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CANADIAN DIESEL FUEL COMPOSITION AND EMISSIONS - STAGE IV REPORT

Prepared by

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July, 2003

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FOREWORD

The "Canadian Diesel Fuel Research Collaboration",[1] a joint industry/government program, was initiated in 1995 to investigate the emissions behaviour of diesel fuels containing oil sands components in heavy-duty diesel engines. The first three stages of the program were performed using a single-cylinder version of a Volvo TD 123 diesel engine representative of 1994 model year technology. The fourth stage of the research program, described herein, involved the installation of a single-cylinder version of a Caterpillar 3406E diesel engine in a test cell, modifying the engine to meet year 2004 emissions regulations by adding a cooled-EGR system, and performing a limited number of fuel-effect experiments. Additional fuel-effect experiments will be performed using the same engine in the next research stage.

The research program is jointly funded by a number of government agencies and the petroleum industry. The government partners are the National Research Council Canada (NRC), the Government of Canada's Program of Energy Research and Development (PERD), the National Centre for Upgrading Technology (NCUT), and the U.S. Department of Energy's National Renewable Energy Laboratory (NREL). The industry partners are Syncrude Canada Ltd. (Syncrude), Suncor Energy Inc. (Suncor), the Canadian Petroleum Products Institute (CPPI), Shell Canada Ltd. (Shell), and Imperial Oil Ltd. (Imperial Oil). The program also receives funding from the B.C. Clean Air Research Fund, a joint government/industry initiative. The research activities are currently directed by a Steering Committee consisting of Mr. Stuart Neill (NRC), Dr. Craig Fairbridge (NCUT), Dr. Robert McCormick (NREL), Dr. Jean Cooley (Syncrude), Mr. Mike Doma (Suncor), Mr. Ken Mitchell (Shell), and Mr. Bob Falkiner (Imperial Oil).

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[1] The research program was originally entitled "Canadian Diesel Fuel Composition and Emissions."

EXECUTIVE SUMMARY

In 1995, the National Research Council Canada (NRC) initiated a collaborative industry/government program to better understand the emissions behaviour of diesel fuels containing oil sands components in current- and next-generation engines. The first three stages [1-3] were conducted using a single-cylinder version of a Volvo TD123 diesel engine calibrated to meet the U.S. EPA on-highway heavy-duty diesel emissions regulations for the 1994 model year. A status report [4] was written upon the completion of Stage III of the research program to summarize the emissions behaviour of Canadian diesel fuels in current-generation, heavy-duty diesel engines.

A single-cylinder version of a Caterpillar 3406E diesel engine was equipped with cooled exhaust gas recirculation (EGR) and calibrated to meet the 2004 emissions regulations for the fourth stage of the research program. EGR rates were established at the AVL eight-mode steady-state test conditions by measuring the trade-off between soot and NO_x emissions using NRC's laser-induced incandescence (LII) system and a standard chemiluminescent analyzer. EGR was found to be effective in reducing the composite NO_x emissions from the engine by 42%, from 4.25 to 2.47 g/hp-hr. Dilution of the intake air charge by the recirculated exhaust gases, however, led to a 92% increase in PM emissions from 0.039 to 0.076 g/hp-hr. Advances in diesel fuel injection technology by 2004 are expected to reduce the negative impact of EGR on PM emissions.

The effect of fuel sulphur content on PM emissions from the Caterpillar research engine was determined by blending various quantities (up to 480 ppm by mass) of single- and four-compound sulphur dopants with low sulphur base fuels. The PM emissions increased linearly by 0.001 g/hp-hr for each 60 ppm of fuel-bound sulphur. In other words, the PM emissions from this engine increase by 13% as the fuel sulphur content increases from 0 to 500 ppm. The experimental data suggests that PM emissions were affected by the fuel sulphur content, but not by the type of sulphur compound.

A preliminary experiment was performed with a reference fuel and two test fuels containing 30% aromatics, one derived from oil sands sources and the other derived from conventional sources. The fuels were tested in the engine, with and without EGR, at the AVL eight-mode test conditions. EGR reduced the composite NO_x emissions from the engine by 42% for all three fuels, but the three fuels had different sensitivities to EGR in terms of increased PM emissions. The influence of EGR on PM emissions will be evaluated after the remaining ten fuels of this matrix have been tested.

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1 INTRODUCTION

In 1995, the National Research Council Canada (NRC) initiated a collaborative industry/government program to better understand the emissions behaviour of diesel fuels containing oil sands components in current- and next-generation engines. The first three stages were conducted using a single-cylinder version of a Volvo TD123 diesel engine. The engine was calibrated to meet the U.S. EPA on-highway heavy-duty diesel emissions regulations for the 1994 model year. In the first stage, the exhaust emissions from the engine operated with diesel fuels derived from oil sands and conventional sources were compared [1]. The impact of fuel cetane number and sulphur content on engine exhaust emissions was quantified. In the second stage, the effect of fuel aromatic type on particulate matter (PM) and oxides of nitrogen (NO_x) emissions was investigated using test fuels containing both conventional and oil sands components [2]. In the third stage, the impact of fuel sulphur content and fuel aromatic content and type were further studied using test fuels blended from a low-sulphur base fuel, solvents, and pure compounds [3]. Key results from the first three stages of the research program using current-generation diesel engine technology are summarized in a status report [4] and in Appendix A.

In October 1997, the U.S. EPA adopted new emission standards for model year 2004 and later on-highway heavy-duty diesel engines to limit the sum of NO_x+HC emissions to 2.5 g/hp-hr. In October 1998, a court settlement was reached between the U.S. EPA, Department of Justice, California Air Resources Board and six major engine manufacturers to advance the introduction of these standards to October 2002 in exchange for other considerations. Significant advances in diesel engine technology were required to meet the new standard. Most notably, many of the major North American manufacturers have adopted cooled exhaust gas recirculation (EGR) to reduce NO_x emissions from their engines.

The U.S. Department of Energy (DOE) established a joint industry/government program on Advanced Petroleum-Based Fuels-Diesel Emissions Control[2] (APBF-DEC) in February 2000 [5]. The objectives of the program are to identify and evaluate: the optimal combinations of low-sulphur diesel fuels, lubricants, diesel engines, and emission control systems to meet projected emission standards for the 2001-2010 time period; and properties of fuels and vehicle systems that could lead to even lower emissions beyond 2010. The National Renewable Energy Laboratory (NREL) has been designated program manager for implementation of various portions of the APBF-DEC program. As part of its mission under APBF-DEC, NREL is conducting a number of projects to evaluate fuels and the performance of engines and vehicles operated with them. NREL has identified a need to obtain data on diesel fuels that vary from the conventional diesel fuels used in the U.S. This research program will contribute to this effort by collecting information on the properties and performance of oil sands derived diesel fuel.

Research programs have also being carried out in Europe[3] and Japan[4] to determine the role that fuel reformulation might play in helping heavy-duty diesel engines to meet future

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[2] See http://www.ott.doe.gov/apbf.shtml

[3] See http://europa.eu.int/comm/environment/autooil/

[4] See http://www.pecj.or.jp/jcap/framebase1-jcap-e.htm

legislated emission reductions and to better understand the relationship between fuel properties and diesel emissions. In 1996, the European Auto-Oil Programme studied the relationship between fuel properties and the emissions behaviour of five 1996 heavy-duty diesel engines using an eleven-fuel matrix [6]. A similar study of fuel effects on diesel emissions was recently completed as part of the Japanese Clean Air Program [7].

The U.S., European, and Japanese programs have largely concentrated on diesel fuels that do not reflect the Canadian situation. In particular, these studies have not considered diesel fuels containing oil sands derived components or winter diesel fuels with very low temperature operability requirements. There is a strong need to understand how the performance and emissions of next-generation diesel engines are impacted by Canadian diesel fuel composition.

In Stage IV of this research program, a single-cylinder version of a Caterpillar 3406E diesel engine was equipped with exhaust gas recirculation and calibrated to meet the diesel emission regulations for the 2004 model year. Preliminary experiments were conducted to examine the effect of exhaust gas recirculation on engine emissions for two test fuels, one derived from oil sands sources and the other derived from conventional sources. In Section 2, the experimental set-up is described. Experimental results are reported in Sections 3 to 5. The effect of exhaust gas recirculation on engine NO_x and PM emissions is discussed in Section 3. The impact of fuel sulphur content on PM emissions is the subject of Section 4. In Section 5, preliminary diesel exhaust emissions data obtained using test fuels derived from oil sands and conventional sources is presented. Finally, conclusions are drawn in Section 6.

2 EXPERIMENTAL SET-UP

2.1 Research Engine

NRC acquired a new research engine in March 2001 to investigate the relationship between fuel properties and emissions from a prototype year 2004 diesel engine. The engine is a single-cylinder version of Caterpillar's 3400-series heavy-duty diesel engine. The engine has four valves, a displacement of 2.44 litres, electronically-controlled fuel injection, and produces 74.6 kW at 2100 rpm. Further details of the engine configuration may be found in Table 2-1. The base engine is representative of Caterpillar's engine technology for the 1994-1997 model years. The single-cylinder research engine was set up to simulate one cylinder of a 500-hp, six-cylinder version of the engine sold in model year 2000. Then, a cooled EGR system was added to produce a prototype year 2004 engine. A photograph of the engine installation may be found in Figure 2-1.

Compressed and temperature-controlled air is supplied to the research engine to simulate the parent engine's turbocharging and intercooling system. An air surge tank at the inlet to the research engine prevents pressure pulsations from disturbing airflow measurement or charge pressure control. The intake air mass flow is measured by a turbine flow meter (EG&G Flow Technology, model FT-20C1NA-GEA-1). The exhaust system has been fitted with a back pressure valve to provide a cylinder pressure pumping loop similar to that of the parent engine. A tank in the exhaust line reduces pressure pulsations and provides complete mixing of the exhaust gases before sampling.

Diesel fuel is filtered, gravity-fed to an AVL fuel balance (model 733), and then delivered to the engine's fuel injection pump. A 500 Hz pulse width modulated signal serves as the throttle-input signal to the engine's electronic control module (ECM).

Filtered lubricating oil (Shell Rotella™ T with XLA, 15W-40) is supplied to the engine at a

Table 2-1 Research Engine Configuration

Parameter	Value
Engine Model	Caterpillar 3401E
Number of Cylinders	1
Parent Engine	Caterpillar 3400 series
Bore x Stroke	137.2 mm x 165.1 mm
Compression Ratio	16.25:1
Displacement	2.44 liter
Number of Valves	4
Combustion Chamber Type	Quiescent
Fuel Injection Type	Direct Injection
Fuel Injection	Mechanically-Actuated Electronic Unit Injection
Exhaust Gas Recirculation	External Cooled
Maximum Power Output	74.6 kW (2100 rpm)

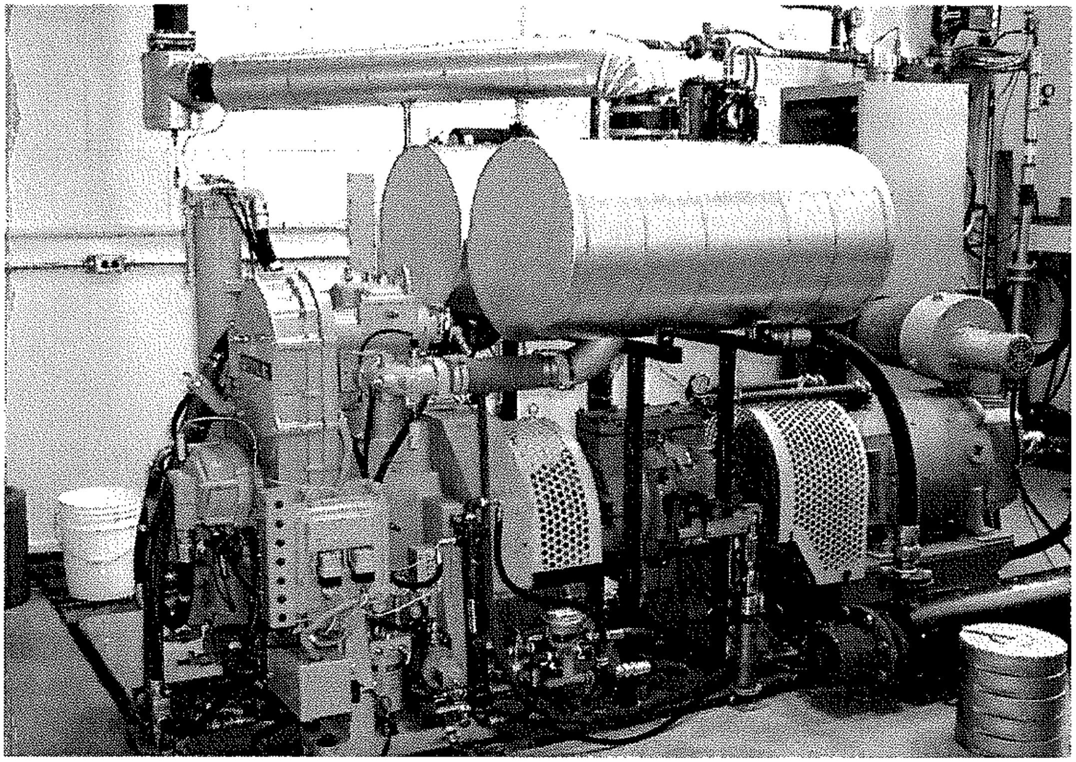

Figure 2-1 Caterpillar 3401E Engine

pressure of 400 kPa by an external pump. The lubricating oil is cooled by an integral oil-to-water heat exchanger. An external flow control valve and a 5 kW heater are used to maintain an engine oil temperature of 95°C.

Engine coolant temperature is maintained at 85°C using the engine's integral coolant-to-water heat exchanger. The coolant temperature is controlled using a valve that adjusts the water flow to the heat exchanger.

The engine is connected to the dynamometer by a flexible drive coupling (KopFlex Inc., model Holset 3.0 Max-C "CB"). Engine loading is accomplished by an eddy-current dynamometer (Mid-West, model 1014) rated to absorb 131 kW at 2500 rpm. A load cell (Lebow, model 3169) measures the dynamometer load. Engine speed is sensed by a Hall-effect transducer. A DC electric motor is used to start and motor the engine.

2.2 Prototype Cooled EGR System

A prototype cooled exhaust gas recirculation (EGR) system was produced by connecting the exhaust and intake surge tanks to one another. The EGR system is activated by restricting the engine exhaust to raise the back pressure above the intake air pressure, which causes engine exhaust to flow from the exhaust surge tank through the EGR system into the intake air surge tank. The EGR is driven by the pressure differential between the exhaust and intake surge tanks and is regulated by a flow control valve. Cooling of the recirculated exhaust gas is accomplished by a tube-and-shell heat exchanger supplied by Caterpillar Inc. A photograph of the EGR system may be seen in Figure 2-2.

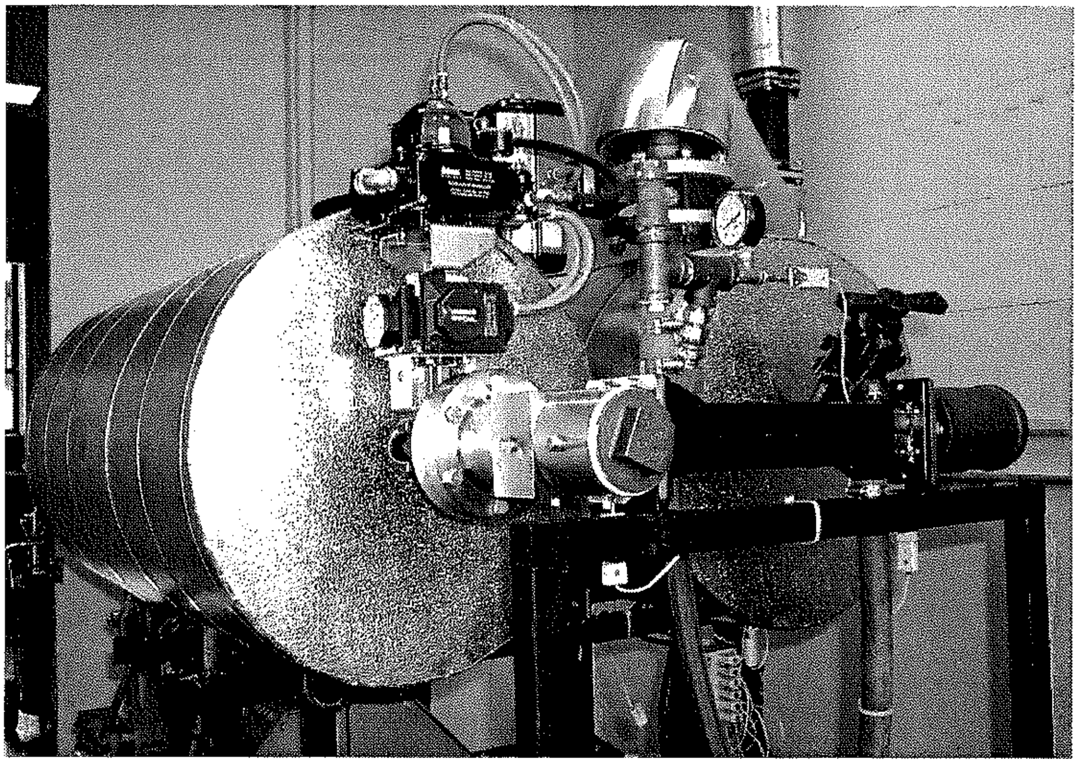

Figure 2-2 Close-up of the Cooled EGR System

2.3 Test Cell Data Acquisition and Control

The test cell is operated using a data acquisition and control system (KineticSystems Inc.) based on the VXI standard. The hardware consists of the following modules: 4-channel 16-bit analogue/digital converter (model V208); 96-channel multiplexer (model V243); 16-channel digital/analogue converter (model V266); 16-channel digital I/O module (model V387); and an 8-channel frequency counter (model V635). The test cell equipment is controlled using optically-isolated solid-state relays (Opto 22) connected to the digital I/O module. The hardware is configured and controlled using commercial software (KineticSystems Inc., model DAQ Director II). Figure 2-3 is a photograph of the test cell data acquisition and control system.

The speed and load of the research engine are controlled independently by the engine's electronic control module (ECM) and a dynamometer controller (Digalog, model 1022A), respectively. The fuel injection timing is adjustable by uploading the desired timing to ECM memory using custom software supplied by Caterpillar.

2.4 Standard Emissions Instrumentation

A heated probe is mounted after the exhaust surge tank to sample the gaseous emissions. The emissions instrumentation (Rosemount, model NGA 2000) consists of a chemiluminescent oxides of nitrogen (NO_x) analyzer, a flame ionization total hydrocarbon (HC) analyzer, a non-dispersive infrared carbon monoxide (CO) analyzer, and a paramagnetic oxygen (O_2) analyzer. Non-dispersive infrared analyzers are used to measure

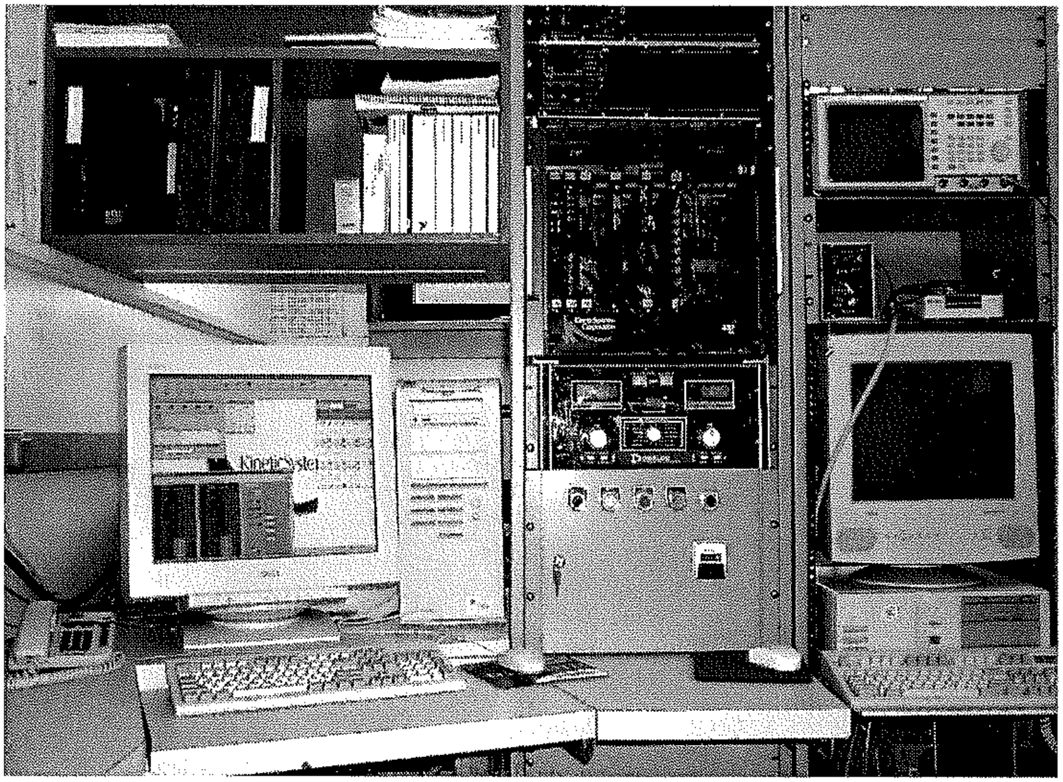

Figure 2-3 Photograph of the Test Cell Data Acquisition and Control System

the carbon dioxide (CO_2) concentration in the engine intake and exhaust streams (Rosemount, model NGA 2000). Figure 2-4 is a schematic of the emissions instrumentation. Figure 2-5 is a photograph of the instrumentation used to measure gaseous emissions.

Engine particulate matter (PM) emissions are measured using a fully automated particulate sampling system (Sierra Instruments Inc., model BG-2), shown in Figure 2-6. The system operates by diluting a portion of the exhaust gas stream with a measured amount of dry, hydrocarbon-free air in a patented dilution chamber and passing the dilute exhaust gas through a pair of 90-mm filter membranes (Pallflex, fiberfilm T60A20). The dilution ratio of the chamber is selected such that the particulate sampling temperature is 52°C or lower. The system satisfies ISO 8178-1 requirements for equivalency as compared with the U.S. EPA full dilution test systems operated on a steady-state basis. The U.S. EPA has awarded engine certifications under regulation 40 CFR 89 using this particulate measurement system. The PM filters are conditioned before the test and after sampling in an environmental chamber (Lunaire Ltd., model Tenney BTRS) and are weighed by a micro-balance (Sartorius AG, model M5P-000V001).

Figure 2-7 is a photograph of the gaseous and PM sampling systems hanging from the exhaust system downstream of the exhaust mixing tank. The removable PM filter holder is located below the dilution chamber enclosure in the lower right-hand-side of the picture. Reference filters are maintained in the environmental chamber and are weighed before and after each experiment at the same time as the sample filters. The net weight of each sample is adjusted to correct for any weight gain or loss by the reference filters.

