	y33	3.86	5	0.40	0.25
6	y21	0.38	5	0.42	0.25

Table A1.2.f Soot Sampling Data for newer Detroit Series 60 Engine on 6-Mode Test Using Esso fuel (Waterous, 4 :50 PM, Feb. 26, 2001).

Mode	Filter Number	Soot Weight	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y22	2.49	5	0.38	0.25
2	y27	6.83	5	0.40	0.29
3	y32	7.86	5	0.40	0.25
4	y30	1.62	5	0.37	0.25
5	y26	5.73	5	0.37	0.23
6	y40	7.78	5	0.38	0.23

Table A1.3.a Power and Consumption for CAT 3406 Engine on 6-Mode Test Using Shell Diesel (Waterous, 10:00 AM, Feb. 27, 2001).

Mode	Power	Speed	Fuel Flow (scale)	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	0	700	0.43	81
2	215	1200	15.00	313
3	60	1200	5.22	167
4	253	1450	17.50	349
5	60	1450	5.90	207
6	75	1700	7.36	257

Table A1.3.b Power and Consumption for CAT 3406 Engine on 6-Mode Test Using Esso Diesel (Waterous 10 :00 AM, Feb. 27, 2001).

Mode	Power	Speed	Fuel Flow	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	0	700	0.64	80
2	225	1200	16.11	289
3	61	1200	5.05	168
4*	*253*	*1450*	*17.50*	*349*
5	60	1450	5.77	212
6	75	1700	7.66	261

** Mode 4 was skipped because of filter shortage. Data from Shell Mode 4 were used.

Table A1.3.c Exhaust Emissions for CAT 3406 Engine on 6-Mode Test Using Shell Diesel (Waterous, 10 :00 AM, Feb. 27, 2001).

Mode	CO	CO2	HC	NOx	02	Opacity
	(%)	(%)	(ppm)	(ppm)	(%)	(%)
1	0.03	1.2	0	310	20.9	5.1
2	0.09	10.4	1	777	6.7	16.1
3	0.02	3.9	9	420	16.1	15
4	0.02	9.4	6	785	8.4	22
5	0.01	5.7	0	580	14.4	20.5
6	0.01	5.6	0	540	14.2	19

Snap idle test result was 20.7% Opacity

Table A1.3.d Exhaust Emissions for CAT 3406 Engine on 6-Mode Test Using Esso Diesel (Waterous, 11 :00 AM, Feb. 27, 2001).

Mode	CO	CO2	HC	NOx	02	Opacity
	(%)	(%)	(ppm)	(ppm)	(%)	(%)
1	0.01	1.2	0	251	19.4	11.2
2	0.07	10.9	0	848	6	19.6
3	0.01	5.8	0	724	13	26
4**	0.02	9.4	6	785	8.4	22
5	0.01	5.4	0	561	13.6	26.9
6	0.01	5.5	0	744	13.5	25.4

Snap idle test result was 30.8% Opacity.

** Mode number 4 was skipped on Esso fuel because no filters were available.

Table A1.3.e Exhaust Emissions for CAT 3406 Engine on 6-Mode Test Using Shell Diesel (Waterous, 10:00 AM, Feb. 27, 2001).

Mode	Filter Number	Soot Weight	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y37	0.16	5	0.40	0.29
2	y45	7.58	3	0.40	0.25
3	y55	0.35	5	0.37	0.26
4	y35	0.75	3	0.40	0.24
5	y38	5.72	3	0.40	0.24
6	y52	0.51	3	0.41	0.25

Table A1.3.f Soot Sampling Data for CAT 3406 Engine on 6-Mode Test Using Esso Diesel (Waterous, 11 :00 PM, Feb. 27, 2001).

Mode	Filter Number	Soot Weight	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y46	0.24	5	0.38	0.25
2	y57	6.22	3	0.37	0.26
3	y44	1.39	4	0.37	0.25
4**		0.75	3	0.40	0.24
5	y51	4.77	4	0.40	0.26
6	y56	1.11	4	0.42	0.25

** Mode number 4 was skipped because of filter shortage.

Table A1.4.a Power and Consumption for older Detroit Diesel Engine on 6-Mode Test Using Shell Diesel (Waterous, 9:00 AM, March 1, 2001).

Mode	Power	Speed	Fuel Flow (scale)	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	0	600	0.68	60
2	195	1215	14.04	256
3	62	1240	5.69	159
4	230	1470	15.49	310
5	61	1460	6.10	183
6	81	1709	7.68	224

Table A1.4.b Power and Consumption for older Detroit Diesel Engine on 6-Mode Test Using Esso Diesel (Waterous, 10:30 AM, March 1, 2001).

Mode	Power	Speed	Fuel Flow	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	0	600	0.42	60
2	201	1210	13.59	255
3	60	1210	5.23	150
4	236	1450	15.86	334
5	44	1460	5.93	182
6	55	1720	7.48	227

Table A1.4.c Exhaust Composition for older Detroit Diesel Engine on 6-Mode Test Using Shell Diesel (Waterous, 9:00 AM, March 1, 2001).

Mode	CO	CO2	HC	NOx	O2	Opacity
	(%)	(%)	(ppm)	(ppm)	(%)	(%)
1	0.02	1	0	153	19.9	4.9
2	0.24	10.1	0	1280	6	23
3	0.01	7	0	1345	10.5	3.2
4	0.1	9.3	0	1270	7.3	6.3
5	0.01	6.3	0	1323	11.8	8.9
6	0.01	6.4	0	1204	11.8	7.3

Snap idle test result was 8.2% Opacity (cold) and 9.5% Opacity (warmed up).

Table A1.4.e Exhaust Composition for older Detroit Diesel Engine on 6-Mode Test Using Esso Diesel (Waterous, 10:30 AM, March 1, 2001).

