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# Emissions from Heavy-Duty Diesel Engine with EGR using Fuels Derived from Oil Sands and Conventional Crude

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## ABSTRACT

The exhaust emissions from a single-cylinder version of a heavy-duty diesel engine with exhaust gas recirculation (EGR) were studied using 12 diesel fuels derived from oil sands and conventional sources. The test fuels were blended from 22 refinery streams to produce four fuels (two from each source) at three different total aromatic levels (10, 20, and 30% by mass). The cetane numbers were held constant at 43. Exhaust emissions were measured using the AVL eight-mode steady-state test procedure. PM emissions were accurately modeled by a single regression equation with two predictors, total aromatics and sulphur content. Sulphate emissions were found to be independent of the type of sulphur compound in the fuel. $NO_x$ emissions were accurately modeled by a single regression equation with total aromatics and density as predictor variables. PM and $NO_x$ emissions were significantly affected by fuel properties, but crude oil source did not play a role.

## INTRODUCTION

The diesel engine's high power density and fuel conversion efficiency makes it an attractive power source for the transportation sector. Diesel-powered vehicles emit higher levels of particulate matter (PM) and oxides of nitrogen ($NO_x$) than vehicles powered by spark-ignition engines, however, which has led to environmental concerns. Although the diesel combustion process involves complex physical and chemical processes that are not completely understood, technology advances over the past 15 years have led to nearly one order of magnitude reduction in PM and $NO_x$ emissions. Furthermore, new regulations in North America call for another order of magnitude reduction in these two emissions by the year 2010.

Although exhaust emissions from diesel engines are determined primarily by engine design, fuel properties do have a measurable impact. In 1995, the National Research Council Canada (NRC) initiated a collaborative research program to investigate the emissions behaviour of Canadian diesel fuels, particularly those containing oil sands components. The oil sands deposits in Alberta contain approximately 1.6 trillion barrels of bitumen, a naturally occurring viscous mixture of hydrocarbons. Approximately 20% of these bitumen reserves are recoverable with current technology. The oil sands industry produced 800,000 barrels of crude oil per day

(31% of Canadian oil production) in 2002 and production is expected to increase to almost 2 million barrels per day by the year 2011 [1]. It is estimated that 75% of the oil sands production in 2010 will be pipelined to the U.S. market.

The unique characteristics of oil sands derived crude reflect the bitumen source and the upgrading processes that the bitumen undergoes before it is pipelined to the refinery. The oil sands derived crude used in this study has low sulphur content and very good low temperature properties. Compared to conventional crude, oil sands crude tends to have more cycloparaffins and mono-aromatics.

Li et al [2] compared the exhaust emissions of 12 diesel fuels derived from oil sands and conventional sources in a single-cylinder version of a Volvo TD123 heavy-duty engine. The fuels had three levels of total aromatics (10, 20, and 30% by mass). The fuels derived from oil sands sources produced 5-10% higher sulphate-corrected PM emissions, which were attributed to their higher densities. The $NO_x$ emissions from the engine depended on fuel density and total aromatics, but not on the crude oil source. Mitchell [3] tested a subset of the fuels from [2] in a number of multi-cylinder engines to confirm the single-cylinder engine results.

The focus of the present study is to compare the emissions behaviour of the same 12 test fuels in a prototype year 2004 heavy-duty diesel engine equipped with exhaust gas recirculation. In particular, the objectives were to determine whether or not PM and $NO_x$ emissions from a modern diesel engine are influenced by crude oil source and total aromatic content.

## EXPERIMENTAL SET-UP

RESEARCH ENGINE AND INSTRUMENTATION

A single-cylinder version of Caterpillar's 3400-series heavy-duty diesel engine was used for this research. The engine has a displacement of 2.44 litres, electronically-controlled fuel injection, four valves, and produces 74.6 kW at 2100 rpm. Further engine configuration details may be found in Table 1. The base engine is representative of Caterpillar's engine technology for the 1994-1997 model years.

Simulated turbocharging with intercooling was accomplished by supplying compressed and temperature-controlled air to the research engine. An air surge tank at the inlet to the engine prevents pressure pulsations from disturbing airflow measurement or charge pressure control. 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.