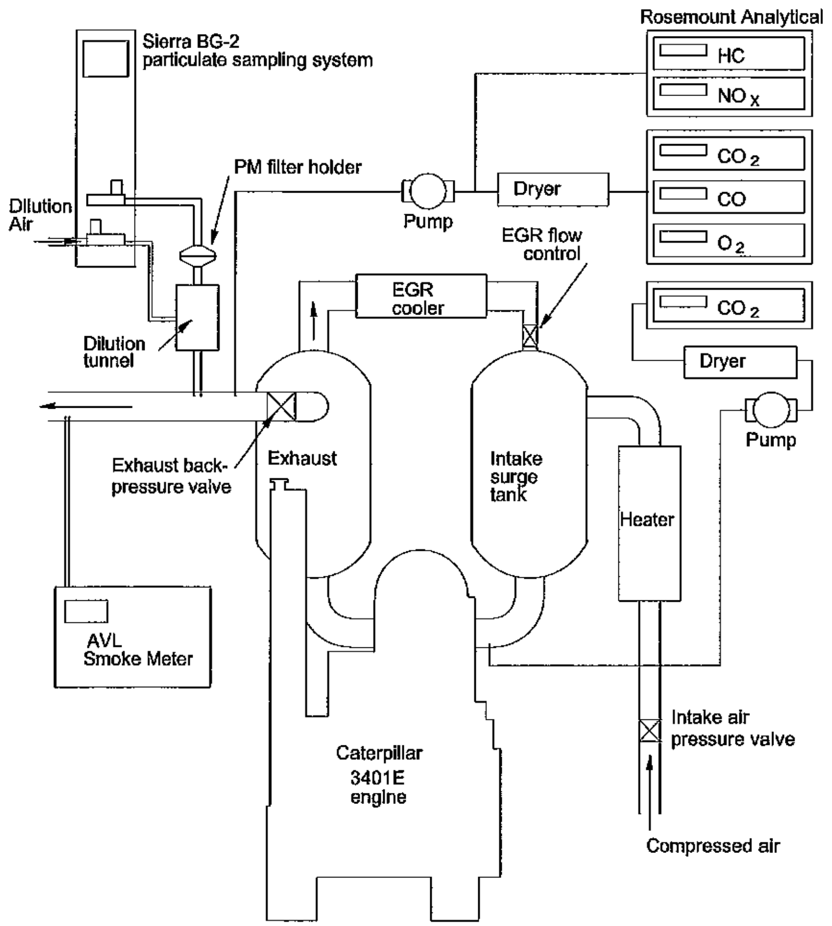

Figure 2-4 Schematic of the Emissions Instrumentation

2.5 Laser-Induced Incandescence

Laser-induced incandescence (LII) is a powerful optical diagnostic for studying soot (elemental carbon-based particles emitted from combustion sources) formation and oxidation in complex combustion flow fields. LII measures the soot volume fraction, active surface area, and primary particle size in real-time under both steady state and transient conditions. An excellent review of LII theory and practical applications of the method is available in [8].

NRC has successfully developed and applied the LII method to measure soot concentrations covering a range of six orders of magnitude, as shown in Figure 2-8. The applications include laminar diffusion flames [9], carbon black production [10, 11], diesel engine exhaust streams [10, 12, 13], and direct injection spark ignition (DISI) vehicle exhaust [14]. LII has been shown by Wainner et al. [15] to be sensitive to soot concentrations as low as one part-per-trillion (ppt). In this study, the LII method was used to rapidly investigate the trade-off between soot and NO_x emissions from the Caterpillar 3401E engine in order to select appropriate EGR rates at the AVL eight-mode test conditions.

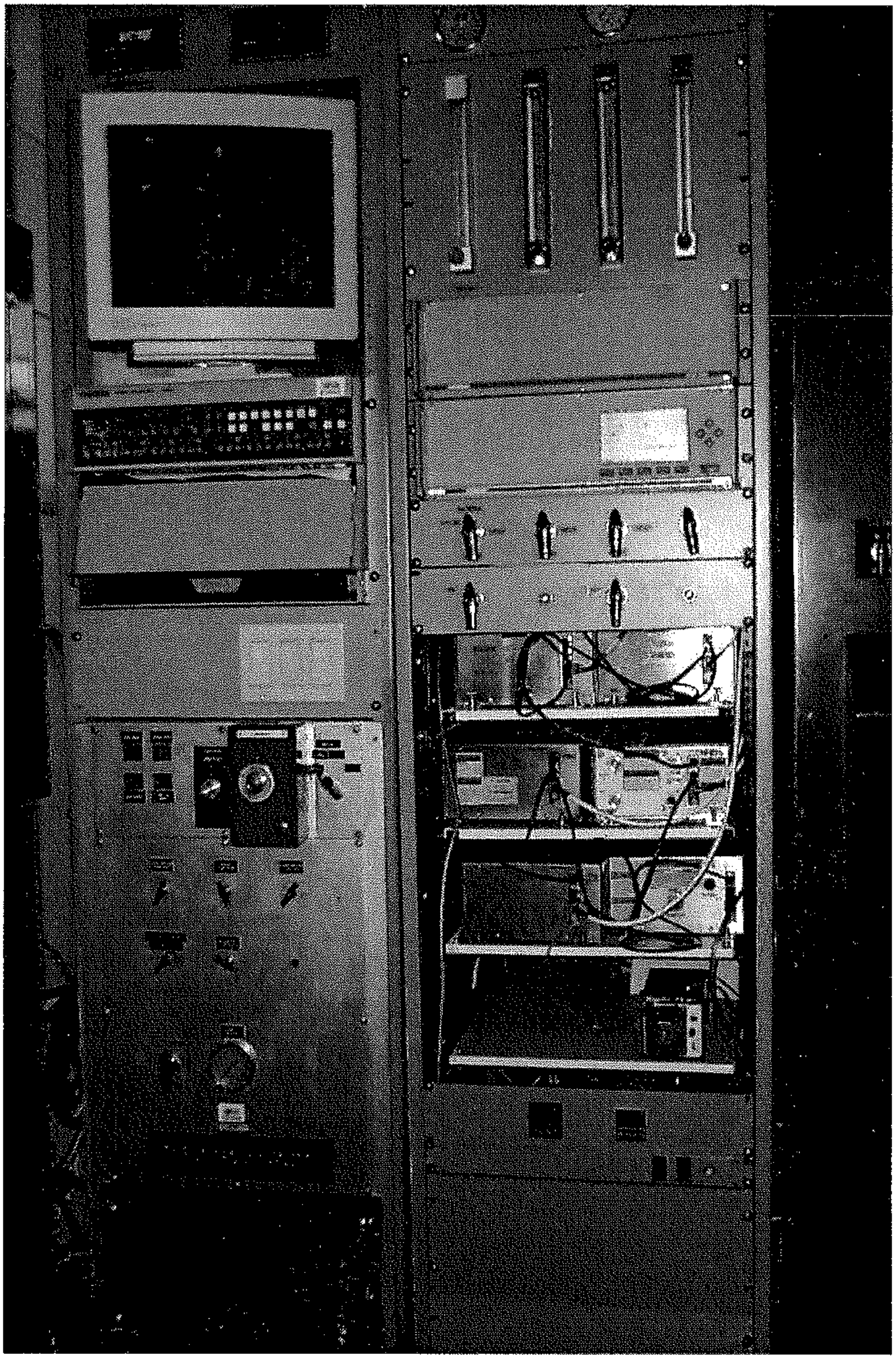

Figure 2-5 Photograph of the Gaseous Emissions Instrumentation

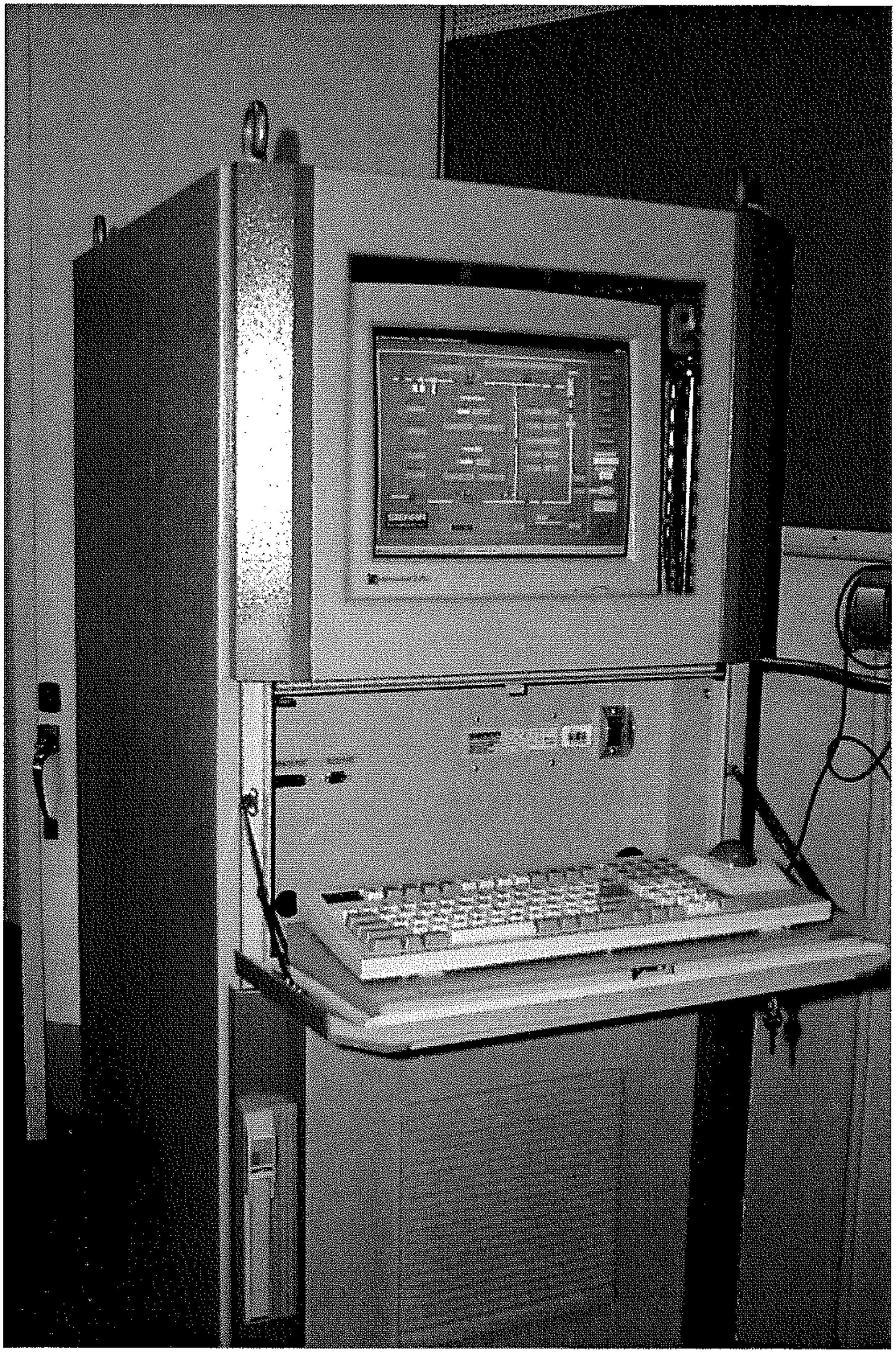

Figure 2-6 Photograph of the PM Emissions Instrumentation

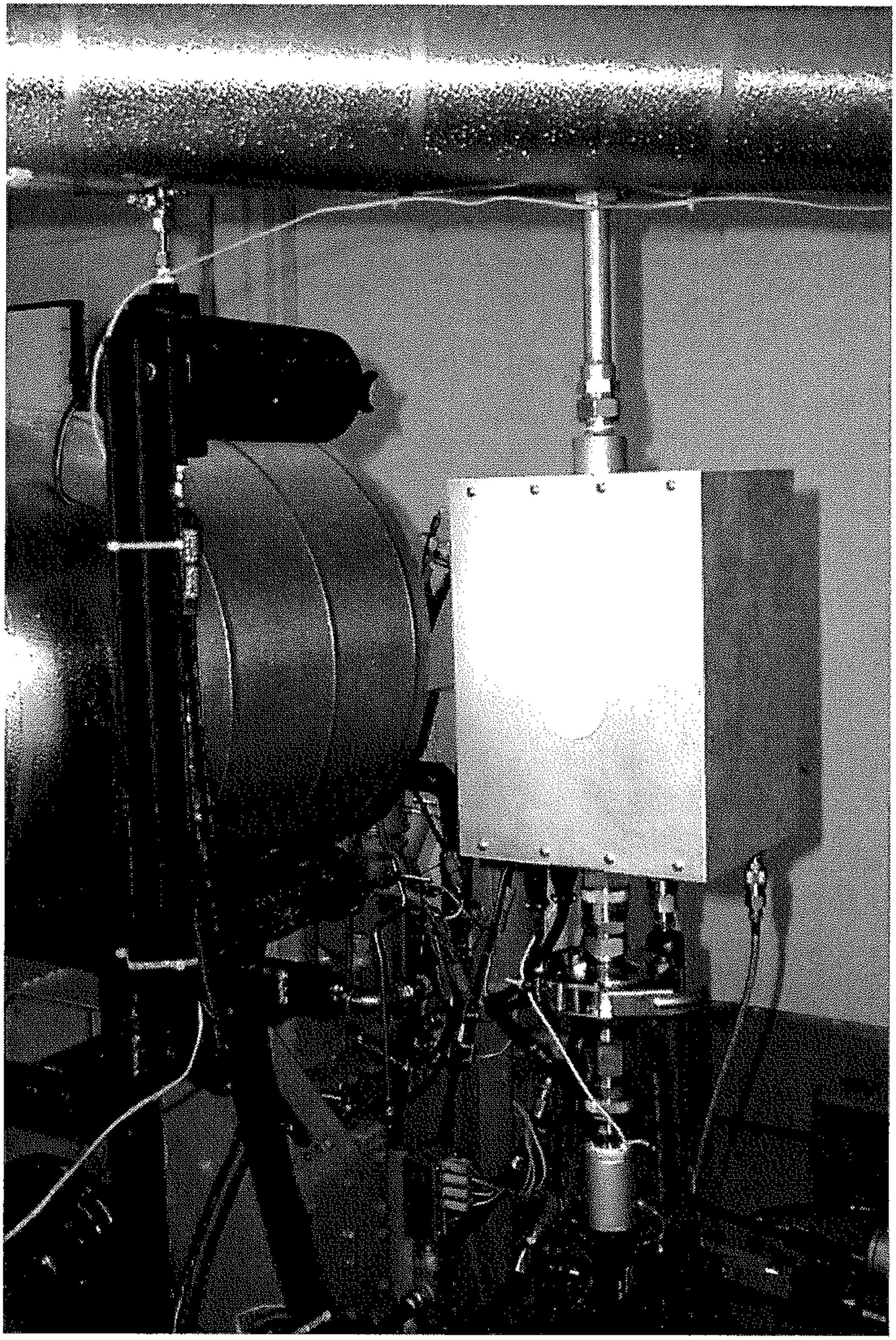

Figure 2-7 Photograph of the Gaseous and PM Emissions Sampling Systems

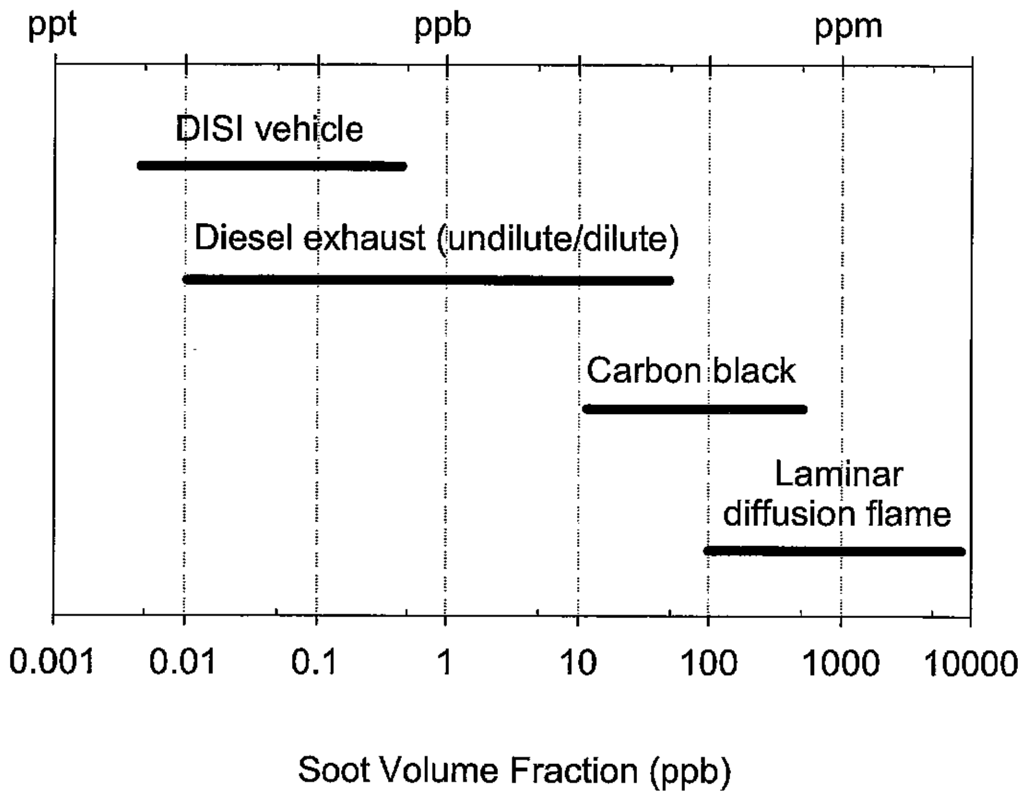

Figure 2-8 Range of Soot Volume Fractions Studied by NRC using LII Method

For this experiment, a pulsed Nd:YAG laser (Big Sky Laser Technologies Inc., model Ultra CFR), operating with 15 mJ/pulse at 20 Hz and 1064 nm, was used as the excitation source. A half-wave plate (to rotate the plane of polarization) in combination with a thin film polarizer (angle-tuned to transmit horizontally polarized radiation) was used to adjust the laser energy as required. A second half-wave plate was used to return the plane of polarization to vertical. Near top-hat (i.e. spatially uniform) laser energy profiles were used for all measurements to ensure that the soot particles inside the sample volume were heated to a uniform temperature. A schematic of the LII system may be seen in Figure 2-9.

The 1064-nm output beam of the laser was geometrically filtered by a 1.25 mm wide by 2.35 mm tall slit. Relay imaging of the slit (2:1) was used to generate a 2.5 mm wide by 4.7 mm tall rectangular laser beam at the probe volume with a top-hat energy distribution profile. The LII signal from the center of the laser beam was imaged at 2:1 magnification onto a 1 mm diameter aperture, which was direct-coupled to a two-channel demultiplexer detector box. The imaging system was arranged such that the imaging axis was at an angle of 35° from the forward direction of the laser beam.

An optical cell was placed in the line between the dilution tunnel and the PM filter holder. When the laser was pulsed, particulates passing through the center of the cell were heated and the subsequent incandescence was measured. The LII signal was recorded by two photomultipliers, equipped with narrowband interference filters centered at 400 nm and 780 nm, respectively. Transient signals from the photomultipliers were recorded and subsequently transferred to a computer for further analysis. A total of 400 LII signals were collected at each engine operating condition.

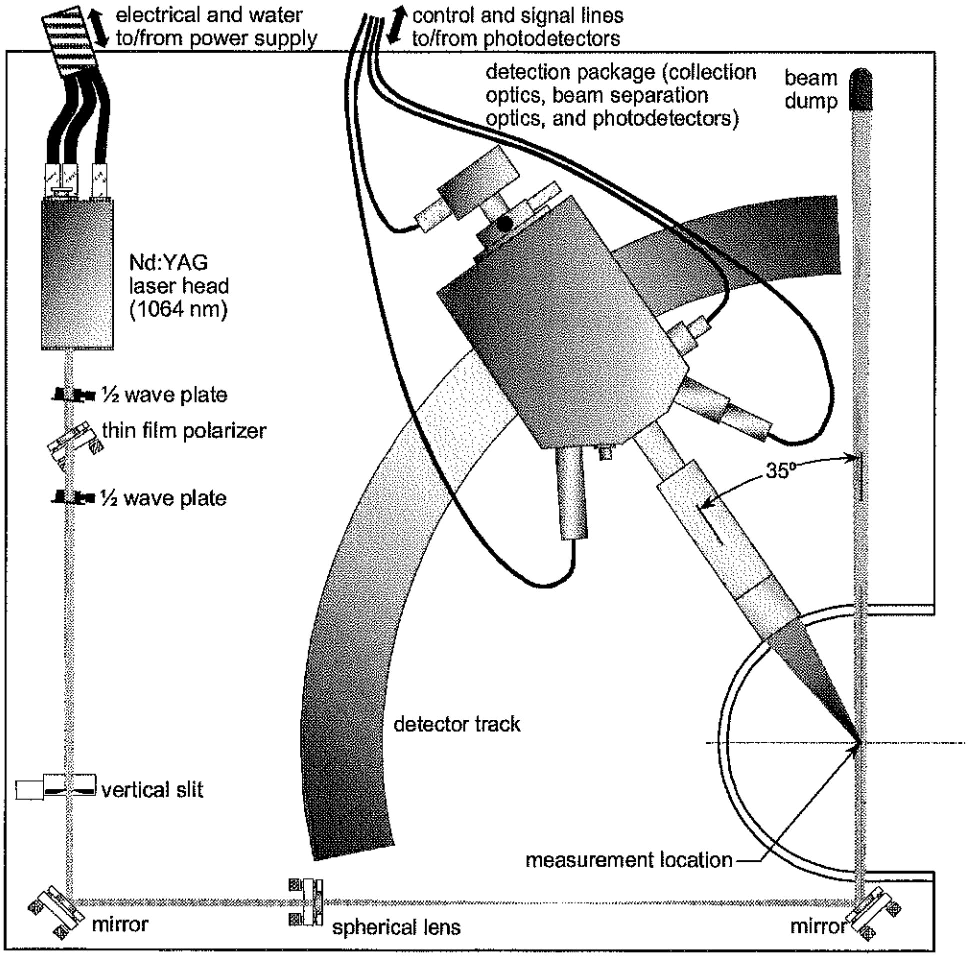

Figure 2-9 Top-view Schematic of the LII Optical Apparatus

The methodology to determine the soot concentration is as follows. It is based upon knowledge of the particulate surface temperature, determined by two-wavelength pyrometry. A single point calibration is made in a known source at a known temperature, which results in an absolute sensitivity (in W/m^3·ster). By recording the time-resolved exhaust data at two wavelengths, the temperature of the particulate can be determined at any point in time by solving the following equation

$$\frac{I_{\lambda_1}}{I_{\lambda_2}} = \frac{\lambda_2^{\ 6}}{\lambda_1^{\ 6}} \frac{\left(e^{\frac{hc}{k\lambda_2 T}} - 1\right)}{\left(e^{\frac{hc}{k\lambda_1 T}} - 1\right)} \frac{E(m)_{\lambda_1}}{E(m)_{\lambda_2}} \qquad (2\text{-}1)$$

where T is the particle surface temperature, I_λ is the LII intensity, λ is the detection wavelength, $E(m)$ is a refractive index dependent function, h and k are Planck and Boltzmann constants, respectively, and c is the velocity of light. $E(m)$ was assumed to be 0.278 and 0.336 at the detection wavelengths of 400 and 780 nm, respectively, based on experimental data by Krishnan et al. [16].