Mode	CO	CO2	HC	NOx	O2	Opacity
	(%)	(%)	(ppm)	(ppm)	(%)	(%)
1	0.02	0.8	0	140	19.8	6.6
2	0.26	10.4	0	1323	6.3	23.3
3	0.01	6.8	0	1416	11.3	6.4
4	0.11	9.7	0	1330	7.2	10.7
5	0	6	0	1335	12	11.3
6	0.01	6.3	0	1255	11.9	8.3

Snap Idle test result was 13.7% Opacity.

Table A1.4.e Soot Sampling Data for older Detroit Diesel Engine on 6-Mode Test Using Shell Diesel (Waterous, 9:00 AM, March 1, 2001).

Mode	Filter Number	Soot Weight	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y47	2.27	5	0.41	0.28
2	y41	6.12	4	0.40	0.29
3	y39	8.04	5	0.42	0.29
4	y60	3.78	4	0.41	0.29
5	y58	1.80	5	0.41	0.29
6	y50	3.82	5	0.44	0.28

Table A1.4.f Soot Sampling Data for older Detroit Diesel Engine on 6-Mode Test Using Esso Diesel (Waterous, 10:30 AM, March 1, 2001).

Mode	Filter Number	Soot Weight	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y59	1.98	5	0.42	0.31
2	y54	4.68	3	0.40	0.29
3	y43	2.30	5	0.41	0.29
4	y31	4.43	4	0.43	0.31
5	y74	0.46	5	0.42	0.29
6	y53	3.97	5	0.41	0.28

Table A1.5.a Power and Consumption for Dodge pickup / Cummins Engine on 6-Mode Test Using Shell Diesel (U of A, 10:00 AM, March 15, 2001).

Mode	Power	Speed	Fuel Flow (scale)	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	0	750	0.20	36
2	63	1250	4.85	85
3	14	1250	1.45	62
4	70	1900	4.57	81
5	18	1900	2.17	98
6	31	2400	3.3	132

Table A1.5.b Power and Consumption for Dodge pickup / Cummins Engine on 6-Mode Test Using Esso Diesel (U of A, 11:00 AM, March 15, 2001).

Mode	Power	Speed	Fuel Flow (scale)	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	0	750	0.25	30
2	60	1270	4.96	81
3	13	1250	1.31	55
4**	*70*	*1900*	*4.57*	*81*
5**	*18*	*1900*	*2.17*	*98*
6**	*31*	*2400*	*3.3*	*132*

**** modes 4, 5 and 6 could not be completed because a lab started and the vehicle needed to be returned before testing could be completed..**

Table A1.5.c Exhaust Composition for Dodge pickup / Cummins Engine on 6-Mode Test Using Shell Diesel (U of A, 10:00 AM, March 15, 2001).

Mode	CO	CO2	HC	NOx	O2
	(ppm)	(%)	(ppm)	(ppm)	(%)
1	200	1.61	133	450	18.2
2	4110	12.2	153	690	3.8
3	174	4.85	96	490	14
4	66	8	87	600	9.9
5	202	4.45	78	400	14.4
6	151	4.93	73	360	13.9

Table A1.5.c Exhaust Composition for Dodge pickup / Cummins Engine on 6-Mode Test Using Esso Diesel (U of A, 11:00 AM, March 15, 2001).

Mode	CO	CO2	HC	NOx	O2
	(ppm)	(%)	(ppm)	(ppm)	(%)
1	92	1.57	72	210	18.6
2	3675	11.59	82	790	4.8
3	100	4.75	57	480	14.1
4**	*66*	*8*	*87*	*600*	*9.9*
5**	*202*	*4.45*	*78*	*400*	*14.4*
6**	*151*	*4.93*	*73*	*360*	*13.9*

** modes 4, 5 and 6 could not be completed because a lab started and the vehicle needed to be returned before testing could be completed..

Table A1.5.e Soot Sampling Data for Dodge pickup / Cummins Engine on 6-Mode Test Using Shell Diesel (U of A, 10:00 AM, March 15, 2001).

Mode	Filter Number	Soot Weight	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y64	0.19	5	0.42	0.38
2	y42	6.30	3	0.38	0.31
3	y77	0.24	3	0.40	0.27
4	y80	1.64	3	0.40	0.02
5	y78	1.00	3	0.40	0.07
6	y65	1.03	3	0.41	0.07

Table A1.5.e Soot Sampling Data for Dodge pickup / Cummins Engine on 6-Mode Test Using Esso Diesel (U of A, 11:00 AM, March 15, 2001).

Mode	Filter Number	Soot Weight	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y79	0.14	3	0.40	0.35
2	y68	5.83	3	0.40	0.33
3	y62	0.03	3	0.42	0.25
4**		1.64	3	0.40	0.02
5**		1.00	3	0.40	0.07
6**		1.03	3	0.41	0.07

** modes 4, 5 and 6 could not be completed because a lab started and the vehicle needed to be returned before testing could be completed..

Table A1.6.a Power and Consumption for for ISUZU 4BE1 Engine on 6-Mode Test Using Shell Diesel (U of A, 5:00 PM, March 21, 2001).

Mode	Power	Speed	Fuel Flow (scale)	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	1.05	600	0.15	16.5
2	27.4	1360	1.8	40.3
3	7.97	1360	0.61	41.9
4	41.7	2040	2.7	59.9
5	11.7	2040	1.06	61.3
6	34.4	2720	2.43	76.6

Table A1.6.b Power and Consumption for ISUZU 4BE1 Engine on 6-Mode Test Using Esso Diesel (U of A, 6:00 PM, March 21, 2001).

Mode	Power	Speed	Fuel Flow (scale)	Air Flow
	(kW)	(rpm)	(g/s)	(g/s)
1	0.54	600	0.15	16.2
2	27.2	1360	1.81	40
3	7.8	1360	0.64	41
4	41.9	2040	2.7	59.1
5	11	2040	1.35	60
6	33.4	2720	2.26	75

Table A1.6.c Exhaust Composition for ISUZU 4BE1 Engine on 6-Mode Test Using Shell Diesel (U of A, 5:00 PM, March 21, 2001).