**Table 1.** Research Engine Configuration

| Parameter | Value |
|---|---|
| Engine Model | Caterpillar 3401E engine |
| 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 | Quiescent |
| Fuel Injection Type | Direct Injection |
| Fuel Injection | Mechanically-Actuated EUI |
| Exhaust Gas Recirculation | External Cooled |
| Maximum Power Output | 74.6 kW (2100 rpm) |

Exhaust gas recirculation (EGR) appears to be the method of choice for reducing $NO_x$ emissions from heavy-duty diesel engines to meet the year 2004 regulations in North America. For this study, a prototype cooled 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. 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. The EGR rate, defined as the volume percentage of the intake air charge that is exhaust products, is calculated as follows

$$\%EGR = 100 \frac{\%CO_2(intake) - \%CO_2(ambient)}{\%CO_2(exhaust) - \%CO_2(ambient)}. \quad (1)$$

A heated probe was mounted downstream of the exhaust surge tank to sample the gaseous emissions. The emissions instrumentation (Rosemount, model NGA 2000) consists of a chemiluminescent analyzer for oxides of nitrogen ($NO_x$), 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 the carbon dioxide ($CO_2$) concentrations in the engine intake and exhaust streams (Rosemount, model NGA 2000). A schematic of the emissions instrumentation is provided as Figure 1.

Engine particulate matter (PM) is collected using a fully automated particulate sampling system (Sierra Instruments Inc., model BG-2). 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
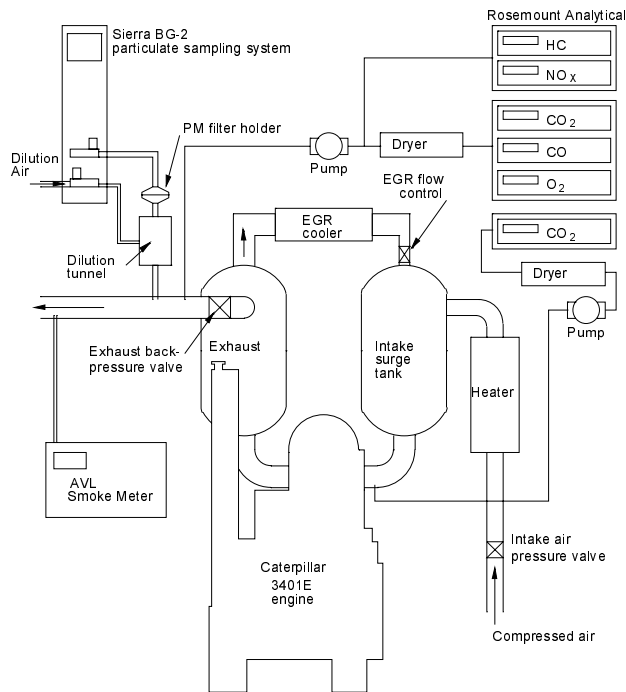
**Figure 1.** Schematic of the Emissions Instrumentation

selected such that the particulate sampling temperature is 52°C or lower. The PM filters are weighed following procedures in the U.S. Code of Federal Regulations [4].

TEST FUEL DESIGN AND BLENDING

Shell Canada Products blended 12 test fuels using refinery streams produced in Canada [2]. Six of the test fuels were blended using fuel components derived from oil sands sources, while the other six fuels were derived from conventional crude oil sources. 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% by mass) subject to the following constraints:

- the target cetane number was 43;
- the sulphur content was less than 500 ppm by mass;
- fuel properties such as viscosity, cloud point, and distillation range were maintained within the typical range of commercial diesel fuel in Canada; and
- at each total aromatics level, the distillation curves of the two fuels from the same source were varied as

much as possible.

The test fuels were coded as "S" (for oil sands derived) or "C" (conventional crude derived); 10, 20, or 30 for the nominal total aromatics content; and "A" or "B" to differentiate different blends with the same crude source and total aromatic content. Test fuels S20B, S30A, and S30B had 0.071, 0.138, and 0.090% by volume of 2-ethyl hexyl nitrate (EHN) cetane improver added to achieve the target cetane number. Selected properties of the test fuels are provided in Tables A-1 and A-2.

**TEST PROCEDURE**

The AVL eight-mode steady-state simulation [5] of the U.S. EPA Transient Test Procedure was used. The emissions measured at each of the eight speed/load conditions are multiplied by a mode weight, as indicated in Table 2, and summed to produce composite emissions. It should be noted that the mode weights 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 does not measure transient engine behaviour, which contributes significantly to PM emissions. However, previous research has shown that the eight-mode test procedure produces the correct emission trends [3].