The radiation, P_p, from a single primary particle of diameter, d_p, and known temperature, T, can be determined as

$$P_p(\lambda) = \frac{8\pi^3 c^2 h}{\lambda^6 \left(e^{\frac{hc}{k\lambda T}} - 1\right)} d_p^3 \, E(m) \tag{2-2}$$

The number of primary particles, N_p, is then determined from the ratio of the experimental intensity to P_p. The soot volume fraction, f_v, can then be determined from

$$f_v = \frac{\pi \, d_p^3}{6} \cdot \frac{N_p}{V} \tag{2-3}$$

where V is the sample volume determined by the product of the cross-sectional area of the laser sheet viewed and the sheet thickness. Solving Eq. (2-2) for d_p^3, and substituting into Eq. (2-3), one obtains

$$f_v = \frac{N_p P_p(\lambda) \, \lambda^6 \left(e^{\frac{hc}{k\lambda T}} - 1\right)}{48\pi^2 c^2 h E(m) V} \tag{2-4}$$

In Eq. (2-4), the soot volume fraction is proportional to the experimentally-measured absolute LII intensity, $N_p P_p(\lambda)$, and may be calculated without knowing the primary particle size. If desired, the specific surface area and primary particle size, d_p, can also be determined by analyzing the decay rate of the soot temperature [13].

The absolute light intensity method for calibrating LII signals [11] applies two-wavelength pyrometry principles to determine soot particle temperatures. The method, developed at NRC, relates the measured LII signals to the absolute sensitivity of the LII signal collection system as determined with a strip filament lamp. The adoption of this approach provides for continuous self-calibration of the LII technique. This allows lower laser fluences to be used, which results in lower maximum soot temperatures. Thus, issues associated with evaporating a significant portion of the soot are avoided.

2.6 Test Procedure

The AVL eight-mode steady-state simulation [17] of the U.S. EPA Transient Test Procedure was adopted. In this simulation, engine emissions are measured at eight speed/load conditions as shown in Figure 2-10. The emissions measured at the eight modes are weighted according to the factors indicated in the graph to produce composite emissions. It should be noted that the weighting factors do not sum to unity because the motoring portions of the EPA transient test procedure are assumed to generate negligible emissions. The weighting scheme of the AVL steady state simulation was designed to produce gaseous emissions that are comparable to those obtained using the U.S. EPA Transient Test Procedure. The steady-state simulation offers information on pollutant formation at eight speed/load conditions, but does not measure transient engine behaviour.

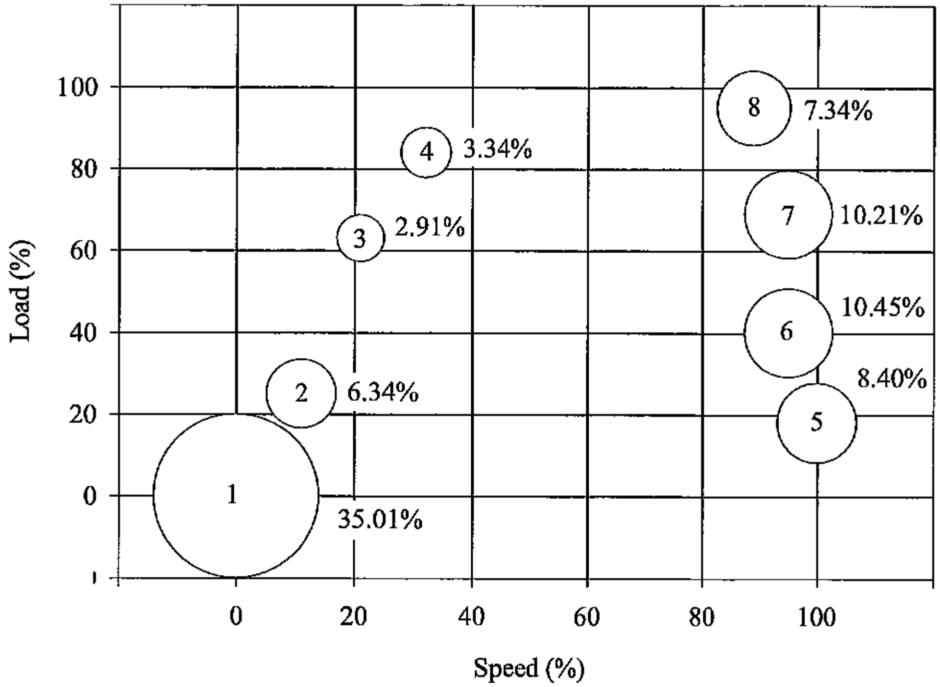

Figure 2-10 AVL Eight-Mode Steady-State Test Conditions

The research engine was configured to simulate one cylinder of a Caterpillar 3406E six-cylinder engine (model year 2000) that produces 373 kW at 1800 rpm. The engine speed settings for the AVL eight-mode simulation vary from 600 rpm (0 percent or low idle speed) to the engine's rated speed of 1800 rpm (100 percent speed). The brake power settings were obtained by determining the fuelling rates in the parent engine at the eight modes [18] and then by recording the powers produced by the research engine at the same cylinder fuelling rates when operated with a reference fuel. The fuel injection timings, as well as the intake and exhaust air pressures, are provided in Table 2-2. The brake torque produced by the research engine at each mode is approximately one-sixth of that of the parent engine. However, differences in frictional losses between the single-cylinder and parent engines resulted in minor torque scaling discrepancies.

The engine warm-up and cool-down, fuel change, and testing procedures are described in Appendix B. The procedures are similar to those employed during the first three stages of this research program, except that the time allowed for engine and test cell conditions to stabilize has been increased to one hour. After steady state is achieved at each mode, gaseous emissions data are collected for a minimum of fifteen minutes and three PM filter measurements are taken. As a result, each eight-mode test requires two days to complete. It is anticipated that the instrumentation upgrades and new test procedures will improve the repeatability of the PM emission measurements and reduce the need for replicating tests in the future. The improvements made to the PM emission measurement repeatability will be discussed further in Section 3.2.

Table 2-2 AVL Eight-Mode Settings for Caterpillar 3401E Engine

AVL Mode	Engine Speed (rpm)	Brake Torque (N-m)	Injection Timing (°BTDC)	Intake Air Temp. (°C)	Intake Air Pressure (kPa abs.)	Exhaust Back Pressure (kPa abs.)
1	600	8.0	0	30	100	100
2	732	55.3	0	30	104	104
3	852	205.3	0	30	134	120
4	984	327.7	0	30	195	150
5	1800	61.3	2	30	120	134
6	1740	142.1	2	30	165	162
7	1740	245.2	2	34	235	209
8	1668	353.4	5	36	283	229

3 EFFECT OF EXHAUST GAS RECIRCULATION

3.1 Introduction

Cooled exhaust gas recirculation (EGR) has been adopted by most North American engine manufacturers to meet the model year 2004 emission standards for on-highway heavy-duty diesel engines. EGR involves reintroducing a portion of the exhaust gases into the engine's intake air. This is known to affect the combustion process in three ways [19]. Firstly, the CO_2 and H_2O present in the exhaust replace some of the oxygen in the intake charge. This reduces the oxygen concentration in the combustion chamber, as well as the stoichiometric flame temperature, and is known as the dilution effect of EGR. Secondly, the CO_2 and H_2O from the exhaust dissociate at high temperatures and participate in the combustion process. This is known as the chemical effect of EGR. Thirdly, the specific heats of CO_2 and H_2O are slightly higher than that of air, which reduces the combustion chamber temperature during the compression stroke. This is known as the thermal effect of EGR. Experiments have shown that the dilution effect is the dominant mechanism that lowers NO_x emissions [19].

Although EGR is an effective technique for reducing NO_x emissions from diesel engines, it also leads to higher PM emissions. The increase in PM emissions has been shown to be due to higher soot emissions as the EGR rate increases, while the soluble organic fraction (SOF) of PM from the fuel and lubricating oil decreases [20]. Thus, EGR must be applied judiciously at each engine operating condition in order to reduce NO_x emissions without excessively increasing PM emissions.

The objective of this study was to establish appropriate EGR settings at the AVL eight-mode test conditions using LII and chemiluminescent analyzers to rapidly measure the soot and NO_x emissions, respectively. In Section 3.2, baseline emissions data for the Caterpillar 3401E engine are provided. Soot concentrations measured by the LII method are correlated with those measured by the gravimetric method. In Section 3.3, the effect of EGR on engine emissions is shown at each of the eight-modes. Due to time limitations, exhaust soot mass concentrations were measured by the LII method and an AVL smoke meter instead of the standard gravimetric method. Composite emissions from the research engine with the EGR rates selected at each mode are presented in Section 3.4.

3.2 Baseline Engine Emissions without EGR

The baseline emissions from the engine without EGR were determined by conducting three eight-mode tests using a reference fuel (Ref5). Ref5 is a commercial winter diesel fuel purchased in the Ottawa area. It has a density of 833.2 kg/m^3, 43 cetane number, 26% total aromatics by mass (SFC), and 356 ppm by mass sulphur content. Further properties of Ref5 may be found in Table C-3 of Appendix C.

A summary of the composite emissions data is provided in Table 3-1. The composite PM emissions averaged 0.039 g/hp-hr and the standard deviation was 0.002 g/hp-hr. Emissions data for individual modes are provided in Appendix E. The current PM emissions standard

Table 3-1 Baseline Composite Emissions of Caterpillar 3401E Engine

Fuel	Statistic	PM (g/hp-hr)	NO_x (g/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)
Ref5	***mean***	0.039	4.25	0.094	0.535	168.6
	s.d.	0.002	0.02	0.003	0.007	0.2
	***c.v.* (%)**	4.2	0.4	3.3	1.4	0.1
1998 Standard		0.1	4.0	1.3	15.5	

for on-highway heavy-duty diesel engines is 0.1 g/hp-hr using the U.S. EPA Transient Test Procedure. PM emissions measured using steady-state test conditions are typically much lower than those obtained using the standard transient test procedure because engine transients produce substantial quantities of soot. PM emissions measured during steady-state tests show the correct trend for fuel property variations. Composite gaseous emissions measured at the AVL eight-mode test conditions, on the other hand, accurately predict gaseous emissions from the U.S. EPA Transient Test Procedure. The composite NO_x emissions were 4.25 g/hp-hr, which is close to the 1998 standard of 4.0 g/hp-hr. Composite HC and CO emissions from the Caterpillar 3401E engine are well below the current standards of 1.3 and 15.5 g/hp-hr, respectively. The measured BSFC was 168.6 g/hp-hr. The BSFC for single-cylinder versions of multi-cylinder engines are usually slightly higher due to increased friction in the single-cylinder engine. The BSFC calculations for the Caterpillar 3401E engine assume that the increased friction (per cylinder) of the single-cylinder engine was offset by lower parasitic engine losses because an external oil pump was used to circulate the lubricating oil.

New instrumentation were acquired prior to Stage IV of the research program to take more precise measurements of PM emissions. The observed standard deviation of the PM emission measurements for the three tests with the reference fuel using the new instrumentation was 0.002 g/hp-hr. This result compares favourably with standard deviations of 0.003-0.004 g/hp-hr for PM emissions typically measured using the old instrumentation from a higher emitting Ricardo Proteus engine [4]. The improvement in measurement precision is likely due to a combination of better instrumentation, improved test procedures, and improved control of the combustion process (intake air and exhaust back pressures). The coefficient of variation (*c.v.*) for PM emissions was more-or-less unchanged because the Caterpillar 3401E engine without EGR produced less PM. However, the *c.v.* for PM emissions will be significantly lower when the engine is operated with EGR, as shown in Section 3.4.1, due to the higher PM emissions associated with replacing some of the engine intake air with recirculated exhaust gases.

3.2.1 Comparison with Composite Emissions of Ricardo Proteus Engine

The composite emissions produced by the Caterpillar 3401E engine are compared to those of the Ricardo Proteus engine in Table 3-2. The PM emissions from the Caterpillar engine were 56% lower over the eight-modes using a common reference fuel (Ref5). The Caterpillar 3401E engine incorporates advanced engine technologies like electronically-controlled fuel injection and four valves per cylinder for improved fuel injection and air exchange, respectively. These technologies are known to reduce PM emissions. The

Table 3-2 Comparison of Engine Composite Emissions using Ref5 Fuel

Engine	PM (g/hp-hr)	NO_x (g/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)
Caterpillar 3401E	0.039	4.25	0.094	0.535	168.6
Ricardo Proteus	0.089	4.59	0.256	0.895	164.3
Difference (%)	**-56**	**-7**	**-63**	**-40**	**+3**

composite NO_x emissions from the Caterpillar 3401E engine were 7% lower than those from the Ricardo Proteus. This is most likely due to the very short time delay between the start of fuel injection and ignition in modern engines, which leads to a small premixed fuel burn fraction and lower NO_x emissions. HC and CO emissions from the Caterpillar 3401E engine were 63% and 40% lower than those produced by the Ricardo Proteus engine, respectively. The BSFC from the Caterpillar 3401E engine was 3% higher. However, it should be noted that a correction was applied to the brake horsepower produced by the Ricardo Proteus engine to compensate for the additional friction horsepower of the single-cylinder engine compared to the multi-cylinder engine manufactured by Volvo [1].

3.2.2 Comparison of LII and Gravimetric Soot Concentrations

A comparison was made between LII soot mass concentration and the gravimetric PM mass concentration in the exhaust of the Caterpillar 3401E engine without EGR. The experimental results are summarized in Table 3-3. An ultra low sulphur test fuel (Shell_base) was used to minimize the fuel contribution to sulphate emissions since the gravimetric method measures the sum of the carbonaceous (soot) fraction, the adsorbed hydrocarbons from the fuel and lubricating oil and the sulphate fraction. The test fuel, produced by blending oil sands derived streams at the Shell Canada Scotford refinery, had a density of 838 kg/m^3, 12.1% total aromatics by mass, and 3 ppm sulphur by mass. Additional properties of the test fuel may be found in Appendix C.

Figure 3-1 compares the LII soot mass and gravimetric PM concentrations at the AVL eight-mode test conditions. The gravimetric PM concentrations were determined by dividing the PM mass collected on the filter by the total volume of exhaust passing through the filter during the collection period. The LII soot concentrations were determined by multiplying the measured soot volume concentrations by an assumed soot density of 1900 kg/m^3. The soot mass concentrations measured by the LII method were lower than the PM mass concentrations measured by the gravimetric method at all eight modes. This result is not surprising because the gravimetric method measures the adsorbed hydrocarbons and sulphates from the lubricating oil and fuel in addition to the soot mass. The largest discrepancy between the LII and gravimetric methods occurred at the idle condition (mode 1). This result is due to the large fraction of soluble organic components in diesel engine exhaust at the idle operating condition.

The soluble organic fraction (SOF) was removed from loaded PM filters collected at each of the eight modes using an accelerated solvent extraction system (Dionex Corp., model 200). The extractions were done for 15 minutes at 100°C and 2000 psi using dichloromethane as the solvent following a procedure developed previously by NRCan [21]. Blank filters were also subjected to the same procedure to estimate the filter material lost during the extraction

Table 3-3 Soot Concentrations Measured by LII and Gravimetric Methods

Mode	LII Soot Concentration (mg/m^3)	Gravimetric PM Concentration (mg/m^3)	Gravimetric Soot Concentration (mg/m^3)
1	0.3	2.1	1.1
	0.2	1.9	1.0
2	1.0	2.7	2.2
	1.1	2.9	2.4
3	8.6	11.9	11.3
	8.9	11.2	10.6
4	8.9	14.5	14.2
	9.2	13.4	13.1
5	7.7	13.8	13.0
	8.4	15.1	14.2
6	9.2	13.0	12.5
	10.2	13.2	12.6
7	1.7	3.9	3.1
	2.0	3.9	3.1
8	0.7	2.0	1.3
	0.8	1.8	1.2

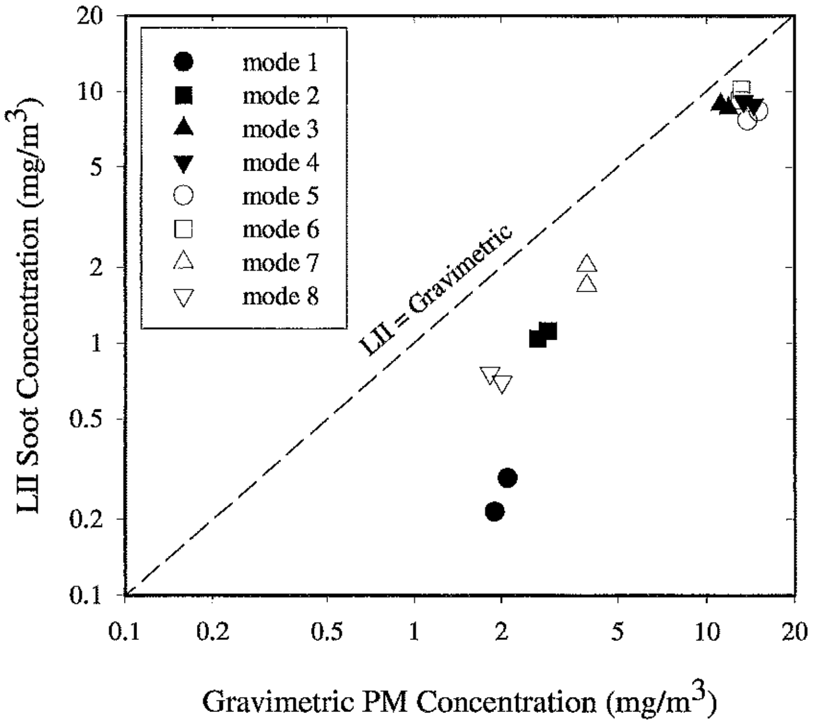

Figure 3-1 LII Soot Concentration vs. Gravimetric PM Concentration

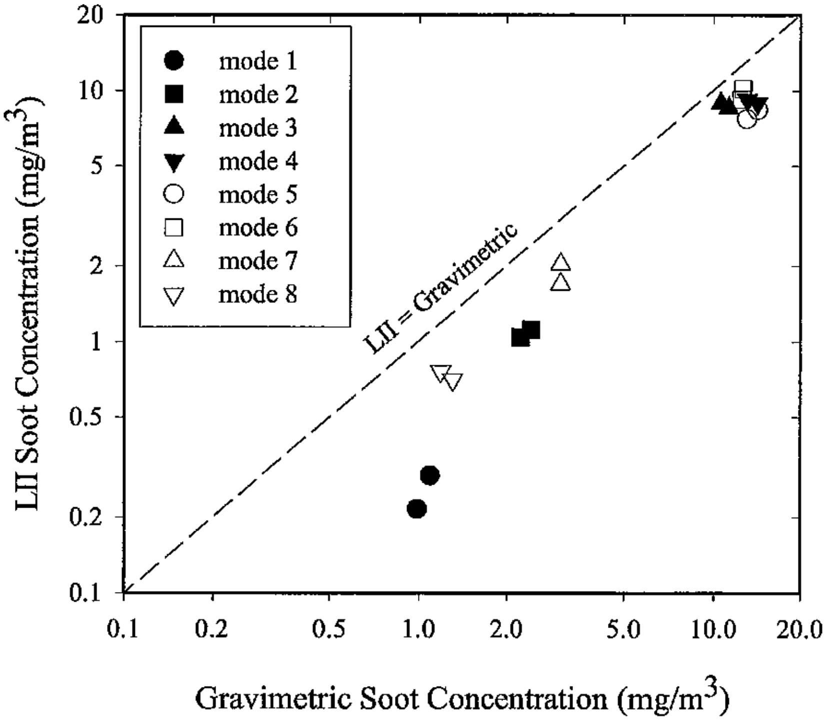

Figure 3-2 LII Soot Concentration vs. Gravimetric Soot Concentration

procedure. The PM filters were weighed before and after the extraction procedure using a microbalance and a correction was applied to account for the blank filter weight loss.

Figure 3-2 compares the LII soot concentration to the soot fraction of the gravimetric PM mass concentration for the same two experiments. The soot concentrations measured by LII are lower than those measured by the gravimetric method by roughly 50%, except at mode 1 where the difference is larger. The discrepancy between the soot concentrations measured by the two methods at mode 1 may be related to the uncertainty in determining the soot fraction of PM collected on the sample filters. Further experiments will be conducted using a variety of methods in the next research phase to more accurately determine the soot and soluble organic fractions of PM emissions, particularly at mode 1.

3.3 Effect of EGR on Trade-off between Soot and NO$_x$ Emissions

The effect of EGR on the soot-NO$_x$ emissions trade-off for the Caterpillar 3401E engine was investigated at the AVL eight-mode test conditions. The engine was operated with a reference fuel (Ref5) for this experiment. The differential pressure between the exhaust and intake surge tanks was set to a high enough value at each mode to drive the full range of anticipated EGR rates. Once the pressure differential between the exhaust and intake surge tanks was fixed, the EGR rate was regulated by a flow control valve.

Increasing the exhaust back pressure to drive the EGR flow affects engine operation in two ways. Firstly, additional pumping work is required during the exhaust stroke due to the higher back pressure needed to drive the flow of recirculated exhaust. A small adjustment to the load set point was made for modes where the engine back pressure was increased.

Secondly, the increased engine back pressure leads to an increase in the exhaust gas residual between engine cycles, which is commonly called internal EGR. Internal EGR is generally less desirable than cooled EGR because the exhaust gases are reintroduced into the combustion chamber at a much higher temperature than cooled EGR, which reduces the mass of intake air available for combustion.

The EGR rate, defined as the volume percentage of the intake air charge that is recirculated exhaust gases, is calculated as follows

$$\%EGR = 100\frac{\%CO_2(intake) - \%CO_2(ambient)}{\%CO_2(exhaust) - \%CO_2(ambient)} \qquad (3\text{-}1)$$

At each mode, NO_x and soot concentrations in the engine exhaust were recorded as increasing levels of EGR were applied. The experimental data is provided in Table 3-4. The NO_x and soot emissions are plotted as a function of the EGR rate at low speed, low load (mode 2) and high speed, high load (mode 7) operating conditions in Figures 3-3 and 3.4, respectively. Figure 3-5 summarizes the NO_x - soot emission trade-off for all eight modes.