Mode	CO	CO2	HC	NOx	O2
	(ppm)	(%)	(ppm)	(ppm)	(%)
1	193	1.52	127	316	18.15
2	843	9.49	175	1540	7.69
3	329	2.99	130	448	16.2
4	464	9.58	139	1380	7.69
5	517	3.22	143	324	15.9
6	245	6.64	120	740	11.5

Table A1.6.d Exhaust Emissions for ISUZU 4BE1 Engine on 6-Mode Test Using Esso Diesel (U of A, 6:00 PM, March 21, 2001).

Mode	CO	CO2	HC	NOx	O2
	(ppm)	(%)	(ppm)	(ppm)	(%)
1	165	1.57	140	352	18.2
2	1500	10.5	237	1540	6.99
3	325	3.52	145	540	15.9
4	860	10.8	187	1520	6.8
5	435	3.7	140	396	15.7
6	270	7.57	148	788	11.1

Table A1.6.e Soot Sampling Data for ISUZU 4BE1 Engine on 6-Mode Test Using Shell Diesel (U of A, 5:00 PM, March 21, 2001).

Mode	Filter Number	Soot Weight	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y66	0.51	5	0.30	0.27
2	y61	0.94	3	0.30	0.24
3	y99	0.97	5	0.31	0.25
4	y85	1.70	3	0.31	0.19
5	y94	0.98	5	0.30	0.18
6	y96	0.52	3	0.29	0.12

Table A1.6.f Soot Sampling Data for ISUZU 4BE1 Engine on 6-Mode Test Using Esso Diesel (U of A, 6:00 PM, March 21, 2001).

Mode	Filter Number	Soot Weight	Sample Time	Sample + Dilution Flow	Dilution Flow
		(mg)	(min)	(g/s)	(g/s)
1	y75	0.59	5	0.29	0.26
2	y72	0.67	3	0.29	0.23
3	y88	0.36	5	0.29	0.23
4	y84	1.49	3	0.30	0.18
5	y93	1.65	5	0.31	0.19
6	y95	0.89	3	0.31	0.12

PARTICULATE MATTER EMISSION PROFILES

OF ALBERTA HEAVY DUTY VEHICLES

March 2001

APPENDIX B

CALCULATED MEASUREMENT RESULTS

Appendix B1 Emissions and in grams/sec

Table B1.1.a Emission in grams/second for Cummins N14 460 Engine on 6-Mode Test Using Shell Diesel (Waterous, 8:45 AM, Feb. 22, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.01	0.98	0	0.014	17.9	3.67
2	0	39.57	0.002	0.315	80.7	32.5
3	0.02	10.61	0.005	0.176	30.4	7.92
4	0	69.36	0.009	0.465	47.6	14.24
5	0	15.07	0	0.203	39.1	9.34
6	0	63.14	0	0.396	55.5	27.31

Table B1.1.b Emission in grams/second for Cummins N14 460 Engine on 6-Mode Test Using Esso Diesel (Waterous, 11:00 AM, Feb. 22, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.01	1.38	0	0.022	22.7	4.21
2	0	54.08	0	0.447	54.5	24.4
3	0.02	10.22	0	0.188	35.6	15.6
4	0	69.36	0.009	0.465	47.6	14.2
5	0	15.07	0	0.203	39.1	9.34
6	0	54.76	0.002	0.395	64.8	21.8

Table B1.2.a Emission in grams/second for newer Detroit Diesel Series 60 on 6-Mode Test Using Shell Diesel (Waterous, 3:30 PM, Feb. 26, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.01	1.08	0	0.013	13.9	2.33
2	0.50	30.3	0	0.215	35.3	30.9
3	0	12.4	0	0.143	27.3	19.7
4	0.22	41.4	0	0.287	48	14.2
5	0	13.1	0	0.135	32.4	17.2
6**	*0.032*	*32.6*	*0*	*0.418*	*43.7*	2.53

Table B1.2.b Emission in grams/second for newer Detroit Engine Series 60 on 6-Mode Test Using Esso Diesel (Waterous, 4:50 PM, Feb. 26, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.01	0.91	0	0.01	13.7	4.09
2	0.56	31.1	0	0.27	35.3	64.9
3	0	11.4	0	0.18	25.8	28.7
4	0.22	38.7	0	0.27	48.8	16.5
5	0	14.2	0	0.10	32.0	27.5
6**	*0.03*	*32.2*	*0*	*0.44*	*44.2*	58.7

** Mode 6 gas analysis values were missed due to a frozen sample line for both fuels. Data values are those from the other Detroit Diesel Series 60 test on March 1.

Table B1.3.a Emissions in grams/second for CAT 3406 Engine on 6-Mode Test Using Shell Diesel (Waterous, 10 :00 AM, Feb. 27, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.02	1.49	0	0.026	18.8	0.43
2	0.28	50.1	0.00	0.255	23.5	93.1
3	0.03	10.1	0.01	0.074	30.3	1.83
4	0.07	50.7	0.01	0.289	33.0	9.83
5	0.02	18.1	0	0.126	33.3	43.5
6	0.03	22.1	0	0.146	40.8	4.66

Table B1.3.b Emissions in grams/second for CAT 3406 Engine on 6-Mode Test Using Esso Diesel (Waterous, 11 :00 AM, Feb. 27, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.01	1.46	0	0.021	18.2	0.46
2	0.20	48.8	0	0.259	18.6	96.1
3	0.00	17.0	0	0.128	22.5	8.59
4**	0.07	50.7	0.01	0.289	33.0	9.85
5	0.02	18.2	0	0.125	32.0	32.5
6	0.03	22.9	0	0.203	39.4	7.57

** Instability at the start of testing wasted two filters.
Insufficient filters were available so no filter was sampled for Mode 4.