Brake power settings were obtained by determining the fuelling rates in the parent engine (model year 2000, 373 kW) at the eight modes and then by recording the torque produced by the research engine at the same fuelling rates when operated with a reference fuel. The EGR settings and fuel injection timings were selected to limit the $NO_x$ emissions to 2.5 g/hp-hr and minimize PM emissions [6]. The engine and environmental settings for the eight modes are provided in Table 2. The brake torque produced by the 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.

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

| AVL Mode | Mode Weight (%) | Engine Speed (rpm) | Brake Torque (N-m) | Injection Timing (°BTDC) | EGR Setting (%) | Intake Air Temp. (°C) | Intake Air Pressure (kPa abs.) | Exhaust Air Pressure (kPa abs.) |
|---|---|---|---|---|---|---|---|---|
| 1 | 35.01 | 600 | 8.0 | 0 | 50 | 50 | 100 | 104 |
| 2 | 6.34 | 732 | 55.3 | 0 | 25 | 40 | 104 | 106 |
| 3 | 2.91 | 852 | 205.3 | 0 | 6 | 34 | 134 | 127 |
| 4 | 3.34 | 984 | 327.7 | 6 | 5 | 30 | 195 | 198 |
| 5 | 8.40 | 1800 | 61.3 | 2 | 20 | 42 | 120 | 134 |
| 6 | 10.45 | 1740 | 142.1 | 2 | 12 | 36 | 165 | 173 |
| 7 | 10.21 | 1740 | 245.2 | 2 | 8 | 34 | 235 | 245 |
| 8 | 7.34 | 1668 | 353.4 | 5 | 6 | 36 | 283 | 293 |

## RESULTS AND DISCUSSION

### MEASUREMENT REPEATABILITY

A winter-grade low-sulphur diesel fuel obtained from a local supplier was used as the reference fuel. Selected properties of the reference fuel are provided in Table A-3. The reference fuel was tested a total of seven times during the time period that the experimental program was run to ensure that the engine and instrumentation were functioning properly. The experimental data obtained during these tests were used to estimate the repeatability of the composite emissions measurements. The data were analyzed statistically to determine if there were any systematic drifts in the PM and $NO_x$ emissions during the test period.

The mean, standard deviation (s.d.), and coefficient of variation (c.v.) of the four regulated exhaust emissions and BSFC are shown in Table 3. The coefficients of variation of the reference fuel composite emissions, expressed as percentages, are 4.0% for PM, 0.5% for $NO_x$, 10.5% for HC, and 2.9% for CO. There were no systematic trends in the emissions data.

### COMPOSITE EMISSIONS OF THE TEST FUELS

The 12 fuels were tested in a random order, except that pairs of fuels having the same total aromatic content but derived from different sources (oil sands or conventional) were run back-to-back in the engine. The composite emissions from the engine are provided in Table 4. The emissions ranged from 0.059 to 0.079 g/hp-hr for PM and from 2.21 to 2.56 g/hp-hr for $NO_x$.

Although the test fuels were designed to compare oil sands and conventional derived fuels at three levels of aromatics, Pearson correlation coefficients between fuel properties and exhaust emissions are provided in Table A-4. Amongst the fuel properties, it is important to note that there was a 0.67 correlation coefficient between density and total aromatic content for the 12 test fuels. Also, there was a 0.74 correlation coefficient between fuel sulphur content and poly-aromatics, defined in this study as aromatics with two or more ring structures. The composite PM emissions correlated strongly with fuel total aromatic and sulphur contents. Not surprisingly, fuel mono- and poly-aromatic contents were also highly correlated with PM emissions. The composite $NO_x$ emissions correlated strongly with fuel total aromatic content and density.

**Table 3.** Composite Emissions of Reference Fuel

| Statistic | PM (g/hp-hr) | $NO_x$ (g/hp-hr) | HC (g/hp-hr) | CO (g/hp-hr) | BSFC (g/hp-hr) |
|---|---|---|---|---|---|
| mean | 0.074 | 2.469 | 0.056 | 0.694 | 170.7 |
| s.d. | 0.003 | 0.012 | 0.006 | 0.020 | 0.7 |
| c.v. (%) | 4.0 | 0.5 | 10.5 | 2.9 | 0.4 |