3.3.1 Mode 2

Mode 2 is a low speed (732 rpm), low load (55 N-m), engine operating condition. Figure 3-3 shows that the NO_x emissions from the engine decreased linearly from 540 to 235 ppm as the EGR rate increased from 0 to 30%. Conversely, the LII soot concentrations increased

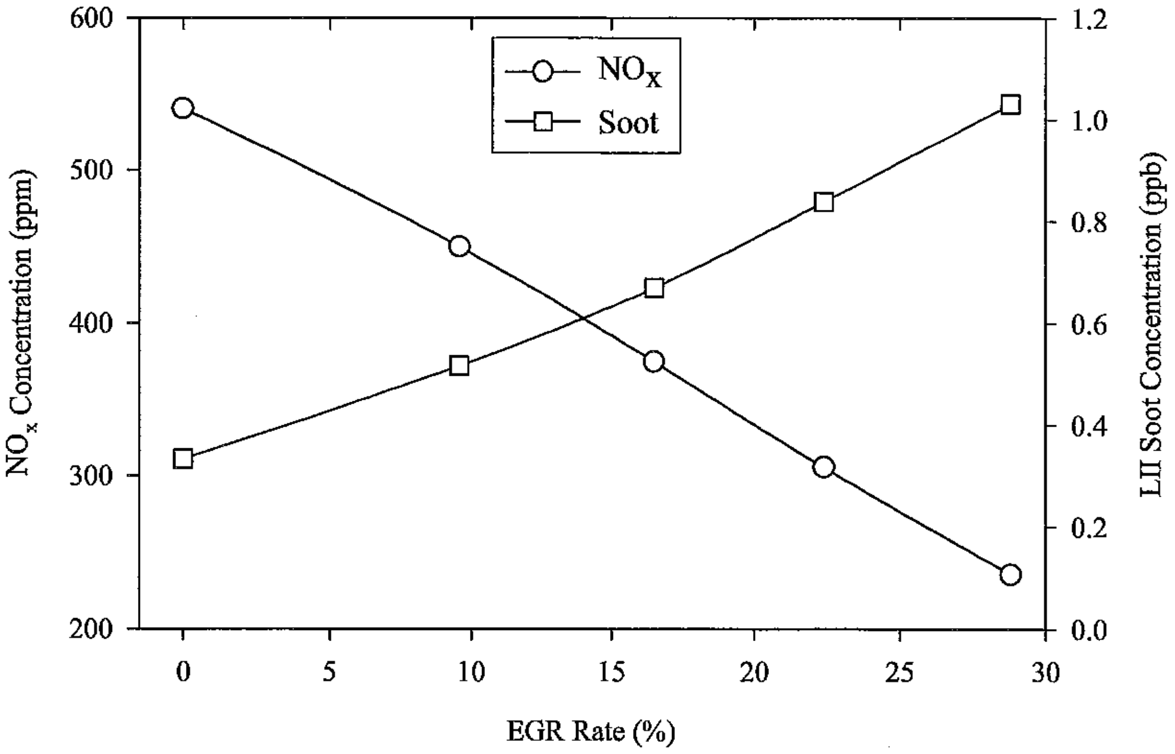

Figure 3-3 NO_x and Soot Concentrations vs. EGR Rate at Mode 2

Table 3-4 NO_x – Soot Emission Trade-off vs. EGR Rate

AVL mode	EGR Rate (%)	NO_x Concentration (ppm)	LII Soot Concentration (ppb)	AVL Soot Concentration (mg/m^3)
1	0.0	315	0.15	0.1
1	30.4	252	0.1	0.6
1	40.0	214	0.1	0.5
1	49.9	158	0.1	1.0
2	0.0	540	0.3	1.7
2	9.6	450	0.5	2.1
2	16.5	375	0.7	2.9
2	22.4	306	0.8	4.3
2	28.8	235	1.0	5.5
2	0.0	991	n/a	n/a
3	2.2	853	7.1	19.1
3	3.3	789	9.2	25.7
3	4.4	722	10.7	28.4
3	5.5	658	13.3	36.2
3	6.5	605	18.4	48.6
3	7.5	542	24.4	61.9
4	0.0	1194	25.3	6.0
4	3.3	972	3.3	9.6
4	4.9	853	4.7	10.7
4	6.1	752	7.5	16.9
4	7.0	699	8.8	20.4
5	0.0	287	3.1	11.1
5	3.7	264	3.2	12.4
5	7.9	238	3.9	15.9
5	11.7	217	6.0	19.9
5	15.6	193	6.6	27.2
5	19.8	168	8.5	32.7
6	0	432	3.1	10.3
6	2.9	393	4.0	13.2
6	6.0	348	5.5	17.6
6	9.1	306	7.3	22.5
6	12.0	270	10.1	31.7
6	15.2	232	13.6	47.7
7	0.0	506	0.8	2.1
7	2.7	457	1.0	2.4
7	4.7	417	1.2	3.1
7	9.2	334	2.0	5.8
7	13.1	261	3.5	9.2
7	15.0	236	4.7	11.8
8	0.0	710	0.3	0.6
8	3.9	588	0.5	1.0
8	5.4	536	0.6	1.4
8	7.0	486	0.9	1.9
8	8.6	435	1.2	2.6
8	10.0	392	1.6	3.4

from 0.3 to 1.0 ppb over the same range of EGR rates. Fairly high rates of EGR (25% or more) may be used at mode 2 because the soot concentrations were very low (0.3 ppb) without EGR and increased in a linearly manner as EGR was applied up to 30% by volume.

3.3.2 Mode 7

Mode 7 is a high speed (1740 rpm), high load (245 N-m), engine operating condition. Figure 3-4 shows that the NO_x concentration decreased linearly from 505 to 235 ppm as the EGR rate increased from 0 to 15%. In contrast, the soot concentration measured by LII increased linearly for EGR rates up to about 6%, but then increased exponentially for higher EGR rates. The exponential increase in soot emissions at mode 7 is due to the reduced oxygen concentration in the intake air as the EGR rate is increased. Since the fuel/air equivalence ratio is much higher at mode 7 than at mode 2, the engine is less tolerant of higher EGR rates. At a fixed EGR rate of 15%, the soot concentration in the engine exhaust was approximately one order of magnitude higher at mode 7 than at mode 2.

3.3.3 All 8 Modes

Figure 3-5 is a graphical representation of the trade-off between NO_x and soot emissions at the AVL eight-mode test conditions. The modal weightings for the eight-mode test are provided in the legend for convenience. Figure 3-5 shows that EGR is effective in reducing the NO_x concentration in the engine exhaust at all modes, but that the resultant increase in exhaust soot concentration depends strongly on the engine mode.

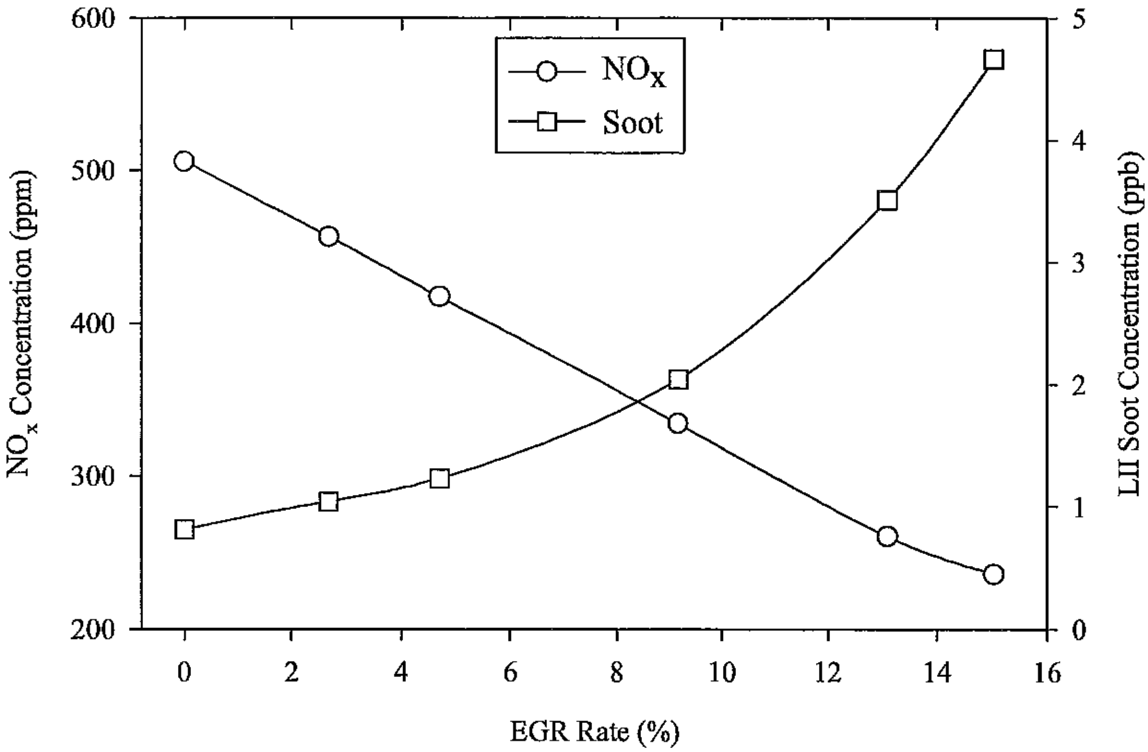

Figure 3-4 NO_x and Soot Concentrations vs. EGR Rate at Mode 7

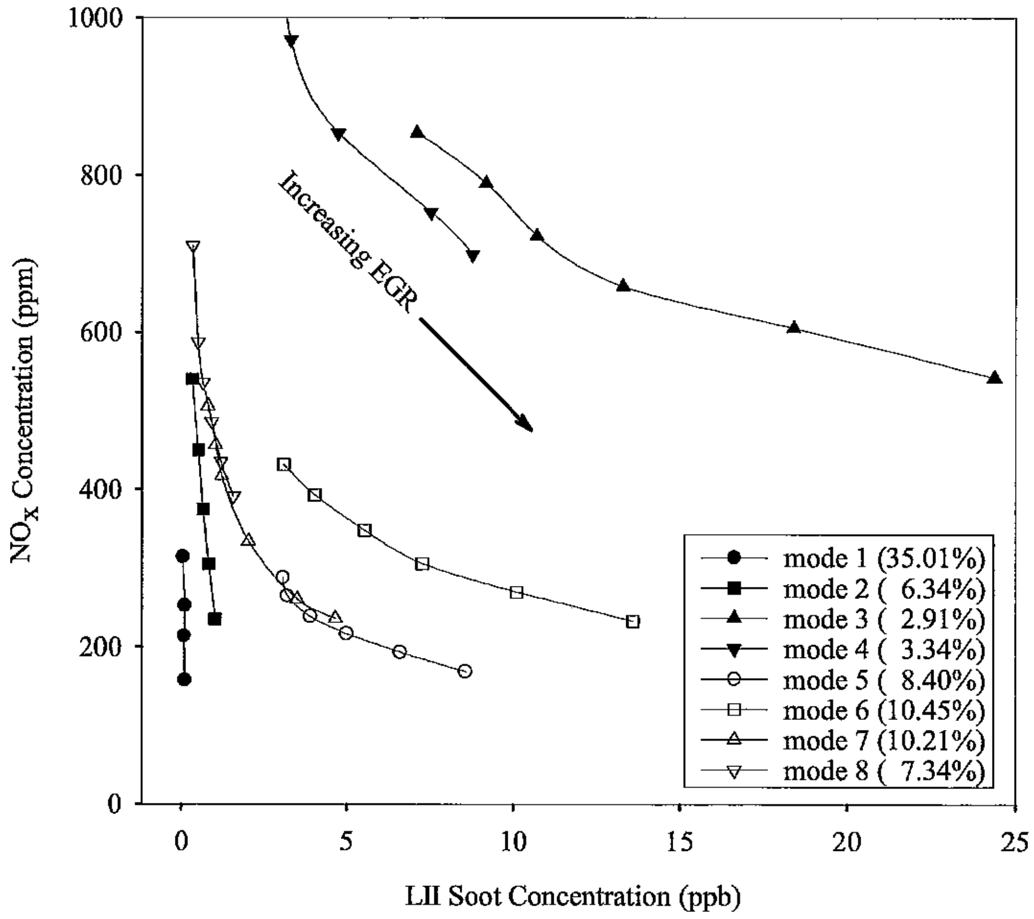

Figure 3-5 NO_x vs. Soot Concentration for all Eight Modes

Modes 1 and 2 (low speed, low load) are characterized by very low fuel/air equivalence ratios and low exhaust flow rates. The soot concentrations in the exhaust were below 1 ppb for all EGR rates. High EGR rates may be applied to reduce the exhaust NO_x concentration without dramatically increasing the soot concentration. The final EGR rates selected for modes 1 and 2 were 50% and 25%, respectively.

Modes 3 and 4 (low speed, high load) are operating conditions with relatively high fuel/air equivalence ratios and higher exhaust flow rates than modes 1 and 2. The engine exhaust has relatively high soot and NO_x concentrations. Figure 3-5 shows that the soot concentration increases significantly as the EGR rate increased at these two operating conditions. Thus, the use of EGR must be limited to achieve an acceptable trade-off between NO_x and soot emissions. The final EGR rates selected for modes 3 and 4 were 6% and 5%, respectively.

At modes 5 and 6 (high speed, low load), the fuel/air equivalence ratios are fairly low, but the exhaust flow rates are higher than at mode 4 due to the higher engine speeds. The NO_x concentrations were fairly low, however, the soot concentrations were higher than at modes 1 and 2. As a result, the exhaust soot concentration began to increase in an exponential manner at higher levels of EGR. This behaviour is different than what was observed at modes 1 and 2, as shown in the figure. The final EGR rates selected for modes 5 and 6 were 20% and 12%, respectively.

Modes 7 and 8 (high speed, high load) are characterized by lower fuel/air equivalence ratios than at modes 3 and 4. This is because the engine's turbocharger (simulated in this case) is more effective in boosting the intake air pressure at higher engine speed/load conditions. The additional combustion air available at modes 7 and 8 led to somewhat reduced engine sensitivity to EGR, relative to modes 3 and 4. This provides an opportunity to apply slightly higher EGR rates at modes 7 and 8, which lowers the NO_x concentrations in the exhaust to levels below what is achievable at modes 3 and 4. As a result, the final EGR rates selected for modes 7 and 8 were 8% and 6%, respectively.

3.3.4 Soot Concentrations Measured by LII Method and AVL Smoke Meter

Soot concentrations in the engine exhaust were measured by LII and an AVL smoke meter for all of the engine modes and EGR settings. The AVL smoke meter samples a fixed volume of exhaust gas through a filter paper and then measures the reflectivity of the blackened filter paper, which AVL has correlated to soot concentration. As before, The LII

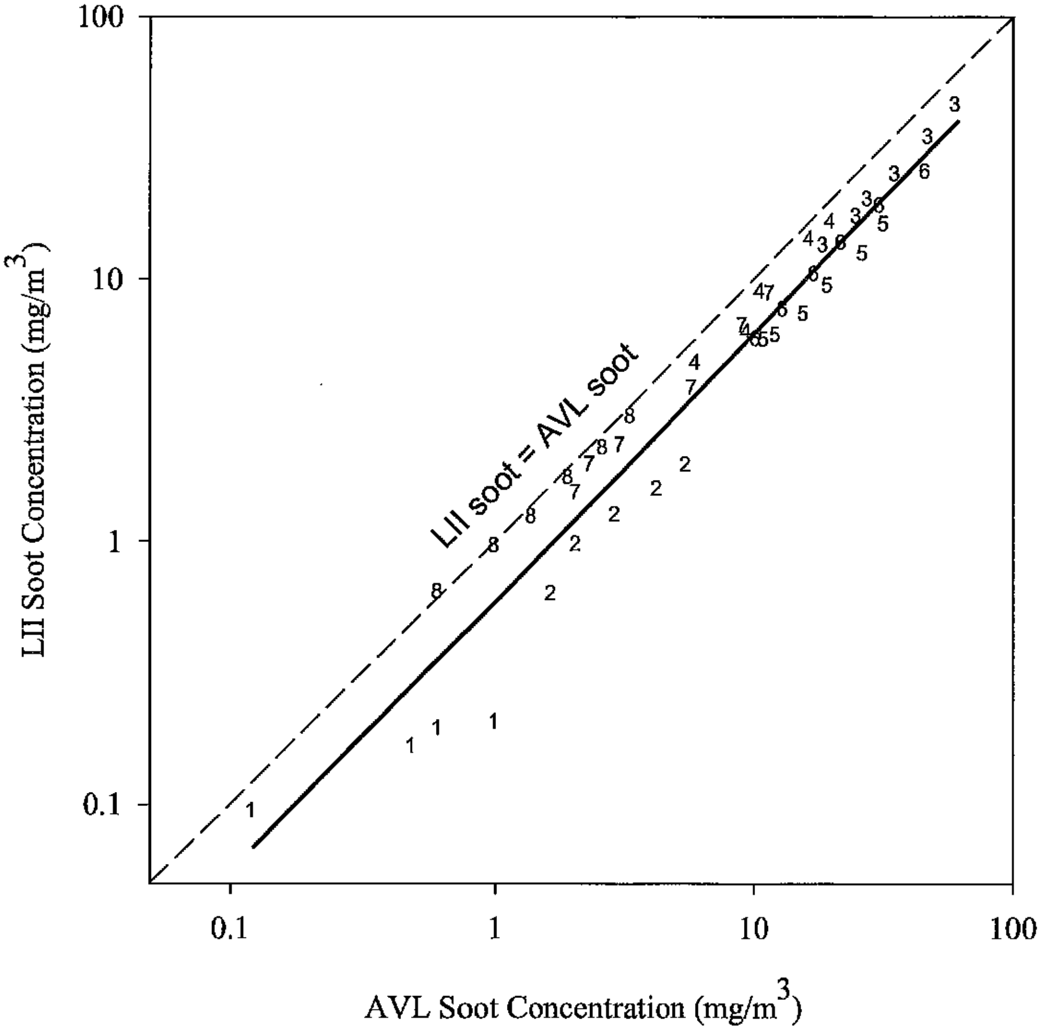

Figure 3-6 LII Soot vs. AVL Smoke Meter Soot Concentration

soot concentrations were determined by multiplying the measured soot volume concentrations by an assumed soot density of 1900 kg/m^3.

Figure 3-6 shows that there was excellent correlation between the two measurement techniques over a range of 2.5 orders of magnitude variation in soot concentration. The coefficient of determination (r^2) was 0.95, which provides strong evidence of a linear relationship between the two measurement techniques. Comparing the solid regression line to the dashed line representing perfect agreement between the two methods, it appears that the soot concentrations measured by LII are approximately 50% lower than those measured by the AVL smoke meter over the entire measurement range. Since the gravimetric soot concentrations were also observed to be higher than those measured by LII, it is likely that part of the difference may be due to inaccuracies in the LII method.

3.4 Engine Emissions with Final EGR Settings

The final EGR rates at the eight modes were selected to give composite NO_x emissions of approximately 2.5 g/hp-hr, and were based on the NO_x-soot emissions trade-off data in Figure 3-5. The engine operating conditions for the eight modes are provided in Table 3-5. The EGR settings ranged from 5% by volume at mode 4 up to 50% at mode 1. The fuel injection timings were not adjusted to account for any increase in ignition delay due to the application of EGR, however, the fuel injection timing was advanced by 6° crank angle at mode 4 to limit the exhaust temperature to 600°C.

3.4.1 Effect of EGR on Composite Emissions from Caterpillar 3401E Engine

The composite emissions from the engine were established by performing three eight-mode tests with a reference fuel (Ref5), using the EGR rates shown in Table 3-5. A summary of the composite emissions data is provided in Table 3-6. The effect of EGR on the composite emissions from the engine is summarized in Table 3-7.

EGR was effective in reducing the composite NO_x emissions from 4.25 to 2.47 g/hp-hr, which corresponds to a reduction of 42%. Similarly, the HC emissions were reduced by 43%

Table 3-5 AVL Eight-Mode Settings for Caterpillar 3401E Engine with EGR

AVL Mode	Engine Speed (rpm)	Adj. Brake Torque (N-m)	Injection Timing (°BTDC)	EGR Setting (% vol)	Intake Air Temp. (°C)	Intake Air Pressure (kPa abs.)	Exhaust Back Pressure (kPa abs.)
1	600	8.0	0	50	50	100	104
2	732	55.3	0	25	40	104	106
3	852	205.3	0	6	34	134	137
4	984	327.7	6	5	30	195	198
5	1800	61.3	2	20	42	120	134
6	1740	142.1	2	12	36	165	173
7	1740	245.2	2	8	34	235	245
8	1668	353.4	5	6	36	283	293

Table 3-6 Composite Emissions of Caterpillar 3401E Engine with EGR

Fuel	Statistic	PM (g/hp-hr)	NO_x (g/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)
Ref5	*mean*	0.076	2.47	0.054	0.696	171.4
	s.d.	0.0005	0.01	0.003	0.018	0.4
	c.v. (%)	0.7	0.4	6.2	2.6	0.2

from 0.094 to 0.054 g/hp-hr. However, the reduction in oxygen available in the combustion chamber caused the PM emissions to increase by 95%, from 0.0039 to 0.0076 g/hp-hr. The CO emissions also increased by 30%, but they remain well below regulated levels.

3.4.2 Comparison with Emissions from Caterpillar 3176 Engine with EGR

During mid-1999, Southwest Research Institute (SwRI) performed a major study to investigate the effects of fuel properties on diesel emissions from a prototype year 2004 heavy-duty diesel engine equipped with exhaust gas recirculation [22]. The project participants were the US Environmental Protection Agency (EPA), the American Petroleum Institute (API), and the Engine Manufacturers Association (EMA). The engine used was a Caterpillar 3176 truck engine with a 1994 engine calibration.

In late 1999, the Canadian Petroleum Products Institute[5] (CPPI) contracted Southwest Research Institute (SwRI) to test three oil sands derived diesel fuels and a Phillips DF-2 certification reference fuel in their prototype year 2004 engine. Complete results of the test program may be found in their final report [23].

The objective of this section is to compare the emissions produced by the SwRI prototype year 2004 engine operated with a Phillips reference fuel (SwRI Ref) and the NRC Caterpillar 3401E engine with EGR operated with a NRC reference fuel (Ref5). Table 3-8 provides a comparison of the two prototype 2004 diesel engines. Further details of the NRC research engine are available in Section 2.1. The SwRI engine has six cylinders, a displacement of 10.3 liters, four valves per cylinder, and is turbo-charged and after-cooled. The engine was equipped with a low pressure EGR system that lowered the engine's NO_x emissions to meet the year 2004 NO_x emission standard for on-highway heavy-duty diesel engines. Comparing the two engines, the volumetric displacement of the NRC engine is 41% larger. Otherwise, the level of technology is fairly similar for the two engines.

Table 3-7 Effect of EGR on Composite Emissions from Caterpillar 3401E Engine

Engine	PM (g/hp-hr)	NO_x (g/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)
Caterpillar 3401E with EGR	0.076	2.47	0.054	0.696	171.4
Caterpillar 3401E	0.039	4.25	0.094	0.535	168.6
Difference (%)	**+95**	**-42**	**-43**	**+30**	**+2**

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[5] NRCan and Syncrude Canada Ltd. also provided financial support for this research activity.

Table 3-8 Comparison of NRC and SwRI Prototype 2004 Diesel Engines

Parameter	NRC Prototype 2004 Engine	SwRI Prototype 2004 Engine
Engine Model	Caterpillar 3401E	Caterpillar 3176
Number of Cylinders	1	6
Bore x Stroke	137.2 mm x 165.1 mm	125.0 mm x 140.0 mm
Compression Ratio	16.25:1	16.00:1
Displacement	2.44 liter	10.3 liter (1.7 liters/cyl)
Number of Valves	4	4
Fuel Injection Type	Direct Injection	Direct Injection
Fuel Injection	Mechanically-Actuated Electronic Unit Injection	Mechanically-Actuated Electronic Unit Injection
Exhaust Gas Recirculation	External Cooled	External Cooled

The EGR rates used by SwRI were established from previous EGR studies [22] to give composite NO_x emissions of 2.5 g/hp-hr. The EGR rates were also tailored so that the sum of the NO_x and HC emissions did not exceed 3.125 g/hp-hr at each mode (except at modes 1 and 2). The method employed by NRC to establish EGR rates is described in Section 3.3.