Table B1.4.a Emission in grams/second for older Detroit Diesel Engine on 6-Mode Test Using Shell Diesel (Waterous, 9:00 AM, March 1, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.01	0.92	0	0.010	13.3	3.73
2	0.61	40.1	0	0.347	17.3	66.5
3	0.02	17.2	0	0.226	18.8	34.9
4	0.31	44.8	0	0.417	25.6	44.6
5	0.02	17.8	0	0.255	24.3	9.90
6	0.02	22.1	0	0.284	29.6	17.8

Table B1.4.b Emission in grams/second for older Detroit Diesel Engine on 6-Mode Test Using Esso Diesel (Waterous, 10:30 AM, March 1, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.01	0.73	0	0.009	13.2	3.56
2	0.65	41.1	0	0.356	18.1	67.6
3	0.01	15.7	0	0.223	19.0	10.3
4	0.36	50.1	0	0.468	27.4	52.3
5	0	16.9	0	0.256	24.5	2.26
6	0.02	22.0	0	0.300	30.3	25.3

Table B1.5.a Emission in grams/second for Dodge Pickup/Cummins Engine on 6-Mode Test Using Shell Diesel (U of A, 10:00 AM, March 15, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.01	0.90	0.00	0.017	7.30	0.61
2	0.34	16.0	0.01	0.062	3.63	43.3
3	0.01	4.62	0.00	0.032	9.70	0.69
4	0.01	10.1	0.00	0.052	9.09	2.05
5	0.02	6.67	0.00	0.041	15.7	1.70
6	0.02	10.0	0.01	0.050	20.5	2.32

Table B1.5.b Emission in grams/second for Dodge Pickup/Cummins Engine on 6-Mode Test Using Esso Diesel (U of A, 11:00 AM, March 15, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.00	0.72	0.00	0.007	6.10	0.52
2	0.29	14.5	0.00	0.068	4.38	43.3
3	0.01	4.03	0.00	0.028	8.70	0.07
4**	*0.01*	*10.1*	*0.00*	*0.052*	*9.09*	*2.05*
5**	*0.02*	*6.67*	*0.00*	*0.041*	*15.7*	*1.70*
6**	*0.02*	*10.0*	*0.01*	*0.050*	*20.5*	*2.32*

** modes 4, 5 and 6 could not be completed because a lab started and the vehicle needed to be returned before testing could be completed.

Table B1.6.a Emission in grams/second for Isuzu 4BE1 Engine on 6-Mode Test Using Shell Diesel (U of A, 5:00 PM, March 21, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.00	0.38	0.06	0.005	3.33	1.01
2	0.03	5.90	0.22	0.065	3.48	3.80
3	0.01	1.92	0.16	0.020	7.57	2.03
4	0.03	8.85	0.26	0.087	5.17	4.89
5	0.03	3.03	0.26	0.021	10.9	1.73
6	0.02	7.82	0.28	0.059	9.87	1.30

Table B1.6.b Emission in grams/second for Isuzu 4BE1 Engine on 6-Mode Test Using Esso Diese(U of A, 6:00 PM, March 21, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/s)	(g/s)	(g/s)	(g/s)	(g/s)	(mg/s)
1	0.00	0.39	0.07	0.006	3.29	1.18
2	0.06	6.43	0.30	0.064	3.12	2.46
3	0.01	2.21	0.18	0.023	7.27	0.79
4	0.05	9.78	0.35	0.094	4.48	4.10
5	0.03	3.42	0.25	0.025	10.6	2.75
6	0.02	8.68	0.34	0.062	9.24	1.94

Appendix B2 Emissions and Consumption in grams/kg.fuel

Table B2.1.a Emission in grams/kg.fuel for Cummins N14 460 Engine on 6-Mode Test Using Shell Diesel (Waterous, 8:45 AM, Feb. 22, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	14.0	1740	0	24.7	31700	10.5
2	0	1960	0	15.6	4000	1.61
3	6.0	3290	0.002	54.7	9440	2.40
4	0	3110	0	20.9	2130	0.64
5	0	3120	0	42.1	8090	1.93
6	0	3180	0	19.9	2800	1.38

Table B2.1.b Emission in grams/kg.fuel for Cummins N14 460 Engine on 6-Mode Test Using Esso Diesel (Waterous, 11:00 AM, Feb. 22, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	17.6	2490	0	39.9	40,900	9.15
2	0	2660	0	22.0	2680	1.20
3	4.7	2490	0	45.8	8670	4.45
4	0	3110	0.41	20.9	2130	0.64
5	0	3120	0	42.1	8090	1.93
6	0	2780	0.08	20.0	3290	1.10

Table B2.2.a Emission in grams/kg.fuel for newer Detroit Engine Series 60 on 6-Mode Test Using Shell Diesel (Waterous, 3:30 PM, Feb. 26, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	11	1860	0	22.9	23900	6.46
2	38	2330	0	16.5	2710	3.07
3	0	2790	0	32.1	6130	4.43
4	15	2790	0	19.3	3230	0.95
5	0	2680	0	27.6	6640	3.52
6**	*3*	*2840*	*0*	*36.4*	*3800*	0.22

Table B2.2.b Emission in grams/kg.fuel for newer Detroit Engine Series 60 on 6-Mode Test Using Esso Diesel (Waterous, 4:50 PM, Feb. 26, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	19	1440	0	15.4	21,750	8.20
2	41	2290	0	20.0	2600	4.78
3	0	2530	0	40.1	5710	6.35
4	14	2490	0	17.2	3140	1.06
5	0	2880	0	20.4	6510	5.59
6**	*3*	*2800*	*0*	*38.0*	*3840*	5.10

** No gaseous emission data were available for Mode 6 in both fuels because the sampling line froze. Gaseous composition values from the older Detroit Series 60 test were used.