**Table 4.** Composite Emissions of Test Fuels

| Fuel | PM (g/hp-hr) | $NO_x$ (g/hp-hr) | HC (g/hp-hr) | CO (g/hp-hr) | BSFC (g/hp-hr) |
|---|---|---|---|---|---|
| Ref | 0.074 | 2.47 | 0.056 | 0.69 | 170.7 |
| C10A | 0.059 | 2.21 | 0.057 | 0.76 | 167.7 |
| C10B | 0.066 | 2.27 | 0.054 | 0.72 | 169.7 |
| S10A | 0.063 | 2.34 | 0.052 | 0.73 | 170.3 |
| S10B | 0.062 | 2.39 | 0.050 | 0.68 | 169.3 |
| C20A | 0.068 | 2.41 | 0.062 | 0.68 | 168.8 |
| C20B | 0.067 | 2.38 | 0.057 | 0.73 | 169.5 |
| S20A | 0.066 | 2.38 | 0.063 | 0.70 | 167.3 |
| S20B | 0.069 | 2.49 | 0.061 | 0.71 | 170.0 |
| C30A | 0.077 | 2.52 | 0.050 | 0.69 | 171.0 |
| C30B | 0.079 | 2.46 | 0.060 | 0.71 | 169.6 |
| S30A | 0.067 | 2.56 | 0.054 | 0.68 | 171.7 |
| S30B | 0.070 | 2.52 | 0.054 | 0.71 | 170.4 |

It is well known that fuel-bound sulphur is oxidized to form a sulphuric acid aerosol (sulphates) inside the combustion chamber of diesel engines and that a fraction of the sulphates condense on PM filters [7-9]. Since it is generally not possible to control the sulphur content of test fuels derived from refinery streams, the experiment was designed to take sulphate emission variations between test fuels into account so that the effects of other properties are not masked.

The effect of fuel-bound sulphur on PM emissions was studied by doping two low-sulphur base fuels with various quantities of single- and four-compound sulphur dopants. The objectives were to decouple the relationship between fuel sulphur content and total aromatics and to compare two different sulphur dopants. In the first experiment, different quantities of di-tertiary-butyl disulphide were added to a base fuel, derived from oil sands sources, containing 8-ppm sulphur by mass. In the second experiment, a four-compound sulphur dopant was added to a base fuel from the DECSE program [10] containing 3-ppm sulphur by mass. Except for the sulphur content, the DECSE base fuel was blended to be representative of diesel fuels in the United States. The composition of the four-compound sulphur dopant was dibenzo[b]thiophene (50% of total sulphur by mass), benzo[b]thiophene (30%), di-tertiary-butyl disulphide (10%), and ethyl phenyl sulphide (10%) [10]. Selected properties of the two base fuels are provided in Table A-3.

Figure 2 is a graph of composite PM emissions as a function of the fuel sulphur content. The graph shows that the slopes of the regression lines for the single- and four-compound sulphur dopant experiments were very similar. Due to an equipment malfunction, only four fuel sulphur levels were tested for the four-compound sulphur dopant. The experimental data supports the hypothesis that sulphate emissions are independent of the type of
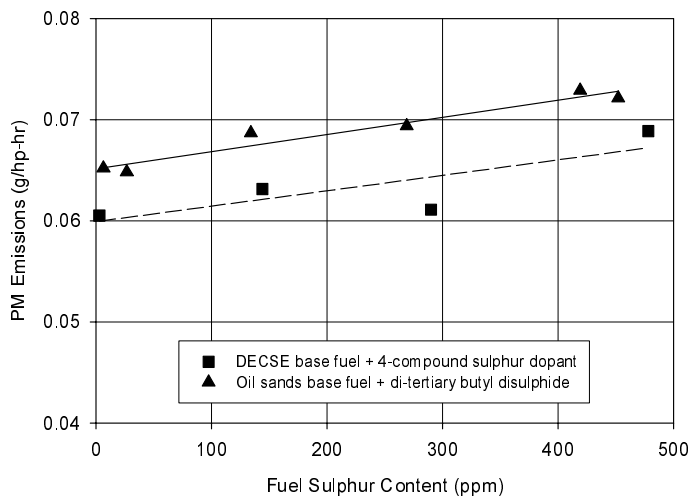
**Figure 2.** Composite PM Emissions vs. Fuel Sulphur Content

sulphur compound in the fuel. Accordingly, the data from the two experiments were combined to estimate the influence of fuel sulphur on PM emissions. The increase in PM emissions due to fuel sulphur was estimated to be $1.7 \times 10^{-5}$ g/hp-hr-ppm. Sulphate-corrected PM emissions from the engine are obtained by subtracting $1.7 \times 10^{-5}$ x fuel sulphur content (ppm by mass) from the measured PM emissions.