A comparison of the EGR rates employed in the NRC Caterpillar 3401E and SwRI Caterpillar 3176 engines is provided in Table 3-9. In general, the EGR rates used were similar for the two engines. However, substantially higher EGR was used at mode 2 with the Caterpillar 3401E engine (25% vs. 12%) because the LII data showed that there was a beneficial emissions trade-off to be gained by increased EGR. Higher EGR rates were also employed at modes 7 and 8 with the Caterpillar 3401E engine, but a somewhat reduced EGR rate was used at mode 6.

Table 3-10 summarizes key properties of the reference fuels used at NRC and SwRI. Detailed characterization of the two reference fuels is provided in Table C- 3. The SwRI reference fuel had a higher density (848.3 vs. 833.2 kg/m^3), cetane number (45 vs. 43), total

Table 3-9 EGR Rates used by NRC and SwRI for Prototype 2004 Diesel Engines

Mode	NRC Caterpillar 3401E engine EGR Rate (% volume)	SwRI Caterpillar 3176 engine EGR Rate (% volume)
1	50	50
2	25	12.5
3	6	6
4	5	5
5	20	20
6	12	16
7	8	6
8	6	4

Table 3-10 Selected Fuel Properties of NRC and SwRI Reference Fuels

Fuel Property	NRC Reference Fuel (Ref5)	SwRI Reference Fuel (SwRI Ref)
Density, D4052, kg/m^3 @ 15°C	833.2	848.3
Viscosity, D445, cSt @ 40°C	1.907	2.532
Cloud Point, D2500, °C	-29	-15
Distillation, D86, °C		
T10	189	217
T50	237	262
T90	298	313
Base Cetane No., D613	43.0	45.1
Sulphur, D5453, ppm mass	356	401
Hydrogen, D3701, % mass	13.37	13.02
Nitrogen, D4629, ppm mass	22	97.1
Total Aromatics, SFC, % mass	26.2	32.6

aromatics (33 vs. 26 by mass) and sulphur content (401 vs. 356 ppm by mass). One might expect that the SwRI reference fuel would produce slightly higher PM and NO_x emissions based on the results of previous studies [1-3].

The SwRI reference fuel was tested once at the beginning of the test program and twice at the conclusion of the program. The average composite emissions from the Caterpillar 3176 engine operated with the SwRI reference fuel are provided in Table 3-11. The average composite emissions from the NRC Caterpillar 3401E engine are reproduced in the table to facilitate the comparison between the two engines.

Comparing the composite emissions for the two prototype year 2004 engines equipped with EGR, the Caterpillar 3401E engine produced 7% higher PM emissions (0.076 vs. 0.071 g/hp-hr) but 2% lower NO_x emissions (2.47 vs. 2.51 g/hp-hr). The HC and CO emissions from the Caterpillar 3401E engine were 66 and 19 percent lower, respectively. The BSFC of the two engines were within 1 percent of one another. In conclusion, the Caterpillar 3401E engine with EGR at NRC produced similar PM and NO_x emission levels to those of the Caterpillar 3176 engine with EGR at SwRI.

Table 3-11 Composite Emissions from Two Diesel Engines Equipped with EGR

Engine	PM (g/hp-hr)	NO_x (g/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)
NRC Caterpillar 3401E	0.076	2.47	0.054	0.696	171.4
SwRI Caterpillar 3176	0.071	2.51	0.160	0.854	169.8
Difference (%)	**+7**	**-2**	**-66**	**-19**	**+1**

4 EFFECT OF FUEL SULPHUR CONTENT

4.1 Introduction

It is well known that fuel-bound sulphur is a significant contributor to PM emissions from diesel engines [1-4, 24, 25]. If there are significant sulphur content variations between fuels in a test matrix, it becomes very difficult to discern the effects of other fuel properties on PM emissions. This is problematic because it is not possible to keep the sulphur content fixed when blending test fuels from refinery streams.

The mechanism by which fuel-bound sulphur is converted to sulphate emissions during diesel combustion is as follows. The first step is for the fuel-bound sulphur to be oxidized in the engine during combustion to form sulphur dioxide (SO_2). Most of this SO_2 is exhausted from the engine as a gas. A fraction of the SO_2 is further oxidized in the oxygen-rich environment of diesel exhaust to form sulphur trioxide (SO_3). The SO_3 is in vapour phase in the high temperature exhaust and has a high affinity towards water (H_2O), which leads to formation of a sulphuric acid (H_2SO_4) aerosol [24]. It is the sulphuric acid and chemically-bound water that are retained as sulphates on the particulate filter.

The objective of the experiments described in this section is to quantify the fuel sulphur content effect on PM emissions from the Caterpillar 3401E engine with EGR. Using this knowledge, PM emissions from the research engine may be corrected to a sulphur-free basis, assuming the mechanism by which fuel-bound sulphur is converted to PM emissions is independent of other fuel properties.

4.2 Fuel Sulphur Content Experiments

4.2.1 Single-Compound Sulphur Dopant

A single sulphur compound, di-tertiary-butyl disulphide, was blended in various quantities with a low-sulphur diesel fuel derived from oil sands sources (Syn3). The sulphur content of the base fuel was 7 ppm and the five doped fuel blends had sulphur contents ranging from 27 to 452 ppm by mass. The fuels were tested in the Caterpillar research engine in a random order.

The composite emissions from the research engine, operated with the six test fuels, are provided in Table 4-1. As expected, the fuel sulphur content did not affect the NO_x emissions from the engine or the BSFC. A simple linear regression model was fit to the specific composite PM emissions data. The form of the specific composite PM emissions equation as a function of fuel sulphur content was

$$sPM = \frac{PM}{P} = A_{sulphur} \times S + sPM_0 \tag{4-1}$$

where sPM is the specific composite PM emissions in g/hp-hr, PM is the composite PM emissions in g/hr, P is the engine power output in hp, $A_{sulphur}$ is the fuel sulphur content

Table 4-1 Composite Emissions for Sulphur-Effect Experiments

Fuel	S (ppm)	PM (g/hp-hr)	NO_x (g/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)
Syn3-0-1	7	0.065	2.56	0.059	0.69	172.3
Syn3-450S-1	419	0.073	2.56	0.062	0.68	172.2
Syn3-150S-1	134	0.069	2.56	0.057	0.69	172.5
Syn3-300S-1	269	0.069	2.54	0.066	0.68	172.6
Syn3-30S-1	27	0.065	2.54	0.059	0.68	172.2
Syn3-480S-1	452	0.072	2.57	0.075	0.69	172.2

correction factor in g/hp-hr-ppm, S is the fuel sulphur content in ppm by mass, and sPM_0 is the sPM for zero fuel sulphur content (intercept of the y-axis).

Figure 4-1 is a graph of the composite PM emissions from the engine as a function of the fuel sulpur content. A linear regression model was fitted to the data. The linear model explained 94.2 percent of the variance ($r^2 = 0.942$) in PM emissions. The slope of the line, $A_{sulphur}$, was equal to 1.7 x 10^{-5} g/hp-hr-ppm. A statistical t-test was performed to determine that the probability of observing a 1.7 x 10^{-5} g/hp-hr-ppm regression line slope is only 0.001 if the actual slope is zero. In other words, there is only a 0.1 percent chance of observing this slope if the population regression slope is zero.

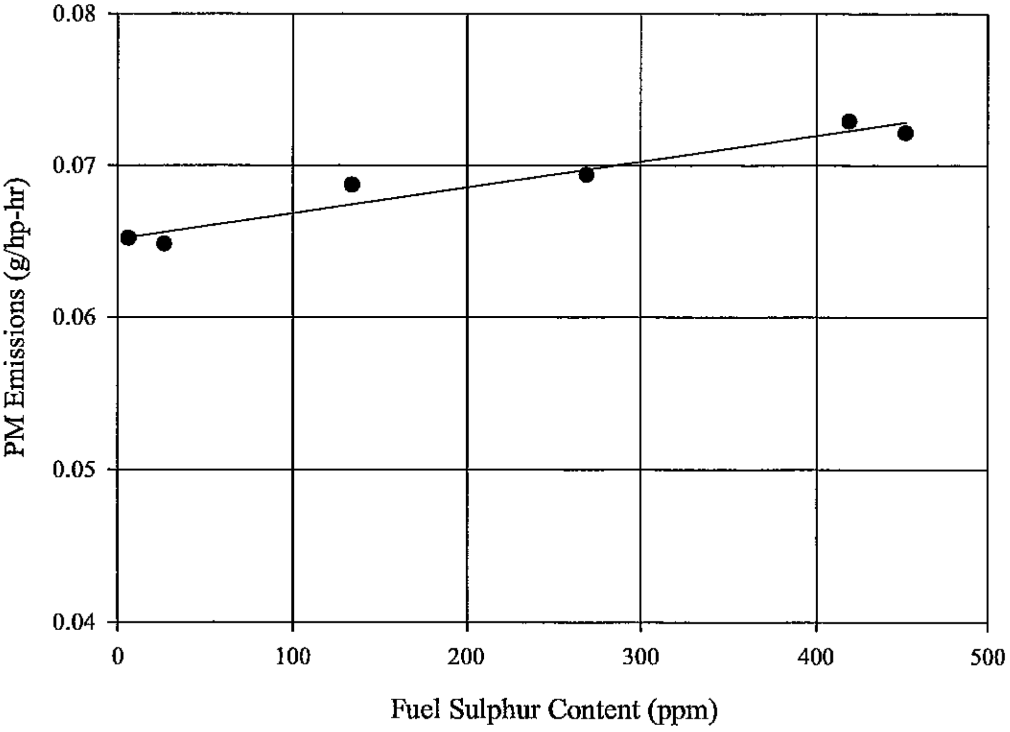

Figure 4-1 PM Emissions vs. Fuel Sulphur Content

4.2.2 DECSE Four-Compound Sulphur Dopant

The Diesel Emission Control-Sulphur Effects (DECSE) program was a joint government/industry initiative supported by the U.S. Department of Energy, two U.S. national laboratories, the Engine Manufacturers Association (EMA), and the Manufacturers of Emissions Control Association (MECA). The program objective was to investigate the impact of diesel fuel sulphur levels on the operation of emissions control devices.

The test fuels for the DECSE program were obtained by adding varying amounts of a four-compound sulphur dopant to an ultra-low sulphur base fuel. The base fuel was representative of diesel fuels used in the U.S., except that it had 3 ppm sulphur content. Properties of the base fuel are provided in Table C- 3. The measured properties were averages of analyses by Phillips Chemical, Southwest Research Institute, and Core Laboratories.

As limited information was available about the chemical identity of naturally occurring sulphur compounds in diesel fuels, the DECSE technical committee developed a dopant composition using representative constituents from the four classes of sulphur compounds commonly found in diesel fuel. The four compounds selected were dibenzo[b]thiophene (50% of total sulphur by mass), benzo[b]thiophene (30%), di-tertiary-butyl disulphide (10%), and ethyl phenyl sulphide (10%).

The objective of the four-compound sulphur dopant experiment at NRC was to verify that the effect of fuel sulphur content on PM emissions is independent of the type of sulphur compounds in the fuel. The initial plan was to test the DECSE base fuel and five test fuels produced by adding various quantities of the four-compound sulphur dopant to the DECSE base fuel in the Caterpillar 3401E engine. Unfortunately, instrumentation malfunctions limited the number of tests that could be performed within the allotted time.

The composite exhaust emissions from the engine operated with the DECSE base fuel and three test fuels are provided in Table 4-2. As expected, the NO_x emissions and BSFC were not affected by the fuel sulphur content. Figure 4-2 is a graph of PM emissions as a function of fuel sulphur content. The solid line, representing the linear regression model fit to the data, has a slope of 1.5×10^{-5} g/hp-hr-ppm. The coefficient of determination (r^2) for the fitted line is 0.665. The coefficient of determination for sulphur-effect experiments is typically much higher than this. If the data point for the test fuel with 293 ppm sulphur is not included, the slope of the regression line for the remaining points is 1.8×10^{-5} g/hp-hr-ppm and the coefficient of determination is 0.999.

Table 4-2 Composite Emissions for DECSE Sulphur-Effect Experiments

Fuel	S (ppm)	PM (g/hp-hr)	NO_x (g/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)
DECSE-0-1	3	0.061	2.52	0.062	0.64	169.8
DECSE-480S-1	478	0.069	2.52	0.067	0.63	170.1
DECSE-150S-1	144	0.063	2.50	0.064	0.63	170.0
DECSE-300S-1	290	0.061	2.50	0.059	0.63	169.1

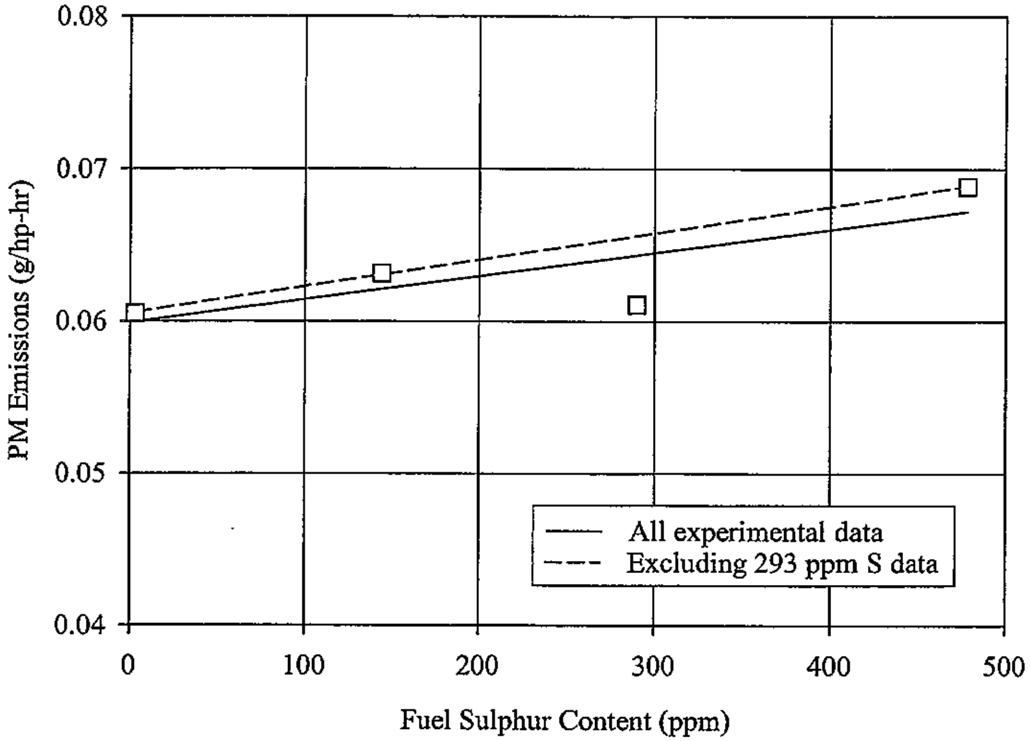

Figure 4-2 PM Emissions vs. Fuel Sulphur Content

4.3 Empirical Estimate of Fuel Sulphur Content Effect

The increase in PM emissions due to fuel-bound sulphur may be estimated using the following empirical equation [25]

$$\Delta PM = 2.3 \times \frac{98}{32} \times \frac{S}{10^6} \times \frac{C}{10^2} \times \dot{W}_{fuel} \qquad (4\text{-}2)$$

where ΔPM is the PM emissions correction in g/hr, S is the fuel sulphur content in ppm by mass, C is the sulphate conversion factor expressed as a percentage, $\dot{W}_{fuel}$ is the fuel consumption rate in g/hr, 98/32 is the ratio of the molar masses of sulphuric acid to sulphur, and the factor of 2.3 accounts for the moisture absorbed by the sulphate. The conversion rate of fuel sulphur to sulphates is the only unknown. Existing data suggests that the fuel sulphur conversion rate is typically one to two percent for modern heavy-duty diesel engines [25], and that the fuel contribution towards sulphate emissions decreases linearly as fuel sulphur content is reduced [1-4, 25].

The PM emissions correction may be estimated using Eq. (4-2), assuming a suitable sulphate correction factor for the research engine. The calculation was done for test 5CE, one of the reference fuel (Ref5) experiments. A mid-range sulphate conversion factor of 1.5 percent was used in the calculations. The results are summarized in Table 4-3. Using the fuel consumption and power data from the experiment, the sulphur content correction factor may

Table 4-3 Estimated PM Emissions Increase At Each Test Mode

Test Mode	Fuel Consumption (g/hr)	Power Output (hp)	$\Delta PM / S$ (x 10^{-5} g/hr-ppm)
1	349.3	0.6	3.7
2	1075.2	5.6	11.4
3	4003.2	24.6	42.3
4	6887.9	45.4	72.8
5	3522.2	15.4	37.2
6	6090.0	34.7	64.3
7	9781.4	59.9	103.4
8	12890.3	82.7	136.2
Composite	3414.1	19.9	36.1

be estimated

$$A_{sulphur} = \frac{\Delta PM}{P \times S} = \frac{36.1 \times 10^{-5}}{19.9} = 1.8 \times 10^{-5} \text{ g/hp-hr-ppm.} \tag{4-3}$$

The expected range of the fuel sulphur correction factor for this engine is 1.2×10^{-5} to 2.4×10^{-5} g/hp-hr-ppm, based on an assumed sulphate conversion factor of 1 to 2 percent.

4.4 Summary of Fuel Sulphur Content Experiments

In this section, the experimental results for the single- and four-compound sulphur content experiments are compared. A composite graph containing the data from the two experiments is provided as Figure 4-3. This figure clearly shows that the slopes of the regression lines are very similar for the two data sets. The slope of the solid line fitted to the data for the single-compound sulphur dopant is 1.7 x 10^{-5} g/hp-hr-ppm. This is similar to the 1.5 x 10^{-5} g/hp-hr-ppm slope of the line fitted to the four-compound sulphur dopant data. The y-axis intercepts of the two regression lines were different because the base fuels were not the same for the two experiments. The PM emissions data using single- and four-compound dopants supports the hypothesis that the amount of sulphur collected in PM filters is independent of the type of sulphur compound in the fuel.

Based on the assumption that sulphate emissions are independent of the type of sulphur compound in the fuel, the data may be pooled into one data set. For the statistical analysis, a dummy variable called "Base_Fuel" was added. The dummy variable was set to zero for the single-compound sulphur experiments with Syn3 as the base fuel and to one for the four-compound sulphur experiments with the DECSE base fuel. A multiple regression model of PM emissions, using the fuel sulphur content and "base fuel" as independent variables, was fit to the data. An analysis of the regression model produced using all ten data points indicated that one data point (four-compound sulphur dopant, 290 ppm sulphur) was an outlier.

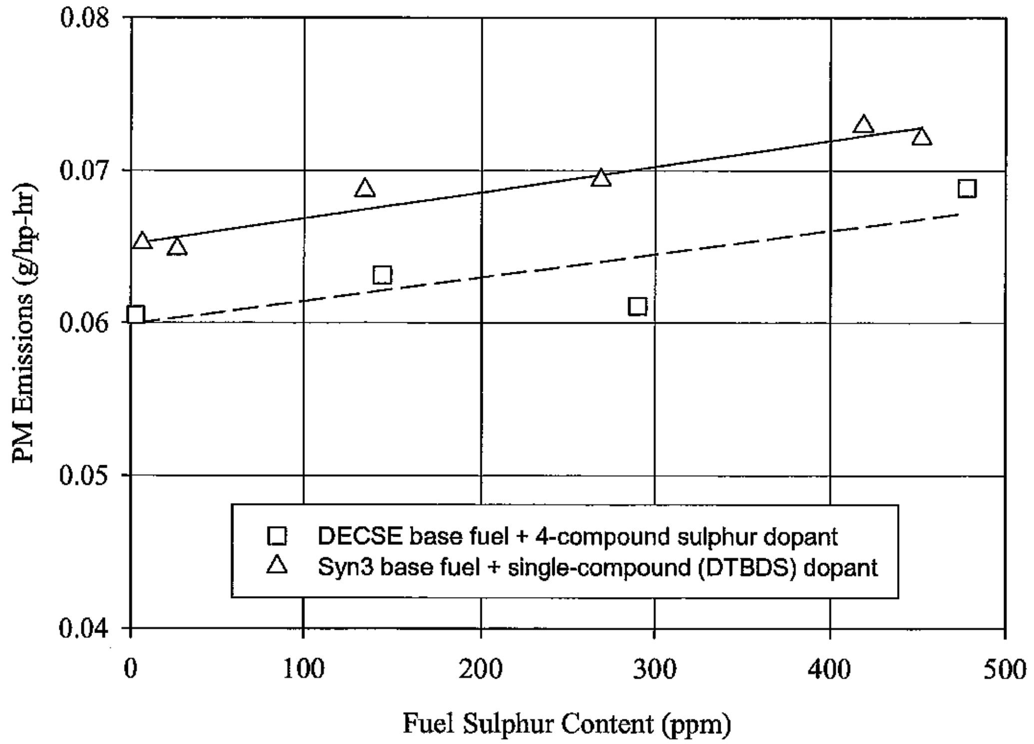

Figure 4-3 PM Emissions vs. Fuel Sulphur Content

A second regression model, fit to the nine remaining data points, produced the following predictor for PM emissions in g/hp-hr

$$PM = 0.056 + 0.005 \times Base\_Fuel + 1.7 \times 10^{-5} S \tag{4-4}$$

The squared multiple-r of 0.98 for the regression is evidence that the model accurately summarizes the data. The fuel sulphur content correction factor, 1.7 x 10^{-5} g/hp-hr-ppm, was found to be statistically significant to 95% confidence using a t-test.

In summary, the effect of fuel-bound sulphur on PM emissions from the Caterpillar 3401E engine with EGR was studied by doping low-sulphur base fuels with various quantities of single- and four-compound sulphur dopants. The available experimental data with single- and four-compound dopants supports the hypothesis that the amount of sulphur in the engine exhaust is independent of the type of sulphur compound in the fuel. The sulphur correction factor, $A_{sulphur}$, was estimated from the experimental data to be 1.7 x 10^{-5} g/hp-hr-ppm and was found to be statistically significant. In other terms, PM emissions were found to increase by approximately 0.001 g/hp-hr for every 60 ppm of sulphur in the fuel. Elimination of the sulphur from a fuel containing 500 ppm sulphur by mass reduces PM emissions from the research engine by approximately 0.0085 g/hp-hr. This result is consistent with the empirical method for estimating the effect of fuel-bound sulphur on PM emissions using a sulphate conversion factor of 1.5 percent.

5 EFFECT OF FUEL ORIGIN – PRELIMINARY RESULTS

5.1 Introduction

In Stage I, the effect of fuel origin on the exhaust emissions from a current-generation heavy-duty diesel engine was investigated using test fuels derived from oil sands and conventional crude oil sources [4]. Twelve test fuels were blended from Canadian refinery streams, covering a wide range of fuel densities and total aromatics. The raw experimental data from Stage I was reprocessed using our new standard calculation procedure to facilitate comparisons between data collected in subsequent stages of the research program.

The objective of this preliminary study was to investigate the effect of fuel origin on the emissions from a Caterpillar 3401E engine configured with and without EGR using two 30% total aromatic test fuels, one derived from conventional sources and the other derived from oil sands sources. The test fuel design and blending strategy is summarized in Section 5.2. Composite emissions from the engine, with and without EGR, are presented in Section 5.3. The remaining 10 fuels in this fuel matrix will be tested in Stage V of the research program. A statistical analysis of the emissions data will be performed after the remaining fuels have been tested in the engine.