Table B2.3.a Emissions in grams/kg.fuel for CAT 3406 Engine on 6-Mode Test Using Shell Diesel (Waterous, 10 :00 AM, Feb. 27, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	55.4	3470	0	61.1	43,900	1.00
2	20.5	3340	0.06	17.0	1560	6.21
3	6.27	1940	0.87	14.0	5800	0.35
4	3.93	2900	0.36	16.5	1880	0.56
5	3.44	3070	0	21.3	5640	7.37
6	3.42	3010	0	19.8	5550	0.63

Table B2.3.b Emissions in grams/kg.fuel for CAT 3406 Engine on 6-Mode Test Using Esso Diesel (Waterous, 11 :00 AM, Feb. 27, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	15.5	2920	0	41.7	36,300	0.93
2	12.4	3030	0	16.1	1150	5.96
3	0	3380	0	25.3	4460	1.70
4**	3.9	2900	0.36	16.5	1880	0.56
5	3.6	3160	0	21.6	5540	5.63
6	3.3	2980	0	26.6	5140	0.99

** Due to a shortage of filters, Mode 4 was skipped, (data per Shell test).

Table B2.4.a Emission in grams/kg.fuel for older Detroit Diesel Engine on 6-Mode Test Using Shell Diesel (Waterous, 9:00 AM, March 1, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	17.2	1350	0	14.1	19,500	5.49
2	43.3	2860	0	24.7	1230	4.74
3	2.75	3030	0	39.7	3300	6.14
4	19.8	2890	0	26.9	1650	2.88
5	2.95	2920	0	41.8	3970	1.62
6	2.86	2880	0	37.0	3860	2.32

Table B2.4.b Emission in grams/kg.fuel for older Detroit Diesel Engine on 6-Mode Test Using Esso Diesel (Waterous, 10:30 AM, March 1, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	27.8	1740	0	20.8	31,400	8.47
2	48.1	3020	0	26.2	1330	4.97
3	2.8	3000	0	42.6	3630	1.98
4	22.8	3160	0	29.5	1730	3.30
5	0	2840	0	43.1	4130	0.38
6	3.0	2950	0	40.0	4050	3.39

Table B2.5.a Emission in grams/kg.fuel for Dodge Pickup /Cummins Engine on 6-Mode Test Using Shell Diesel (U of A, 10:00 AM, March 15, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	35.1	4440	13.3	84.6	36,500	2.43
2	70.8	3300	1.5	12.7	748	8.93
3	7.3	3190	2.3	22.0	6710	0.48
4	1.2	2210	0.9	11.3	1990	0.45
5	9.2	3170	2.0	19.4	7450	0.78
6	5.9	3030	1.6	15.1	6220	0.70

Table B2.5.b Emission in grams/kg.fuel for Dodge Pickup /Cummins Engine on 6-Mode Test Using Esso Diesel (U of A, 11:00 AM, March 15, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	10.8	2890	4.8	26.4	24,400	2.09
2	59.2	2930	0.8	13.6	883	8.82
3	4.1	3070	1.3	21.2	6630	0.04
4**	*1.2*	*2210*	*0.9*	*11.3*	*1990*	*0.45*
5**	*9.2*	*3170*	*2.0*	*19.4*	*7450*	*0.78*
6**	*5.9*	*3030*	*1.6*	*15.1*	*6220*	*1.2*

** modes 4, 5 and 6 could not be completed because a lab started and the vehicle needed to be returned before testing could be completed..

Table B2.6.a Emission in grams/kg.fuel for Isuzu 4BE1 Engine on 6-Mode Test Using Shell Diesel (U of A, 5:00 PM, March 21, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	21.2	2630	418	37.2	22,700	6.73
2	18.5	3270	122	36.1	1930	2.11
3	22.1	3260	265	32.3	12,500	3.32
4	10.1	3280	96	32.2	1910	1.81
5	29.2	2860	245	19.6	10,300	1.63
6	7.55	3220	115	24.5	4060	0.54

Table B2.6.b Emission in grams/kg.fuel for Isuzu 4BE1 Engine on 6-Mode Test Using Esso Diesel (U of A, 6:00 PM, March 21, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)	(g/kgfuel)
1	17.9	2680	456	40.9	22,600	7.85
2	32.6	3560	164	35.7	1730	1.36
3	20.3	3450	275	36.1	11,400	1.24
4	18.4	3620	128	34.8	1660	1.52
5	18.9	2530	186	18.5	7830	2.04
6	8.70	3840	150	27.3	4090	0.86

Appendix B3 Emissions and Consumption in grams/kW.hr

Table B3.1.a Emission in grams/kW.hr fuel for Cummins N14 460 Engine on 6-Mode Test Using Shell Diesel (Waterous, 8:45 AM, Feb. 22, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	0	508	0	4.0	1,040	0.42
3	2.1	1280	0	21.3	3,690	0.95
4	0	817	0	5.5	560	0.17
5	0	1820	0	24.6	4,720	1.12
6	0	847	0	5.3	847	0.37

Table B3.1.b Emission in grams/kW.hr fuel for Cummins N14 460 Engine on 6-Mode Test Using Esso Diesel (Waterous, 11:00 AM, Feb. 22, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	0	669	0	5.5	675	0.30
3	2.3	1230	0	22.7	4,300	1.61
4	0	817	0 .11	5.5	560	0.23
5	0	1820	0	24.6	4,720	1.41
6	0	881	0.02	6.36	1,040	0.61

Table B3.2.a Emission in grams/kW.h for newer Detroit Engine Series 60 on 6-Mode Test Using Shell Diesel (Waterous, 3:30 PM, Feb. 26, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	10.0	610	0	4.3	709	0.62
3	0.0	1000	0	11.5	2200	1.58
4	3.6	667	0	4.6	772	0.23
5	0.0	1050	0	10.8	2610	1.38
6**	*0.8*	*787*	*0*	*10.1*	*1060*	0.06

Table B3.2.b Emission in grams/kW.h for newer Detroit Engine Series 60 on 6-Mode Test Using Esso Diesel (Waterous, 4:50 PM, Feb. 26, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	11.2	625	0	5.5	711	1.31
3	0	920	0	14.6	2080	2.31
4	3.4	602	0	4.1	760	0.26
5	0	1140	0	8.1	2570	2.21
6**	*0.8*	*777*	*0*	*10.6*	*1070*	1.42

** Values for gaseous emissions data in Mode 6 were based on the other Detroit Diesel Series 60 engine for both fuels since the sample line froze during both Mode 6 tests on this engine.

Table B3.3.a Emissions in grams /kW.h for CAT 3406 Engine on 6-Mode Test Using Shell Diesel (Waterous, 10 :00 AM, Feb. 27, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	4.62	839	0.02	4.28	393	1.56
3	1.99	610	0.28	4.48	1830	0.11
4	0.98	722	0.09	4.16	469	0.14
5	1.22	1090	0	7.59	2010	2.62
6	1.22	1070	0	7.03	1970	0.23

Table B3.3.b Emissions in grams / kg fuel for CAT 3406 Engine on 6-Mode Test Using Esso Diesel (Waterous, 11 :00 AM, Feb. 27, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	3.19	780	0	4.14	297	1.54
3	0.98	1000	0	7.51	1330	0.51
4**	*0.98*	*722*	*0.09*	*4.12*	*469*	*0.14*
5	1.24	1090	0	7.43	1910	1.94
6	1.23	1100	0	9.82	1900	0.37

** Due to filter shortage, Mode 4 was not separately tested with Esso fuel.

Table B3.4.a Emission in grams/kW.h for older Detroit Diesel Engine on 6-Mode Test Using Shell Diesel (Waterous, 9:00 AM, March 1, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	11.2	740	0	6.42	321	1.23
3	0.91	1000	0	13.1	1190	2
4	4.80	700	0	6.54	401	0.7
5	1.06	1050	0	15.0	1430	0.58
6	0.98	990	0	12.7	1320	0.8

Table B3.4.b Emission in grams/kW.h for older Detroit Diesel Engine on 6-Mode Test Using Esso Diesel (Waterous, 10:30 AM, March 1, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	11.7	737	0	6.4	325	1.21
3	0.88	936	0	13.3	1130	0.62
4	5.52	765	0	7.2	418	0.8
5	0	1380	0	20.9	2000	0.18
6	1.45	1440	0	19.5	1970	1.65

Table B3.5.a Emission in grams/kW.hr for Dodge Pickup /Cummins Engine on 6-Mode Test Using Shell Diesel (U of A, 10:00 AM, March 15, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	19.7	918	0.42	3.55	208	2.47
3	2.71	1190	0.86	8.18	2490	0.18
4	0.27	517	0.20	2.65	465	0.11
5	3.77	1310	0.83	8.00	3070	0.34
6	2.26	1170	0.63	5.81	2390	0.27

Table B3.5.b Emission in grams/kW.hr for Dodge Pickup /Cummins Engine on 6-Mode Test Using Esso Diesel (U of A, 11:00 AM, March 15, 2001).

Mode	CO	CO2	HC	NOx	O2	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	17.6	871	0.224	4.05	262	2.62
3	1.49	1110	0.486	7.67	2400	0.02
4**	*0.27*	*517*	*0.20*	*2.65*	*465*	*0.11*
5**	*3.77*	*1310*	*0.83*	*8.00*	*3070*	*0.34*
6**	*2.26*	*1170*	*0.63*	*5.81*	*2390*	*0.27*

** modes 4, 5 and 6 could not be completed because a lab started and the vehicle needed to be returned before testing could be completed..

Table B3.6.a Emission in grams/kW.hr for Isuzu 4BE1 Engine on 6-Mode Test Using Shell Diesel (U of A, 5:00 PM, March 21, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	4.38	774	28.9	8.55	456	0.50
3	6.07	867	72.7	8.86	3420	0.92
4	2.36	765	22.5	7.65	446	0.42
5	9.52	932	79.9	6.39	3350	0.53
6	1.92	819	29.3	6.23	1030	0.14

Table B3.6.b Emission in grams/kW.hr for Isuzu 4BE1 Engine on 6-Mode Test Using Esso Diesel (U of A, 6:00 PM, March 21, 2001).

Mode	CO	CO2	HC	NOx	02	Filter Soot
	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)	(g/kW.hr)
1	~	~	~	~	~	~
2	7.77	849	39.2	8.51	413	0.32
3	5.99	1020	81.4	10.7	3350	0.37
4	4.26	841	29.8	8.08	385	0.35
5	8.39	1120	82.3	8.18	3470	0.90
6	2.12	936	36.6	6.64	996	0.21

Appendix B4 Weighted Test Results

Table B4.1 Weighted Test Results for Cummins N14 460 Engine on 6-Mode Test. Waterous (Feb 22, 2001) (Wtd. Power = 134 kW Shell, 122 kW Esso)

	Basic Results		Fuel Specific Results (g / kg.fuel)		Power Specific Results (g / kW.hr)	
	Shell	Esso	Shell	Esso	Shell	Esso
Air Flow	302 g/s	308 g/s	28,800	29,300	8060	9020
Fuel	10.5 g/s	10.5 g/s	-	-	280	308
CO	0.004 g/s	0.005 g/s	0.36	0.44	0.10	0.13
CO2	31.10 g/s	29.85 g/s	2970	2840	831	876
HC	0.001 g/s	0.001 g/s	0.13	0.13	0.037	0.042
NOx	0.225 g/s	0.238 g/s	21.5	22.7	6.02	6.99
O2	39.6 g/s	42.4 g/s	3780	4040	1060	1240
Soot	14.6 mg/s	13.0 mg/s	1.39	1.24	0.389	0.382

Table B4.2 Weighted Test Results for newer Detroit Diesel Series 60 Engine on 6-Mode Test (Waterous, Feb 26, 2001) (Wtd. Power = 87.4kW Shell, 88.2kW Esso)