5.2 Test Fuel Design and Blending

Shell Canada blended a total of 12 test fuels in Stage I using 22 refinery streams produced in Canada. Six of the test fuels were blended using components derived from oil sands crude sources; the remaining six fuels were blended using components from conventional crude oil sources. A total of 11 oil sands derived diesel components were obtained from Syncrude, Suncor Energy, and Shell's Scotford refinery to blend the test fuels. The other 11 components, derived from conventional crude sources, were obtained from Shell's Montreal East and Sarnia refineries and Imperial Oil's Dartmouth and Nanticoke refineries.

The blending was designed to produce four fuels (two each derived from oil sands and conventional sources) at three levels of total aromatic content (10, 20, and 30 percent) subject to the following constraints:

- the sulphur content of the fuels were limited to 500 ppm by weight;
- the target cetane number for the fuels was 43±3, and a cetane improver was used, if needed, to adjust the final cetane number to within this range;
- at each total aromatics level, the distillation curves of the two fuels from the same source were varied as much as possible; and
- other fuel properties such as viscosity, cloud point, and distillation range were maintained within the typical range of current commercial diesel fuel in Canada.

The test fuels were coded as "S" (for synthetic or oil sands derived) or "C" (conventional crude derived); 10, 20, or 30 for the nominal total aromatics content; and "A" or "B" to differentiate between blends with the same crude source and total aromatic content. The test fuels that had a nitrate cetane improver added were given a "n#" designation at the end of the fuel name. A complete characterization of the oil sands and conventional test fuels are provided in Tables C-1 and C-2, respectively.

Table 5-1 Test Fuel Design and Selected Properties

Fuel	Density (kg/m^3)	Cetane Number (-)	Sulphur Content (ppm mass)	Total Aromatics (SFC, % mass)
C30A	835.4	43.9	270	30.0
S30An5	840.8	42.3	85	30.0
Ref5	833.2	43.0	356	26.2

Select properties of the fuels tested in this stage are provided in Table 5-1. The densities, cetane numbers and total aromatics of the two test fuels are very similar. The cetane number of the oil sands derived test fuel, S30An5, was raised from 36.5 to 42.3 by adding 0.138% nitrate cetane improver by volume. The sulphur contents of the test fuels derived from oil sands and conventional sources are 85 and 270 ppm, respectively. The reference fuel had the highest sulphur content, but the lowest level of total aromatics.

5.3 Composite Emissions of Test Fuels

5.3.1 Caterpillar 3401E without EGR

The composite emissions from the research engine operated without EGR for the two test fuels (C30A and S30An5) and the reference fuel (Ref5) are provided in Table 5-2. Test fuel C30A produced approximately 10% higher PM emissions than the reference fuel. Test fuel S30An5 and the reference fuel produced similar PM emissions. NO_x emissions from the engine were also 2-3% higher when operated with the two test fuels. HC and CO emissions were well below the model year 2004 regulations of 0.5 and 15.5 g/hp-hr, respectively. The BSFC of the engine increased by an average of 0.3% for the two test fuels, relative to the average of the three tests with the reference fuel.

Figure 5-1 is a bar graph of the PM emissions for the three test fuels. Test fuel C30A produced higher PM emissions than test fuel S30An5 (0.044 vs. 0.040 g/hp-hr), but it also had a higher fuel sulphur content. Figure 5-2 is a bar graph of the PM emissions for the same fuels after removing the fuel sulphur content effect. This figure shows that the two test fuels with 30% total aromatics, one derived from conventional sources and the other derived from oil sands sources, had similar PM emissions. In comparison, the reference fuel had approximately 18% lower PM emissions than the two test fuels, but the difference was only 0.006 g/hp-hr in absolute terms. The error bar in each of the figures for the reference fuel

Table 5-2 Composite Emissions from Caterpillar 3401E Engine without EGR

Fuel	PM (g/hp-hr)	NO_x (g/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)
C30A	0.044	4.34	0.09	0.52	169.2
S30An5	0.040	4.38	0.10	0.54	169.1
Ref5	0.039	4.25	0.09	0.53	168.6

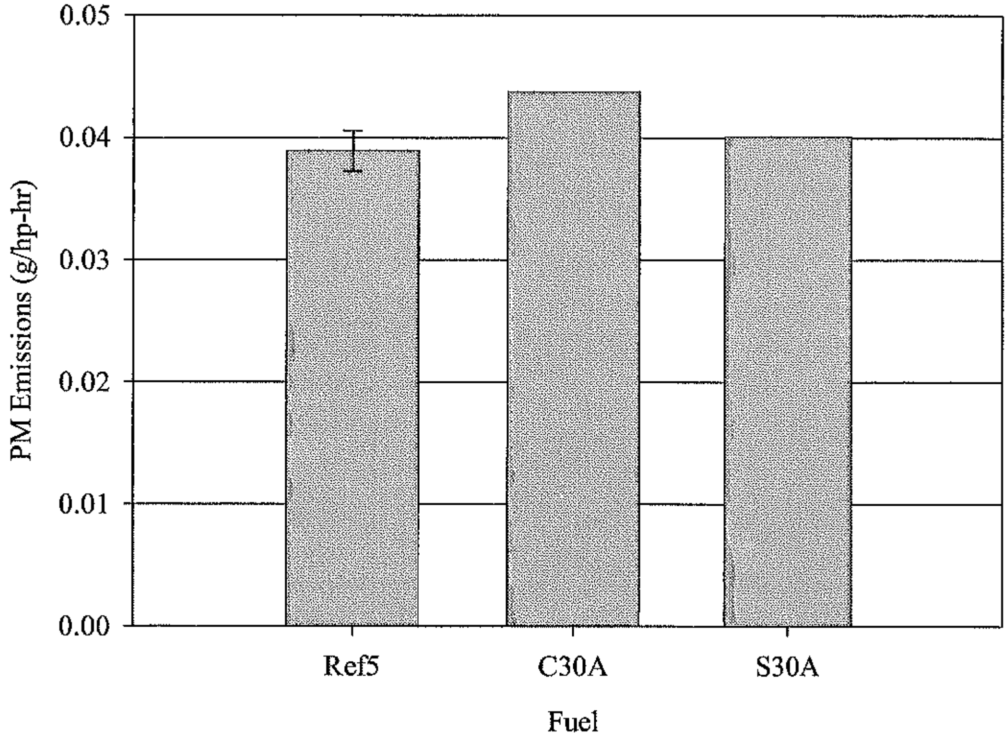

Figure 5-1 Composite PM Emissions from Caterpillar 3401E engine without EGR - Reference and Test Fuels

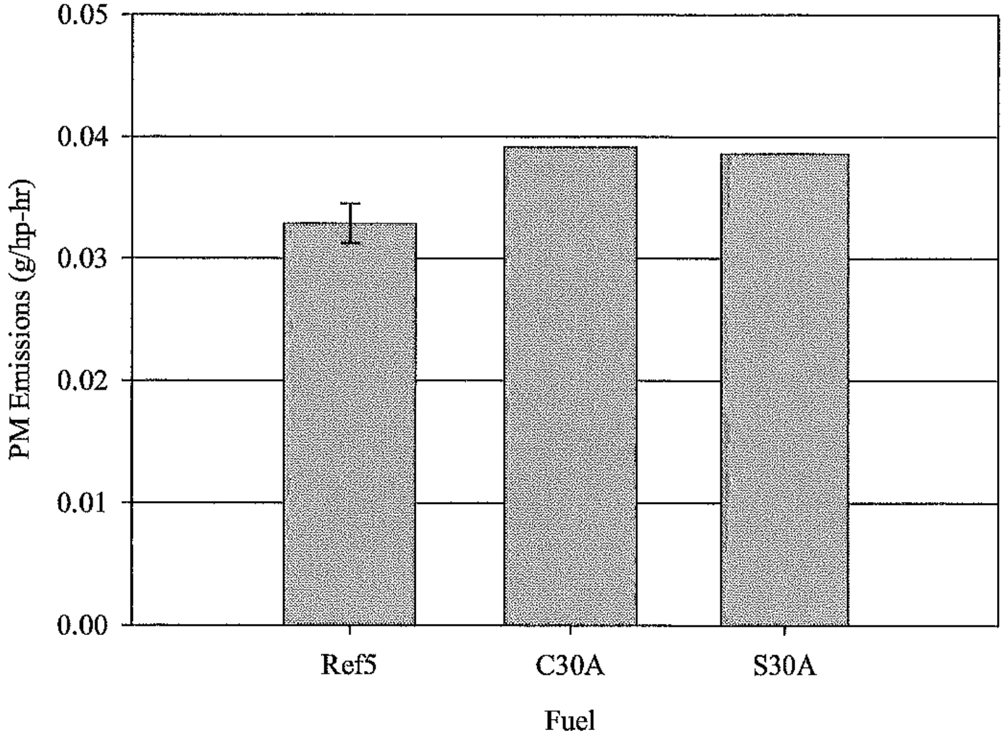

Figure 5-2 Composite PM Emissions from Caterpillar 3401E engine without EGR After Removing the Fuel Sulphur Content - Reference and Test Fuels

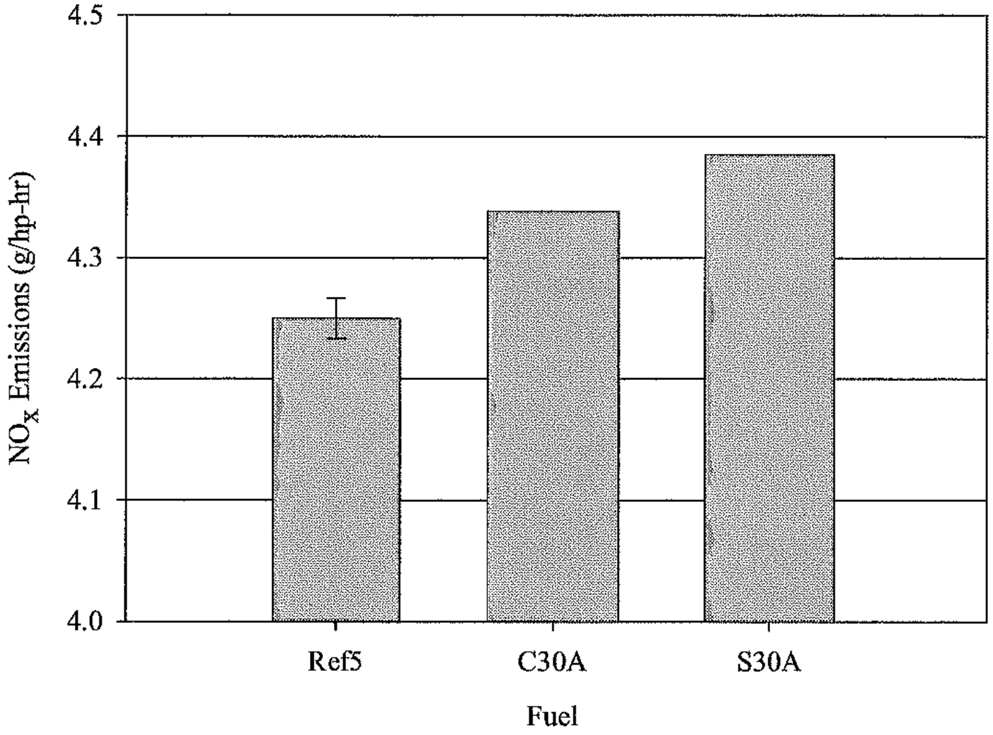

Figure 5-3 Composite NO_x Emissions from Caterpillar 3401E engine without EGR - Reference and Test Fuels

represents ±1 standard deviation in the PM emissions measurement.

Figure 5-3 shows that the NO_x emissions from the engine are within 3% of one another for the three fuels. However, it is well known that NO_x emissions from diesel engines rise with increasing fuel density and total aromatic content [1-4, 22]. Since the reference fuel has the lowest density and total aromatic content of the three fuels, it is not surprising that the engine produced slightly lower NO_x emissions when operated with this fuel. Test fuels C30A and S30An5 have similar total aromatics, but test fuel C30A has a slightly lower density (835.4 vs. 840.8 kg/m^3). The lower density of test fuel C30A leads to slightly lower NO_x emissions.

5.3.2 Caterpillar 3401E with EGR

The composite engine emissions for the two test fuels and the reference fuel are provided in Table 5-3. Test fuel C30A produced similar PM emissions to the reference fuel, while test

Table 5-3 Composite Emissions from Caterpillar 3401E Engine with EGR

Fuel	PM (g/hp-hr)	NO_x (g/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	BSFC (g/hp-hr)
C30A	0.077	2.52	0.05	0.69	171.0
S30An5	0.067	2.56	0.05	0.68	171.7
Ref5	0.076	2.47	0.05	0.70	171.4

fuel S30An5 produced approximately 11% lower PM emissions. The two test fuels produced 2-3% higher NO_x emissions, likely due to their higher densities and total aromatics. The HC emissions were only 0.05 g/hp-hr for all three fuels. CO emissions were slightly higher with EGR due to the replacement of some intake air with recirculated exhaust gases. The composite BSFC for the two test fuels only varied ±0.2% of the baseline BSFC measured with reference fuel.

Figure 5-4 is a graphical representation of the engine PM emissions data for the two test fuels and the reference fuel. Test fuel S30An5 produced the lowest PM emissions (0.067 g/hp-hr), which is partly due to the fact that it has the lowest fuel sulphur content. Figure 5-5 is a bar graph of the PM emissions for the same three fuels after removing the fuel sulphur content effect. This figure shows that test fuel S30An5 produced 5% lower PM emissions than the reference fuel and 10% lower PM emissions than test fuel C30A. This result is a bit surprising because test fuels C30A and S30An5 produced similar emissions when the engine was operated without EGR.

Figure 5-6 shows the effect of EGR on the sulphur-corrected PM emissions for the three test fuels. The commercial reference fuel, Ref5, showed the highest sensitivity to EGR in terms of increased PM emissions. Test fuels C30A and S30An5 showed approximately 10% and 25% less sensitivity to EGR than the reference fuel, respectively. Further experiments with the remaining 10 test fuels derived from conventional and synthetic sources may shed more insight into this preliminary result. Also, the emissions behaviour of test fuel S30An5 may

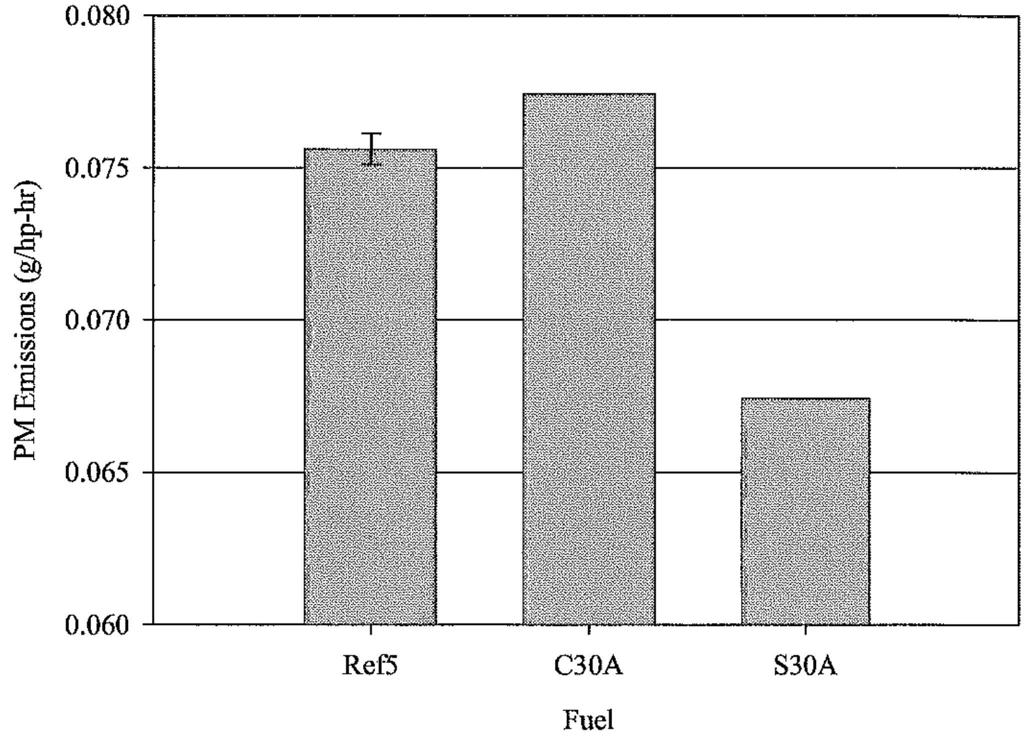

Figure 5-4 Composite PM Emissions from Caterpillar 3401E engine with EGR - Reference and Test Fuels

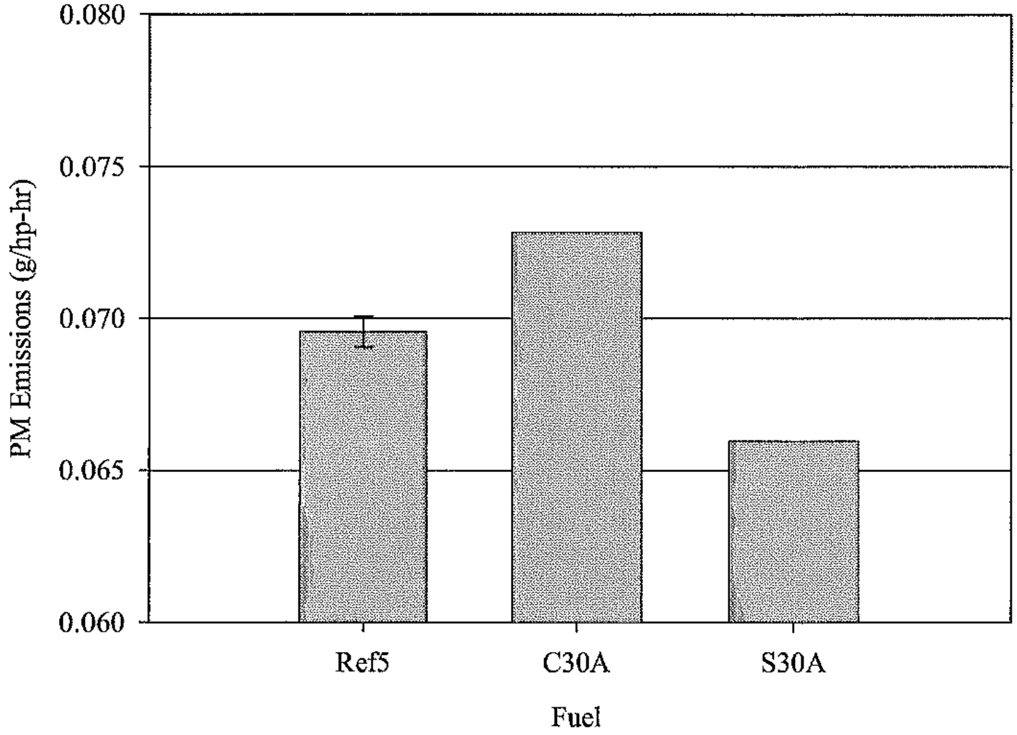

Figure 5-5 Composite PM Emissions from Caterpillar 3401E engine with EGR After Removing the Fuel Sulphur Content - Reference and Test Fuels

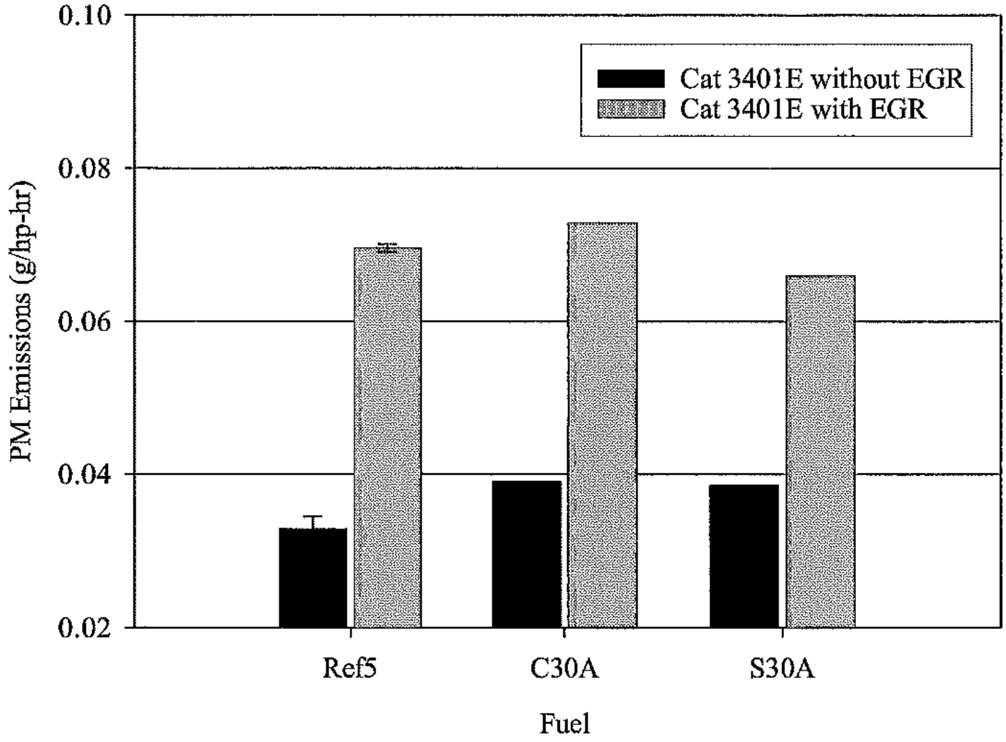

Figure 5-6 Effect of EGR on Composite PM Emissions After Removing the Fuel Sulphur Content Effect - Reference and Test Fuels

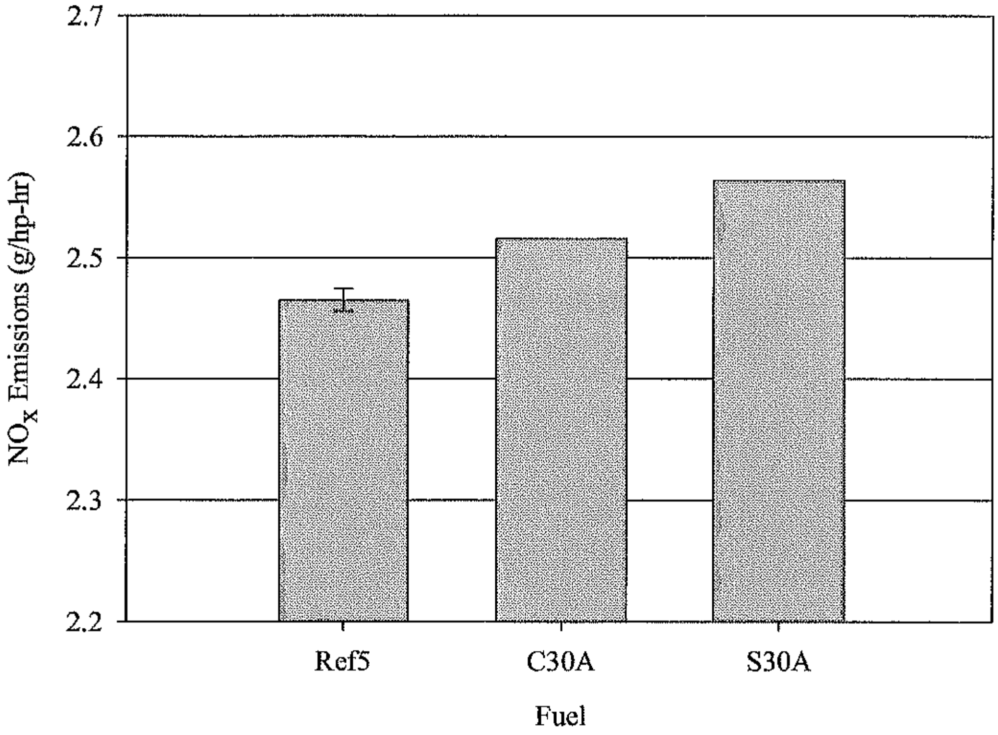

Figure 5-7 Composite NO_x Emissions from Caterpillar 3401E engine with EGR - Reference and Test Fuels