	Basic Results		Fuel Specific Results (g / kg.fuel)		Power Specific Results (g / kW.hr)	
	Shell	Esso	Shell	Esso	Shell	Esso
Air Flow	211 g/s	209 g/s	31700	29800	8690	8530
Fuel	6.87 g/s	7.01 g/s	-	-	272	286
CO	0.071 g/s	0.076 g/s	10.3	10.9	2.89	3.1
CO2	18.6 g/s	18.3 g/s	2710	2610	766	746
HC	0.000 g/s	0.000 g/s	0	0	0	0
NOx	0.195 g/s	0.199 g/s	28.4	28.4	8.03	8.14
O2	30.6 g/s	30.7 g/s	4460	4380	1260	1250
Soot	8.5 mg/s	30.3 mg/s	1.28	4.23	0.35	1.21

Table B4.3 Weighted Test Results for for CAT 3406 Engine on 6-Mode Test.
(Waterous, Feb 27, 2001) (Wtd. Power = 74.4kW Shell, 75.3kW Esso)

	Basic Results		Fuel Specific Results (g / kg.fuel)		Power Specific Results (g / kW.hr)	
	Shell	Esso	Shell	Esso	Shell	Esso
Air Flow	197 g/s	196 g/s	31,700	30,700	9530	9370
Fuel	6.22 g/s	6.39 g/s	-	-	300	305
CO	0.047g/s	0.035 g/s	7.6	5.3	2.27	1.63
CO2	18.6g/s	18.8 g/s	3000	3000	902	916
HC	0.001 g/s	0.001 g/s	0.16	0.11	0.049	0.032
NOx	0.12 g/s	0.14 g/s	19.2	21.5	5.79	6.58
O2	29.4 g/s	27.7 g/s	4730	4350	1420	1330
Soot	14.6 mg/s	14.7 mg/s	2.34	2.29	0.702	0.701

Table B4.4 Weighted Test Results for older Detroit Diesel Series 60 Engine on 6-Mode Test.
(Waterous. Feb 27, 2001) (Wtd. Power = 72.5kW Shell, 64.2kW Esso)

	Basic Results		Fuel Specific Results (g / kg.fuel)		Power Specific Results (g / kW.hr)	
	Shell	Esso	Shell	Esso	Shell	Esso
Air Flow	168 g/s	171 g/s	27,300	28,600	8360	9590
Fuel	6.17 g/s	5.97 g/s	-	-	306	335
CO	0.089 g/s	0.096 g/s	14.5	16.1	4.44	5.41
CO2	17.5 g/s	18.0 g/s	2830	2980	867	1000
HC	0.000 g/s	0.000 g/s	0	0	0	0
NOx	0.20 g/s	0.21 g/s	32.1	34.9	9.84	11.7
O2	21.2 g/s	22.2 g/s	3440	3620	1050	1220
Soot	19.2 mg/s	19.8 mg/s	3.11	3.31	0.950	1.11

Table B4.5. Weighted Test Results for Dodge Pickup /Cummins Engine on 6-Mode Test. (Alberta, Mar 15, 2001) (Wtd. Power = 29.9kW Shell, 28.6kW Esso)

	Basic Results		Fuel Specific Results (g / kg.fuel)		Power Specific Results (g / kW.hr)	
	Shell	Esso	Shell	Esso	Shell	Esso
Air Flow	80.8 g/s	78.0 g/s	36,900	35,100	12,200	11,900
Fuel	2.19 g/s	2.22 g/s	-	-	335	338
CO	0.036 g/s	0.031 g/s	16.4	13.8	5.43	4.66
CO2	6.48 g/s	6.27 g/s	2960	2830	977	955
HC	0.0041 g/s	0.0033 g/s	1.89	1.48	0.63	0.50
NOx	0.037 g/s	0.034 g/s	16.9	15.1	5.59	5.10
02	12.2 g/s	11.8 g/s	5560	5290	1840	1780
Soot	4.41 mg/s	4.39 mg/s	2.00	1.98	0.667	0.669

Table B4.6 Weighted Test Results for Isuzu 4BE1 Engine on 6-Mode Test (Alberta, Mar 21, 2001) (Wtd. Power = 18.5 kW Shell, 18.0 kW Esso)

	Basic Results		Fuel Specific Results (g / kg.fuel)		Power Specific Results (g / kW.hr)	
	Shell	Esso	Shell	Esso	Shell	Esso
Air Flow	47.0 g/s	46.1 g/s	35,300	34,900	9140	9220
Fuel	1.33 g/s	1.32 g/s	-	-	259	265
CO	0.0162 g/s	0.0199 g/s	12.2	15.1	3.15	4.00
CO2	4.22 g/s	4.67 g/s	3180	3540	821	937
HC	0.186 g/s	0.220 g/s	140	167	36.3	44.1
NOx	0.0366 g/s	0.0388 g/s	27.5	29.4	7.11	7.78
02	6.58 g/s	6.23 g/s	4950	4730	1280	1250
Soot	1.85 mg/s	1.97 mg/s	1.39	1.49	0.360	0.394

Appendix C

Supplementary calculations

- **Estimation of NO Formation From the Fuel Nitrogen content**

The purpose of this calculation was to estimate the amount of NO formed from the nitrogen content in the fuel assuming that all the nitrogen will be converted to NO.

- to convert from ppm to N/kg fuel
  b g/ kg fuel = a [ppm /1,000,000] * [1000 g/ kg]
- to convert from N/ kg fuel to NO/kg fuel

1 g NO/kg fuel =1 g of N/kg fuel * molecular weight of NO/molecular weight of N

The difference between N_2 content= 177-59 = 118 ppm
118 ppm = (118/1000,000) * 1000 (g/kg) = 0.118 g/kg fuel
NO = 0.118 * (30/14)= 0.255 g/kg fuel

NO = 0.252 g/kg fuel

where molecular weight for NO and N_2 are 30 and 28 kg/kmol

The calculations were done provided that all the nitrogen in the fuel would form NO.

- **Estimate of SO_4 Formation from the Fuel Sulfur Content**

The purpose of this calculation was to estimate the amount of SO_4 formed from the sulfur content in the fuel assuming that all the sulfur will be converted to SO_4.

- to convert from ppm to g/kg of fuel
  b g/kg fuel = a [ppm/1,000,000] * [1000 g/kg]
- to estimate the amount of formed SO_4

1 g of SO_4/kg fuel = 1 g of S/kg fuel * molecular weight of SO_4/molecular weight of S

837 ppm = (837/1000,000) * 1000 (g/kg) = 0.837 g/kg fuel

Sulfate compound = 0.837 * (96/32)= 2.51 g/kg fuel

Sulfate compound= 2.51 g/kg fuel
sulfur and oxygen (O_2) molecular weight is 32 kg/kmol for both.

- **Uncertainty Analysis**

This topic is covered in detail by Figliola, R. D. and Beasley, D. E., "Theory and Design for Mechanical Measurements, 3rd ed., Wiley, New York, 2000 "

For a result, R, which is determined through some functional relationship between independent variables, X_1, X_2,....... X_n, is defined by

$$R = f_1 \{X_1, X_2, \ldots\ldots X_n\} \qquad \text{C1}$$

where n is the number of independent variables involved.

The best estimate of the mean value R' is:

$$R' = R'' \pm U_R\ (p\%) \qquad \text{C2}$$

and sample mean is given by:

$$R'' = f_2 \{ X''_{1.} X''_2, \ldots\ldots\ldots\ldots X''_n\} \qquad \text{C3}$$

The uncertainty in R is found by:

$$U_R = f_2 \{U_{1.} U_2, \ldots\ldots\ldots U_n\} \qquad \text{C4}$$

the most probable estimate is given by the Kline-McClintock power relation:

$$U_R = \pm[\mathop{}\limits_{1=n}^{n} [(\in R/\in X_n)_{x=}\ ]^2 * [U_n]^2]^{0.5} \qquad \text{C5}$$

- **PM Uncertainty Calculations**

PM uncertainty is calculated according to the following Assumptions:
1- The only contribution is due to the zero-order uncertainty, U_0.

$$U_0 = \pm 0.5 \text{ resolution} \qquad \text{C6}$$

2- The weighted results will replace the average results as following:

weighted Power = 67.75 kW
weighted PM weight = 1.97 mg
weighted time = 4.4 min

$U_P = 0.5$ kW
$U_w = 0.005$ mg
$U_T = 0.5$ sec

Applying Kline-McClintock power relation yields the following"

$$\text{PM (mg/kW.sec)} = f\,\{\text{ power, soot weight, time}\}$$

$$\text{PM (mg/kW.sec)} = f\,\{P, W, T\}$$

$$U_{pm}/\ \text{(mg/kW.sec)} = [\ (-U_P/\ P)^2 + \ (U_w/W)^2 + (-U_T/\ T)^2]^{0.5}$$

$$U_{pm}/\ \text{(mg/kW.sec)} = \pm[\ (-0.5/\ 67.75)^2 + \ (0.005/1.97)^2 + (-0.5/\ 4.4*60)^2]^{0.5}$$

$$U_{pm}/\ \text{(mg/kW.sec)} = \pm\ 0.8\ \%$$

$$U_{pm}/\ \text{(g/kW.hr)} = U_{pm}/\ \text{(mg/kW.sec)} * \text{(g/1000mg)}*\text{(3600 sec/ 1 hr)}$$

$$\mathbf{U_{pm}/\ (g/kW.hr) = \pm\ 2.9\ \%}$$

If a single mode PM measurement has ± 2.9 % uncertainty the uncertainty of a 6-mode test value would be:

$$U_{pm}\ (g/kW.hr)_{6\text{-mode}} = \pm\ 2.9\ \%/(6)^{0.5} = \pm\ 1.2\ \%$$

•NOx Uncertainty Calculations

NOx (g/kW.hr) = f {NOx mass flow rate, power)C7

Power (kW) = (2 * 3.14)/60 * Torque * rpm = Constant * Torque * rpm

Power (kw) = f{ Torque, rpm)

Applying Kline-McClintock power relation for the power:

$$U_p/\ \text{power} = \pm[\ (U_T/\ \text{Torque})^2 + \ (U_{rpm}/\ \text{rpm})^2\ ]^{0.5}$$

Torque = weighted Torque = 59 N.m
Speed = weighted speed = 1540rpm
U_T = 0.5N.m
U_{rpm} = 0.5rpm

$$U_p/\ \text{power} = \pm 2*3.14*[(0.5/59)^2 + (0.5/1540)^2]^{0.5}$$

$$\mathbf{U_p/\ power = \pm\ 5.3\ \%}$$

NOx = f{mass fuel flow rate, mass air flow rate}

Applying RSS method for NOx mass flow rate:

$$U_{nox} = \pm[\ (U_{fuel})^2 + \ (U_{air})^2\ ]^{0.5}$$

U_{fuel}= 0.0005 g/sec
U_{air}= 0.005g/sec

$\mathbf{U_{nox} = \pm\ 0.005\ g/sec}$

substituting the values of U_{nox} & U_p into equation C7
where average weighted NOx = 0.14 g/sec

$$U_{NOx}/(\ g/kW.hr) = \pm[(0.005/0.14)^2 + (0.053)^2]^{0.5}$$

$\mathbf{U_{NOx}/(\ g/kW.hr) = \pm 6.4\%}$

If a single mode NO measurement has ± 6.4 % uncertainty the uncertainty of a 13-mode test value would be:

$$U_{pm}\ (g/kW.hr)_{6\text{-}mode} = \pm\ 6.4\ \%/(13)^{0.5} = \pm\ 1.8\%$$