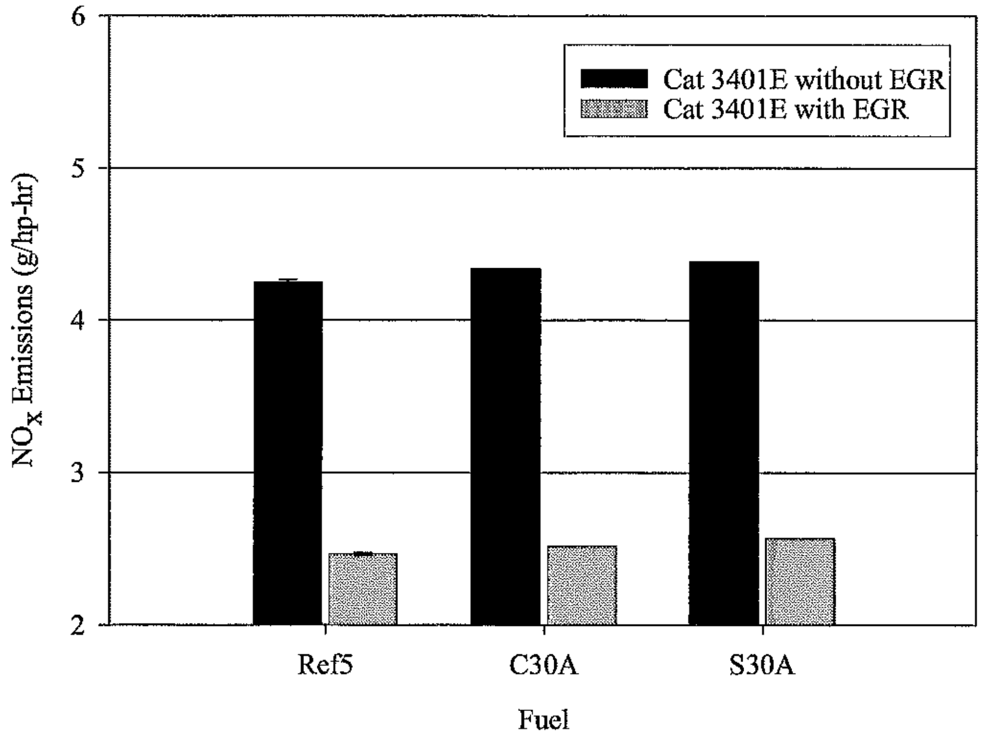

Figure 5-8 Effect of EGR on Composite NO_x Emissions - Reference and Test Fuels

have been affected by the use of a nitrate cetane improver. Further experiments are needed to understand the effect of cetane enhancement on the emissions from this research engine.

Figure 5-7 is a bar graph of the NO_x emissions produced by the engine for the three fuels. This figure shows that the NO_x emissions are 2% and 4% higher with test fuels C30A and S30An5 than with the reference fuel. As stated previously, the higher total aromatics and densities of the test fuels leads to higher NO_x emissions.

Figure 5-8 shows that EGR reduced the NO_x emissions by approximately 42% for all three fuels. This result is consistent with what one might expect if dilution of the intake oxygen concentration is the dominant mechanism by which EGR reduces NO_x emissions from diesel engines.

6 CONCLUSIONS

In Stage IV, a single-cylinder version of a Caterpillar 3406E engine was installed in a test cell. The engine was equipped with a prototype cooled exhaust gas recirculation (EGR) system and calibrated to meet the diesel emission regulations for model year 2004. The effect of fuel sulphur content on PM emissions from the engine was established by blending single- and four-compound sulphur dopants into low-sulphur base fuels. A preliminary experiment was also performed with a reference fuel and two test fuels containing 30% aromatics, one derived from oil sands sources and the other derived from conventional sources. The fuels were tested using the AVL eight-mode steady-state simulation of the EPA Transient Test Procedure. The main findings of the experiments are:

1. EGR was effective in reducing the composite NO_x emissions from the engine by 42%, from 4.25 to 2.47 g/hp-hr, when operated with a reference fuel. Dilution of the intake air charge by the exhaust gases, however, led to a 92% increase in PM emissions from 0.039 to 0.076 g/hp-hr.
2. EGR reduced the composite NO_x emissions produced by the two test fuels by 42%, but the test fuels had different sensitivities to EGR in terms of increased PM emissions.
3. PM emissions from the Caterpillar 3401E engine increased by 0.001 g/hp-hr for every 60 ppm of a sulphur dopant added to the fuel. In other words, the PM emissions increased by 13% as the fuel sulphur content increased from 0 to 500 ppm. The experimental data using single- and four-compound sulphur dopants suggests that PM emissions are affected by the fuel sulphur content, but not by the type of sulphur compound.
4. The EGR rates were established at the eight modes by measuring the trade-off between soot and NO_x emissions using NRC's laser-induced incandescence (LII) system and a standard chemiluminescent analyzer. The LII technique provided a rapid and precise method for determining soot concentrations. Soot concentrations measured by the LII technique and an AVL Smoke Meter correlated strongly ($r^2 = 0.95$) over a range of 2.5 orders of magnitude.
5. The EGR rates selected for NRC's prototype year 2004 engine at the AVL eight-mode test conditions were similar to the rates used by Southwest Research Institute in their prototype year 2004 engine.
6. The repeatability of the PM emissions data collected to date from the Caterpillar 3401E engine using new instrumentation and modified test procedures appears to be better than that obtained during previous stages of the research program. The standard deviation of the composite PM emissions was 0.002 g/hp-hr with the current engine and instrumentation, compared to typical standard deviations of 0.003 – 0.004 g/hp-hr measured during Stages I to III with the Ricardo Proteus engine.

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APPENDIX A SUMMARY OF PREVIOUS RESEARCH

In 1995, the National Research Council Canada (NRC) initiated a joint industry/government program to better understand the emissions behaviour of diesel fuels containing oil sands components in current- and next-generation engines. The first three stages were conducted using a single-cylinder version (Ricardo Proteus) of a Volvo TD123 diesel engine. The engine was calibrated to meet the U.S. EPA on-highway heavy-duty diesel emissions regulations for the 1994 model year. The AVL eight-mode steady-state simulation of the U.S. EPA Transient Test Procedure was adopted for all experiments. In this section, a summary of the research completed on current-generation diesel engines is provided. Further details may be found in the stage reports [1-3] and the status [4] report that was written after completing Stage III of the research program.

In the first stage, the exhaust emissions from a single-cylinder research engine operated with 12 diesel fuels derived from oil sands and conventional crude oil sources were compared [1]. The main findings of the experiment were:

1. The oil sands derived fuels produced 5-10% higher PM emissions at a given fuel total aromatic content. The higher PM emissions were attributed to the higher densities of the oil sands derived test fuels.
2. The oil sands and conventional crude derived fuels produced similar NO_x emissions.

The effect of nitrate- and peroxide-type cetane improvers on diesel emissions was also studied in Stage I. The main conclusion from this study was:

3. Nitrate- and peroxide-type cetane improvers decreased the composite NO_x emissions from the engine by approximately 5% as cetane number was boosted from 44 to 55. The composite PM emissions, however, increased by 5-10%.

The effects of fuel properties on diesel emissions were studied extensively in Stages I to III of the research program using test fuels blended from oil sands and conventional crude oil sources. The main conclusions were:

4. The key properties that affected PM emissions from the engine were fuel sulphur content and density.
   (a) PM emissions from the engine were found to increase by 0.01 g/hp-hr for each 400 ppm of sulphur in the fuel.
   (b) Fuel density had a strong correlation (0.92 correlation coefficient) with engine PM emissions in Stage I, but correlated weakly (0.19 correlation coefficient) with PM emissions in Stage II.
   (c) At a fixed fuel density, fuel poly- or total aromatic content did not significantly affect PM emissions from the engine.

5. The key properties that affected NO_x emissions from the engine were fuel density and total aromatic content. NO_x emissions were reduced by approximately 10% by a combination of lowering the fuel density by 30 kg/m^3 and the mass percentage of total aromatics by 20.

In preparation for future stages of the research program dealing with emissions from next-generation diesel engines, three oil sands derived test fuels were also tested at Southwest Research Institute (SwRI) in a Caterpillar 3176 heavy-duty diesel engine [22]. The engine was equipped with exhaust gas recirculation (EGR) to produce a prototype engine that meets the year 2004 U.S. EPA NO_x emission standard for on-highway heavy-duty diesel engines. The emissions of the prototype year 2004 diesel engine were compared to those of the Ricardo Proteus engine. The experimental results show that:

6. The PM and NO_x emissions from the prototype year 2004 diesel engine were 25% and 50% lower than those from the Ricardo Proteus engine, respectively. The PM emissions from the prototype year 2004 diesel engine also showed a lower sensitivity to variations in fuel aromatic content than the Ricardo Proteus engine for the three test fuels.

APPENDIX B TEST PROCEDURES

B.1 Engine Start-Up and Pre-Test Procedure

1. Weigh clean particulate filters required to complete scheduled test.
2. Follow fuel change procedure, if required.
3. Start-up test cell systems and verify correct operation.
4. Idle engine for 5 minutes.
5. Verify torque calibration (zero and span) using calibration weight.
6. Warm-up engine for 15 minutes.
7. During the engine warm-up period:
    - Verify that all instrumentation is operating correctly
    - Check calibration of mass flow computers in particulate measurement system
    - Lubricate o-ring seals inside particulate filter holder
    - Record barometric pressure and ambient CO_2 concentration

B.2 Fuel Change Procedure

1. Disconnect fuel system from fuel drum.
2. Drain the fuel system lines and the AVL fuel balance. Dispose of fuel following accepted NRC/ICPET procedure.
3. Replace fuel filter.
4. Connect fuel system to drum containing the next test fuel.
5. Flush fuel system and bleed to remove air pockets.

B.3 Emissions Test Procedure

1. Set engine condition (speed, load) and engine parameters for test point.
2. Reset and start stop watch.
3. Wait one hour for engine and test cell conditions to stabilize. A test may begin earlier, however, if all engine parameters and the exhaust temperature downstream of particulate sampling location have stabilized for 10 minutes. While waiting for conditions to stabilize:
    - Verify calibrations (zero and span) of all emissions instrumentation
    - Place particulate measurement system in purge mode
4. After the engine and test cell conditions have stabilized or one hour has elapsed:
    - Verify that all controlled engine and test cell parameters are within tolerance
    - Acquire and store engine and emissions data for a minimum of 15 minutes
    - Acquire and store a minimum of 100 cycles of high-speed engine data
    - Collect a minimum of three particulate filter samples
5. Verify that the emissions levels were stable during the test period and that the engine test log has been completed.

6. Repeat steps 1-5 above for the next test point or follow shutdown procedure if last test point has been completed.

B.4 Engine Shut-Down Procedure

1. Gradually bring engine down to low idle condition.
2. During the engine cool-down period:
    - Convert collected low speed data to engineering units
    - Record barometric pressure and ambient CO_2 concentration
    - Verify that the daily engine test log sheet is complete
3. Shut-down engine and test cell systems.
4. Return loaded particulate filters to environmental chamber and prepare filters for following day's tests.

B.5 Calibration/Maintenance Procedures

1. Clean EGR heat exchanger. (weekly)
2. Verify linearity of all emissions instrumentation. (monthly)
3. Perform leak check on particulate measurement system. (weekly)
4. Perform maintenance on particulate measurement system. (monthly)

APPENDIX C FUEL PROPERTIES

Table C- 1 Fuel Properties of Oil Sands Derived Blends (Stage I)

FUEL ID	**S10A**	**S10B**	**S20A**	**S20B**	**S30A**	**S30B**
Source	Oil sands derived refinery streams					
Density, kg/m^3 @15°C	827.2	834.2	833.6	838.4	840.8	838.4
Viscosity @40°C, cSt	1.65	2.14	1.7	1.92	1.81	1.73
Cloud Point, °C	-44	-27	-26	-25	-28	-33
Distillation, D86, IBP, °C	155.0	158.5	156.5	156.5	170.5	170.5
T10, °C	175.5	183.0	181.0	179.0	185.0	186.5
T50, °C	217.5	244.0	224.0	232.0	222.5	224.5
T90, °C	286.0	317.0	284.5	323.5	324.0	301.5
EP, °C	313.5	344.5	310.5	348.5	347.5	334.5
Cetane In., D976-80	41.0	46.8	40.9	41.8	37.9	39.5
Base Cetane No., D613				39.1	36.5	37.8
Nitrate cetane improver (% vol)				0.071	0.138	0.09
Final Cetane No., D613	41.0	43.4	40.2	42.9	42.3	42.0
Sulphur, ppm (mass)	13.2	2.4	28.8	31.1	84.7	3.0
Hydrogen Content m%	13.75	13.73	13.49	13.42	13.08	13.16
Nitrogen, ppm (mass)	27.9	0.3	56.4	1.5	24.8	2.5
SFC						
Total Aromatics, %m	12.4	12.9	20.2	23.5	30.0	31.4
Mono-Aromatics m%	10.9	9.5	17.9	2.02	25.2	27.4
Di-Aromatics m%	1.5	2.9	2.2	2.7	4.3	3.6
Tri+-Aromatics m%	0.0	0.5	0.1	0.5	0.6	0.3
HPLC						
Total Aromatics, %m	11.7	12.0	20.0	22.8	32.1	31.3
Mono-Aromatics m%	11.2	10.0	19.0	20.9	29.6	28.8
Di-Aromatics m%	0.5	1.5	1.0	1.3	1.9	2.2
Tri+-Aromatics m%	<0.1	0.5	<0.1	0.6	0.6	0.3
Hot FIA						
Aromatics, %v.	10.3	10.6	17.3	20.8	27.8	27.6
Olefins, %v.	2.0	2.0	1.9	2.3	2.9	2.3
Saturates, % v.	87.7	87.4	80.8	76.9	69.3	70.1
GC/MS						
Total Aromatics m%	11.1	12.3	19.7	22.3	30.5	30.2
Mono-Aromatics m%	9.8	9.3	17.6	19.2	26.4	26.2
Di-Aromatics m%	1.2	2.7	2.0	2.8	3.8	3.9
Tri+-Aromatics m%	0.0	0.2	0.0	0.1	0.1	0.1
Aromatic Sulphur m%	0.1	0.1	0.1	0.2	0.2	0.0
Paraffins m%	20.0	21.3	19.0	20.6	22.2	22.7
Mono-Cycloparaffins m%	33.3	32.0	28.2	25.8	19.9	21.0
Di-Cycloparaffins m%	24.1	21.0	22.4	18.7	16.1	16.0
Poly-Cycloparaffins m%	11.5	13.3	10.7	12.5	11.2	10.1

Table C- 2 Fuel Properties of Conventional Crude Oil Derived Blends (Stage I)

FUEL ID	**C10A**	**C10B**	**C20A**	**C20B**	**C30A**	**C30B**
Source	Conventional crude oil derived refinery streams					
Density, kg/m^3 @15°C	804.9	817.1	821.4	823.1	835.4	828.1
Viscosity @40°C, cSt	1.62	2.01	1.97	1.66	2.18	1.70
Cloud Point, °C	<-70	-27	3	-39	-10	-37
Dist, D86, IBP, °C	189.5	201.5	187.0	173.5	178.5	175.5
T10, °C	200.0	207.5	191.0	194.0	198.5	198.5
T50, °C	212.5	221.5	223.0	219.5	244.0	231.0
T90, °C	242.0	285.5	335.0	272.0	317.0	268.0
EP, °C	284.5	320.5	379.0	315.0	352.0	301.0
Cetane In., D976-80	47.4	46.1	45.0	43.2	46.5	45.1
Cetane No. D613	40.4	41.6	46.5	41.9	43.9	44.2
Sulphur, ppm (mass)	8.1	131	31.4	134.0	270.0	202.0
Hydrogen Content (m%)	14.18	14.13	13.72	13.68	13.28	13.40
Nitrogen, ppm (mass)	1.0	17.5	4.7	19.7	41.2	21.8
SFC						
Total Aromatics, %m	10.8	11.0	20.7	20.2	30.0	29.8
Mono-Aromatics m%	9.6	7.8	16.0	16.8	22.1	25.1
Di-Aromatics m%	1.1	2.9	4.3	3.2	7.1	4.4
Tri+-Aromatics m%	0.1	0.3	0.3	0.3	0.8	0.3
HPLC						
Total Aromatics, %m	10.4	10.2	20.0	19.8	29.6	30.2
Mono-Aromatics m%	9.7	8.2	16.8	17.4	24.0	26.9
Di-Aromatics m%	0.7	1.7	2.8	2.2	5.0	3.0
Tri+-Aromatics m%	<0.1	0.3	0.4	0.2	0.6	0.3
Hot FIA						
Aromatics, %v.	8.7	9.2	17.4	17.7	25.0	25.4
Olefins, %v.	1.9	2.4	1.8	2.4	1.6	2.7
Saturates, %v.	89.4	88.4	80.8	79.9	73.4	71.9
GC/MS						
Total Aromatics m%	10.2	10.2	19.9	19.4	28.8	28.8
Mono-Aromatics m%	9.1	7.3	15.5	15.7	21.6	24.5
Di-Aromatics m%	1.1	2.8	4.3	3.6	6.9	4.2
Tri+-Aromatics m%	0.0	0.1	0.1	0.1	0.3	0.1
Aromatic Sulphur m%	0.0	0.0	0.0	0.0	0.0	0.0
Paraffins m%	48.9	44.4	42.7	35.5	37.4	33.4
Mono-Cycloparaffins m%	21.3	23.1	18.9	17.8	16.6	18.7
Di-Cycloparaffins m%	13.1	15.4	9.9	17.3	9.7	13.1
Poly-Cycloparaffins m%	6.5	6.9	8.6	10.0	7.5	6.0

Table C- 3 Properties of the Reference and Base Fuels

FUEL ID	Ref2	Ref5	SwRI Ref	Syn2	Syn3	Shell Base	DECSE Base[6]
Additive							
Density, D4052, kg/m^3 @ 15°C	835.0	833.2	848.3	827.2	832.3	838.0	826.1
Viscosity, D445, cSt @ 40°C	2.21	1.907	2.532	1.231	1.243	2.60	2.42
Cloud Point, D2500, °C	-19	-29	-15	<-60	-40	-29	-21
Distillation, D86, °C							
IBP	173	160	182	162	170	159	185
T10	199	189	217	174	180	197	207
T50	256	237	262	197	202	266	259
T90	311	298	313	238	238	321	314
EP	337	327	341	270	276	348	350
Cetane In., D976-80	49.7	45.1	46.7	32.6	33.1	51.0	53.6
Base Cetane No., D613	46.2	43.0	45.1	41.2	41.9	44.9	44.8
Sulphur, D5453, ppm mass	351	356	401	7.8	7.7	2	3.1
Hydrogen, D3701, % mass	13.37	13.37	13.02	13.05	12.96	13.71	13.40
Nitrogen, D4629, ppm mass	43	22	97	216	361	0	
SFC, CAN/CGSB-3.0 No. 15.0-94, % mass							
Total Aromatics	27.5	26.2	32.6	36.0	37.9	12.1	27.8
Mono-Aromatics	19.9	19.9	21.3	33.5	35.5	7.8	17.9
Di-Aromatics	6.7	5.9	10.4	2.5	2.4	3.8	9.7
Tri+-Aromatics	1.0	0.4	1.0	0.0	0.0	0.5	0.3
Di+-Aromatics	7.7	6.3	11.4	2.5	2.4	4.3	10.0
HPLC, IP 391/95, % mass							
Total Aromatics	26.6	25.5	31.5	37.2	38.8		
Mono-Aromatics	20.8	20.9	23.5	35.0	36.8		
Di-Aromatics	5.0	4.2	7.1	2.2	1.9		
Tri+-Aromatics	0.8	0.4	0.9	<0.1	0.1		
Di+-Aromatics	5.8	4.6	8.0	2.2	2.0		
Hot FIA, UOP 501-83, % vol.							
Aromatics	23.4	22.7	27.8	31.9	33.5	5.4	27.0
Olefins	1.9	1.2	1.8	2.0	1.6		2.3
LC-GC/MS, % mass							
Total Aromatics, D2549	22.9	26.4	33.9	36.5	38.7	13.1	27.4
Mono-Aromatics, D3239	16.6	20.5	23.5	34.9	35.7	8.4	19.8
Di-Aromatics, D3239	5.9	5.7	9.8	1.6	2.9	4.0	7.1
Tri+-Aromatics, D3239	0.4	0.2	0.6	0.0	0.0	0.6	0.5
Aromatic Sulphur, D3239	6.3	5.9	10.4	1.6	0.1	0.0	0.0
Total Saturates, D2549	77.1	73.6	66.1	63.5	61.3	86.9	72.6
Paraffins, D2786	35.0	30.2	31.4	23.4	20.3	19.5	42.9
Mono-Cycloparaffins, D2786	20.2	21.9	17.0	22.9	19.0	30.2	12.9
Di-Cycloparaffins, D2786	13.7	14.5	12.4	12.3	16.7	25.0	10.9
Tri-Cycloparaffins, D2786	8.2	7.0	5.3	4.9	5.3	12.3	5.9

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[6] Average of analyses performed by Phillips Petroleum, Core Laboratories, and Southwest Research Institute.

APPENDIX D ENGINE SOOT EMISSION DATA

Table D- 1 Engine Soot Emission Data from Test 5BD

Soot Emission Data									
Test: 5BD				Fuel: Shell_base		Dates: Sept. 22-23, 2001			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**Brake Power (hp)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Grav. (mg/m^3)**	**SOF (%)**	**Soot Grav. (mg/m^3)**	**Soot LII (mg/m^3)**
1	601	8	0.7	347	47.0	2.1	52	1.1	0.3
2	732	55	5.7	1071	59.5	2.7	84	2.2	1.0
3	853	205	24.6	3912	93.7	11.9	95	11.3	8.6
4	985	328	45.3	7068	164.4	14.5	98	14.2	8.9
5	1801	61	15.5	3455	188.7	13.8	94	13.0	7.7
6	1741	142	34.7	5964	252.8	13.0	96	12.5	9.2
7	1740	245	59.9	9534	359.8	3.9	78	3.1	1.7
8	1670	353	82.9	12459	408.4	2.0	65	1.3	0.7

Table D- 2 Engine Soot Emission Data from Test 5BF

Soot Emission Data									
Test: 5BF				Fuel: Shell_base		Dates: Sept. 27-28, 2001			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**Brake Power (hp)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Grav. (mg/m^3)**	**SOF (%)**	**Soot Grav. (mg/m^3)**	**Soot LII (mg/m^3)**
1	601	8	0.7	355	47.0	1.9	52	1.0	0.2
2	732	55	5.7	1082	59.3	2.89	84	2.4	1.1
3	852	205	24.6	3922	93.2	11.16	95	10.6	8.9
4	982	328	45.2	7042	163.1	13.38	98	13.1	9.2
5	1802	61	15.5	3470	189.3	15.06	94	14.2	8.4
6	1742	142	34.8	6009	253.9	13.16	96	12.6	10.2
7	1742	245	60.0	9547	359.8	3.91	78	3.1	2.0
8	1670	353	82.9	11989	406.0	1.83	65	1.2	0.8

APPENDIX E ENGINE EMISSIONS DATA

Table E- 1 Summary of Engine Emission Tests

Test	Fuel	EGR	Test Objective	Report Sections
5AN	Ref5-0-1	no	baseline repeatability	3.2, 5.3.1
5AO	Ref5-0-1	no	baseline repeatability	3.2, 5.3.1
5AP	C30A-0-1	no	conventional/synthetic study	5.3.1
5AQ	S30A-0.138N-1	no	conventional/synthetic study	5.3.1
5AR	Ref5-0-1	no	baseline repeatability	3.2, 5.3.1
5CE	Ref5-0-1	yes	EGR repeatability	3.4.1, 5.3.2
5CF	Ref5-0-1	yes	EGR repeatability	3.4.1, 5.3.2
5CG	C30A-0-1	yes	conventional/synthetic study	5.3.2
5CH	S30A-0.138N-1	yes	conventional/synthetic study	5.3.2
5CI	Ref5-0-1	yes	EGR repeatability	3.4.1, 5.3.2
5DA	Syn3-0-1	yes	sulphur effect (DTBDS)	4.2.1
5DB	Syn3-450S-1	yes	sulphur effect (DTBDS)	4.2.1
5DC	Syn3-150S-1	yes	sulphur effect (DTBDS)	4.2.1
5DD	Syn3-480S-1	yes	sulphur effect (DTBDS)	4.2.1
5DE	Syn3-300S-1	yes	sulphur effect (DTBDS)	4.2.1
5DF	Syn3-30S-1	yes	sulphur effect (DTBDS)	4.2.1
5DG	Syn3-480S-2	yes	sulphur effect (DTBDS)	4.2.1
5FA	DECSE-0-1	yes	sulphur effect (4 compounds)	4.2.2
5FB	DECSE-480-1	yes	sulphur effect (4 compounds)	4.2.2
5FC	DECSE-150-1	yes	sulphur effect (4 compounds)	4.2.2
5FD	DECSE-300-1	yes	sulphur effect (4 compounds)	4.2.2

Table E- 2 Emission Results of Test 5AN

Emission Results									
Test: 5AN				Fuel: Ref5-0-1		Dates: June 14-15, 2001			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**Brake Power (hp)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	0.7	341	46.3	0.13	16.9	1.0	3.9
2	734	55	5.7	1089	58.5	0.13	41.0	1.1	6.2
3	852	205	24.6	3929	90.3	0.88	126.2	1.1	17.8
4	986	328	45.4	7081	158.7	1.71	216.5	0.6	61.5
5	1800	61	15.4	3466	185.7	2.01	61.5	4.4	21.6
6	1740	142	34.7	6027	245.3	2.44	123.8	4.6	19.9
7	1740	245	59.9	9593	349.4	1.41	211.1	3.7	14.8
8	1669	353	82.8	12531	401.4	1.17	345.1	3.2	14.0
Comp.				168.5 g/hp-hr		0.040 g/hp-hr	4.23 g/hp-hr	0.097 g/hp-hr	0.54 g/hp-hr

Table E- 3 Emission Results of Test 5AO

Emission Results									
Test: 5AO				Fuel: Ref5-0-1		Dates: June 12, 2001 June 19, 2001			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**Brake Power (hp)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO$_x$ Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	0.7	352	46.8	0.09	17.3	1.1	4.3
2	732	55	5.7	1097	58.7	0.14	40.7	1.2	6.4
3	852	205	24.6	3935	90.6	0.86	126.2	1.2	18.0
4	984	327	45.2	7068	159.0	1.69	213.6	0.6	60.2
5	1800	61	15.5	3460	185.3	1.98	62.3	4.0	20.8
6	1740	142	34.7	6041	245.2	2.39	123.4	3.9	20.6
7	1740	245	59.9	9558	349.1	1.24	212.8	3.5	13.7
8	1668	353	82.7	12507	400.6	0.98	345.3	3.2	13.4
Comp.				168.6 g/hp-hr		0.037 g/hp-hr	4.25 g/hp-hr	0.09 g/hp-hr	0.54 g/hp-hr

Table E- 4 Emission Results of Test 5AP

Emission Results									
Test: 5AP				Fuel: C30A-0-1		Dates: June 26-27, 2001			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**Brake Power (hp)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO$_x$ Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	0.7	358	46.4	0.38	17.6	1.3	3.9
2	731	55	5.6	1085	58.6	0.12	40.3	1.2	6.0
3	851	205	24.5	3941	90.4	0.84	129.7	1.1	17.0
4	985	328	45.3	7131	158.8	1.58	217.1	0.4	60.3
5	1800	61	15.4	3481	185.6	2.10	64.6	4.4	20.1
6	1739	142	34.7	6030	245.3	2.60	128.0	3.5	19.5
7	1740	245	59.9	9584	349.4	1.34	216.4	3.3	13.8
8	1668	353	82.8	12569	401.2	0.93	351.5	3.1	13.2
Comp.				169.2 g/hp-hr		0.044 g/hp-hr	4.34 g/hp-hr	0.094 g/hp-hr	0.52 g/hp-hr

Table E- 5 Emission Results of Test 5AQ

Emission Results									
Test: 5AQ				Fuel: S30A-0.138N-1		Dates: June 28-29, 2001			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**Brake Power (hp)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO$_x$ Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	0.7	364	46.4	0.12	18.5	1.2	4.0
2	732	55	5.7	1090	58.6	0.31	41.6	1.4	6.4
3	853	205	24.6	3944	90.6	0.80	130.6	1.3	16.7
4	985	328	45.3	7125	158.9	1.41	217.4	0.6	59.0
5	1800	61	15.5	3471	185.6	2.40	64.6	4.6	21.1
6	1739	142	34.7	6017	245.6	2.69	127.7	4.2	20.3
7	1739	245	59.9	9564	349.0	1.24	219.0	3.7	15.0
8	1668	353	82.8	12602	401.2	0.80	355.2	3.2	14.1
Comp.				169.1 g/hp-hr		0.040 g/hp-hr	4.38 g/hp-hr	0.100 g/hp-hr	0.54 g/hp-hr

Table E- 6 Emission Results of Test 5AR

Emission Results									
Test: 5AR				Fuel: Ref5-0-1		Dates: July 3-4, 2001			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**Brake Power (hp)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO$_x$ Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	0.7	358	46.4	0.19	17.5	1.2	4.1
2	731	55	5.7	1083	58.5	0.32	39.9	1.2	6.4
3	851	205	24.5	3940	90.5	0.83	128.1	1.0	18.1
4	984	328	45.2	7102	158.7	1.53	216.3	0.5	60.8
5	1802	61	15.5	3446	185.6	1.96	63.1	4.1	20.9
6	1740	142	34.7	6012	245.5	2.53	125.2	3.8	19.9
7	1740	245	59.9	9592	349.2	1.34	211.8	3.1	13.1
8	1669	353	82.8	12558	401.5	0.95	346.7	2.8	12.6
Comp.				168.8 g/hp-hr		0.040 g/hp-hr	4.27 g/hp-hr	0.091 g/hp-hr	0.53 g/hp-hr

Table E- 7 Emission Results of Test 5CE

Emission Results									
Test: 5CE				Fuel: Ref5-0-1		Dates: Nov. 27-28, 2001			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	7	50.0	349.3	23.50	0.09	4.3	0.7	4.1
2	731	55	25.1	1075.2	44.11	0.29	14.9	1.0	7.6
3	852	205	5.9	4003.2	84.48	2.98	68.9	0.5	46.0
4	984	328	5.0	6887.9	148.75	2.08	166.1	0.3	64.4
5	1800	61	20.0	3522.2	143.61	4.58	27.8	3.1	27.0
6	1740	142	12.1	6090.0	214.35	5.72	70.2	2.2	27.1
7	1738	245	8.0	9781.4	317.00	1.89	131.4	1.8	17.9
8	1669	353	6.0	12890.3	359.63	1.59	219.5	1.3	20.2
Comp.				171.5 g/hp-hr		0.075 g/hp-hr	2.47 g/hp-hr	0.055 g/hp-hr	0.69 g/hp-hr

Table E- 8 Emission Results of Test 5CF

Emission Results									
Test: 5CF				Fuel: Ref5-0-1		Dates: Nov. 23, 2001 (modes 1-4) Nov. 26, 2001 (modes 5-6) Nov. 29, 2001 (modes 7-8)			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	50.1	350.4	23.64	0.21	4.4	0.7	4.4
2	733	55	25.2	1076.2	44.23	0.24	14.6	0.9	7.6
3	851	205	6.0	3994.2	83.66	3.07	67.8	0.4	46.6
4	986	328	5.0	6971.1	147.82	2.35	161.8	0.3	70.0
5	1799	61	19.9	3447.6	143.72	4.24	27.3	3.3	26.9
6	1741	142	12.0	6073.7	214.56	5.69	70.3	2.2	28.9
7	1739	245	8.0	9776.5	316.56	1.96	132.3	1.8	17.5
8	1668	353	6.0	12868.5	358.63	1.52	220.9	1.3	19.8
Comp.				171.0 g/hp-hr		0.076 g/hp-hr	2.47 g/hp-hr	0.056 g/hp-hr	0.72 g/hp-hr

Table E- 9 Emission Results of Test 5CG

Emission Results									
Test: 5CG				Fuel: C30A-0-1		Dates: Nov. 30, 2001 Dec. 5, 2001			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	7	50.0	342.5	24.02	0.06	4.4	0.5	3.6
2	731	55	25.2	1073.2	44.03	0.31	14.5	0.8	7.4
3	851	205	5.9	3989.8	84.17	2.98	69.8	0.4	45.2
4	988	328	4.9	6964.8	149.13	2.10	167.1	0.2	67.1
5	1801	61	20.0	3463.2	141.94	4.66	28.1	2.8	25.4
6	1738	142	12.1	6086.2	212.23	6.50	70.0	2.0	30.4
7	1741	245	8.0	9777.9	317.99	1.78	133.5	1.7	16.9
8	1669	353	6.0	12848.3	359.42	1.28	228.1	1.5	18.3
Comp.				171.0 g/hp-hr		0.077 g/hp-hr	2.52 g/hp-hr	0.050 g/hp-hr	0.69 g/hp-hr

Table E- 10 Emission Results of Test 5CH

Emission Results									
Test: 5CH				Fuel: S30A-0.138N-1		Dates: Dec. 7, 2001 Dec. 11, 2001			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	50.1	365.7	23.35	0.06	4.6	0.7	4.5
2	733	55	25.0	1079.3	44.21	0.23	15.7	0.9	7.7
3	856	205	6.0	4030.4	84.84	2.73	71.2	0.5	43.3
4	985	328	5.0	6873.9	149.31	1.61	175.6	0.3	60.1
5	1800	61	20.0	3475.3	140.53	4.19	28.5	3.0	26.0
6	1740	142	12.0	6101.5	209.73	5.52	72.6	2.4	27.6
7	1738	245	8.0	9823.5	312.30	1.64	134.7	1.8	18.0
8	1671	353	6.0	12903.7	359.20	1.07	229.5	1.2	19.2
Comp.				171.7 g/hp-hr		0.067 g/hp-hr	2.56 g/hp-hr	0.054 g/hp-hr	0.68 g/hp-hr

Table E- 11 Emission Results of Test 5CI

Emission Results									
Test: 5CI				Fuel: Ref5-0-1		Dates: Dec. 14, 2001 Dec. 17, 2001			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	49.9	347.7	23.55	0.19	4.4	0.6	4.4
2	735	55	25.0	1076.4	43.31	0.23	14.8	0.7	7.4
3	852	205	6.0	3906.5	81.30	2.43	71.7	0.5	34.7
4	985	328	5.0	6919.2	143.26	2.10	163.2	0.2	65.5
5	1800	61	20.0	3481.4	140.78	4.44	27.7	2.9	26.5
6	1740	142	11.9	6108.8	209.92	5.98	69.6	2.1	28.0
7	1741	245	8.0	9885.1	311.32	1.79	129.9	1.5	17.2
8	1669	353	6.0	12950.1	358.82	1.35	219.5	1.1	19.2
Comp.				171.7 g/hp-hr		0.075 g/hp-hr	2.45 g/hp-hr	0.050 g/hp-hr	0.68 g/hp-hr

Table E- 12 Emission Results of Test 5DA

Emission Results									
Test: 5DA				Fuel: Syn3-0-1		Dates: Jan. 24-25, 2002			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	50.0	339.8	24.17	0.04	4.9	0.7	4.6
2	733	55	25.1	1077.1	43.85	0.16	16.3	0.9	7.7
3	852	205	6.0	3953.8	83.86	2.40	72.8	0.6	35.5
4	985	328	4.9	6868.6	147.97	1.53	182.9	0.1	55.1
5	1802	61	20.0	3510.3	142.48	4.36	27.8	3.6	27.2
6	1740	142	12.0	6119.3	212.82	5.30	73.4	2.5	26.6
7	1741	245	8.0	9905.6	310.04	1.49	134.5	1.9	19.6
8	1671	353	6.0	13082.4	357.39	1.12	222.4	1.3	22.9
Comp.				172.3 g/hp-hr		0.065 g/hp-hr	2.56 g/hp-hr	0.059 g/hp-hr	0.69 g/hp-hr

Table E- 13 Emission Results of Test 5DB

Emission Results									
Test: 5DB				Fuel: Syn3-450S-1		Dates: Jan. 28, 2002 Jan. 30, 2002 Feb. 6, 2002			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	50.0	348.2	23.97	0.18	4.7	0.7	4.8
2	730	55	25.1	1076.7	43.93	0.18	16.6	0.9	7.8
3	852	205	6.0	3934.4	84.19	2.30	73.6	0.6	33.2
4	986	328	5.0	6840.8	148.21	1.68	178.8	0.3	53.8
5	1800	61	20.0	3505.8	142.73	3.97	29.4	3.4	25.8
6	1742	142	12.0	6163.5	212.64	5.68	73.1	2.9	27.5
7	1741	245	8.0	9866.7	309.20	1.98	134.4	2.2	19.4
8	1669	353	6.0	13014.2	356.85	1.73	223.4	1.4	20.4
Comp.				172.2 g/hp-hr		0.073 g/hp-hr	2.56 g/hp-hr	0.062 g/hp-hr	0.68 g/hp-hr

Table E- 14 Emission Results of Test 5DC

Emission Results									
Test: 5DC				Fuel: Syn3-150S-1		Dates: Feb. 7-8, 2002			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	50.0	342.3	24.17	0.04	4.8	0.6	4.5
2	733	55	25.1	1086.6	43.92	0.16	16.6	0.8	7.7
3	851	205	6.0	3928.5	83.98	2.44	72.6	0.6	35.9
4	985	328	5.0	6854.3	148.04	1.69	177.0	0.3	54.7
5	1802	61	20.0	3533.1	142.65	4.43	29.4	3.2	26.8
6	1741	142	12.0	6130.8	212.52	5.50	72.6	2.6	27.7
7	1740	245	8.0	9874.5	309.01	1.71	134.2	2.0	19.5
8	1669	353	6.0	13082.5	356.22	1.31	225.3	1.4	21.6
Comp.				172.5 g/hp-hr		0.069 g/hp-hr	2.56 g/hp-hr	0.057 g/hp-hr	0.69 g/hp-hr

Table E- 15 Emission Results of Test 5DE

Emission Results									
Test: 5DE				Fuel: Syn3-300S-1		Dates: Feb. 18-19, 2002			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	50.1	376.0	23.72	0.30	4.6	0.9	5.6
2	733	55	25.0	1124.2	42.82	0.22	15.8	1.0	8.3
3	854	205	6.0	3970.2	80.08	2.37	73.0	0.6	34.9
4	986	328	5.0	6815.9	139.28	1.64	176.5	0.3	54.5
5	1801	61	20.0	3485.6	139.03	3.84	28.9	3.3	25.9
6	1740	142	12.0	6101.1	204.96	5.07	73.0	2.8	25.2
7	1740	245	8.0	9871.1	303.22	1.71	134.6	2.1	18.4
8	1670	353	6.0	13054.6	350.26	1.54	221.8	1.6	21.4
Comp.				172.6 g/hp-hr		0.069 g/hp-hr	2.54 g/hp-hr	0.066 g/hp-hr	0.68 g/hp-hr

Table E- 16 Emission Results of Test 5DF

Emission Results									
Test: 5DF				Fuel: Syn3-30S-1		Dates: Feb. 20-21, 2002			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	50.1	339.2	23.79	0.04	4.7	0.6	4.5
2	732	55	25.1	1071.7	42.78	0.16	16.6	0.9	7.8
3	851	205	5.9	3934.8	80.06	2.14	75.3	0.6	32.3
4	984	328	5.0	6837.0	139.27	1.57	178.8	0.4	54.3
5	1800	61	20.2	3498.8	138.62	4.19	28.6	3.4	27.6
6	1741	142	12.0	6126.2	205.42	5.30	73.0	2.6	27.4
7	1740	245	8.0	9901.6	303.45	1.60	133.1	2.1	19.9
8	1669	353	6.0	13057.2	349.91	1.12	220.5	1.5	21.2
Comp.				172.2 g/hp-hr		0.065 g/hp-hr	2.54 g/hp-hr	0.059 g/hp-hr	0.68 g/hp-hr

Table E- 17 Emission Results of Test 5DG

Emission Results									
Test: 5DG				Fuel: Syn3-480S-2		Dates: Feb. 26-27, 2002			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	50.0	353.4	24.10	0.15	4.8	1.1	5.1
2	733	55	25.1	1075.2	43.20	0.19	16.3	1.2	7.8
3	852	205	6.0	3938.0	80.18	2.57	71.3	0.6	38.3
4	985	328	5.0	6797.7	139.58	1.84	175.6	0.2	54.4
5	1799	61	19.9	3500.4	139.99	4.23	29.9	4.0	26.3
6	1739	142	12.0	6094.8	205.60	5.32	73.4	3.3	26.7
7	1741	245	8.0	9895.7	304.74	1.98	135.5	2.3	19.3
8	1670	353	6.0	13045.7	351.12	1.70	224.7	1.3	21.0
Comp.				172.2 g/hp-hr		0.072 g/hp-hr	2.57 g/hp-hr	0.075 g/hp-hr	0.69 g/hp-hr

Table E- 18 Emission Results of Test 5FA

Emission Results									
Test: 5FA				Fuel: DECSE-0-1		Dates: Sept. 11-12, 2002			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	49.9	342.3	24.44	0.06	4.3	0.7	3.9
2	732	55	25.0	1103.5	43.57	0.24	14.3	1.1	7.9
3	853	205	6.0	3959.8	80.71	2.44	68.2	0.4	40.2
4	986	328	5.0	6869.0	139.81	1.81	165.3	0.2	66.1
5	1801	61	19.9	3455.1	140.46	3.83	28.5	3.7	24.9
6	1741	142	12.0	6035.6	206.91	4.80	71.6	2.7	24.6
7	1740	245	8.0	9730.5	305.29	1.43	134.0	2.1	16.0
8	1668	353	6.0	12749.5	352.50	0.93	228.6	1.2	17.8
Comp.				169.8 g/hp-hr		0.061 g/hp-hr	2.52 g/hp-hr	0.062 g/hp-hr	0.64 g/hp-hr

Table E- 19 Emission Results of Test 5FB

Emission Results									
Test: 5FB				Fuel: DECSE-480S-1		Dates: Sept. 20, 2002 Sept. 23, 2002			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	50.1	350.7	24.33	0.10	4.4	0.8	4.1
2	732	55	25.0	1075.7	43.58	0.41	14.3	1.2	7.9
3	853	205	5.9	3937.6	80.90	2.48	69.5	0.5	37.1
4	984	328	5.0	6849.1	140.32	2.30	164.3	0.3	64.1
5	1800	61	20.0	3461.1	140.62	3.79	28.9	3.7	24.3
6	1740	142	12.0	6067.0	207.02	4.87	72.1	2.8	23.9
7	1740	245	8.0	9705.8	306.47	1.93	133.4	2.4	15.6
8	1668	353	6.0	12800.2	353.23	1.85	226.3	1.5	18.0
Comp.				170.1 g/hp-hr		0.069 g/hp-hr	2.52 g/hp-hr	0.067 g/hp-hr	0.63 g/hp-hr

Table E- 20 Emission Results of Test 5FC

Emission Results									
Test: 5FC				Fuel: DECSE-150S-1		Dates: Sept. 24-25, 2002			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	50.1	350.4	24.29	0.08	4.4	0.7	3.9
2	732	55	25.1	1088.1	43.41	0.25	14.2	1.0	7.6
3	855	205	6.1	3968.2	81.11	2.32	69.4	0.5	37.1
4	984	328	5.2	6881.7	140.16	1.99	163.9	0.2	67.3
5	1800	61	19.9	3430.9	140.24	3.75	28.3	3.6	24.5
6	1738	142	12.0	6056.8	207.01	4.84	72.0	2.7	23.5
7	1741	245	8.0	9702.7	306.25	1.64	132.7	2.3	15.6
8	1669	353	6.0	12796.4	353.18	1.25	223.7	1.6	18.0
Comp.				170.0 g/hp-hr		0.063 g/hp-hr	2.50 g/hp-hr	0.064 g/hp-hr	0.63 g/hp-hr

Table E- 21 Emission Results of Test 5FD

Emission Results									
Test: 5FD				Fuel: DECSE-300S-1		Dates: Sept. 26-27, 2002			
AVL Mode	**Engine Speed (rpm)**	**Brake Torque (N-m)**	**EGR (% vol)**	**Fuel Flow (g/hr)**	**Air Flow (kg/hr)**	**PM Rate (g/hr)**	**NO_x Rate (g/hr)**	**HC Rate (g/hr)**	**CO Rate (g/hr)**
1	601	8	50.1	326.5	24.31	0.06	4.1	0.7	3.9
2	733	55	25.0	1075.9	43.58	0.22	14.6	0.9	7.3
3	851	205	5.9	3937.1	80.68	2.15	69.9	0.4	34.3
4	984	328	5.0	6851.5	139.77	1.98	164.0	0.3	66.1
5	1800	61	20.0	3429.1	140.43	3.59	28.6	3.4	24.7
6	1739	142	12.0	5989.6	206.93	4.54	71.9	2.4	23.3
7	1740	245	8.0	9703.4	306.15	1.70	133.0	2.1	16.2
8	1669	353	6.0	12789.7	353.51	1.43	224.9	1.4	18.0
Comp.				169.1 g/hp-hr		0.061 g/hp-hr	2.50 g/hp-hr	0.059 g/hp-hr	0.63 g/hp-hr