Figure 3 is a graph of the sulphate-corrected composite PM emissions for the reference and test fuels. The sulphate corrections to the PM emissions were larger for the test fuels derived from conventional crude sources due to their higher sulphur contents. Sulphate-corrected PM emissions increased as total aromatic content increased from 10 to 30% for both the conventional and oil sands derived test fuels. A regression equation was fit to the test fuel data. The regression line, shown with the corresponding 95% confidence interval, fits the data well given the measurement repeatability for PM emissions. The figure shows that sulphate-corrected PM emissions from the engine depend on fuel total aromatic content.
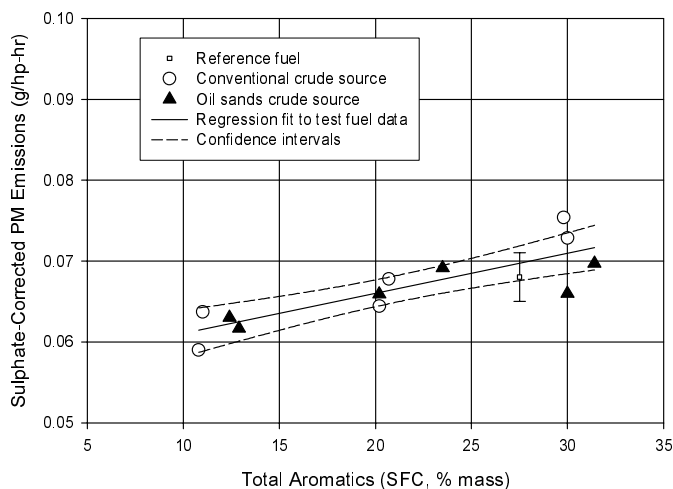
Li et al [2] observed a positive correlation between PM emissions and total aromatic content for the same fuels tested in a Ricardo Proteus engine. In the earlier study, however, the test fuels derived from oil sands sources had 5-10% higher PM emissions at a given total aromatic content, which were attributed to their higher densities. Fuel density did not have the same influence on PM emissions from the research engine used in the current study.

Figure 4 is a graph of the composite $NO_x$ emissions for the reference and test fuels. The graph shows that $NO_x$ emissions increase as the fuel total aromatic content increases from 10 to 30%. In general, the oil sands derived test fuels had slightly higher $NO_x$ emissions at a given total aromatic level. This trend was observed previously for the same test fuels in a Ricardo Proteus engine [2] and was attributed to the higher density of the test fuels derived from oil sands sources at a given total aromatic content. Figure 5 shows that the test fuels derived from oil sands sources had lower $NO_x$ emissions at a given fuel density. This is presumably due to the lower total aromatics of the oil sands derived test fuels at a given density.

The research engine used in the current study has electronic fuel injection, high levels of turbocharging, and EGR. The engine has a very short delay period between the start of fuel injection and ignition under most operating conditions. This results in a combustion process that is predominantly controlled by the diffusion of fuel and air. Figure 6 shows an average apparent mass burn rate at a high-speed high-load operating condition (mode 8) when operated with the reference fuel. The small peak in the mass burn rate that corresponds to pre-mixed combustion is evidence that the combustion process is diffusion-controlled. The fuel injection system in the Ricardo Proteus engine used in the previous study [2], on the other hand, has an in-line fuel injection pump. The fuel injection timing in engines
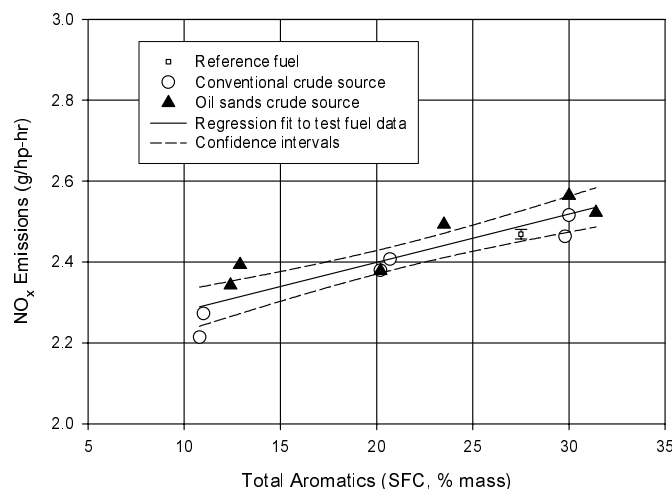


**Figure 3.** Composite PM Emissions of the Reference and Test Fuels After Removing the Fuel Sulphur Content Effect
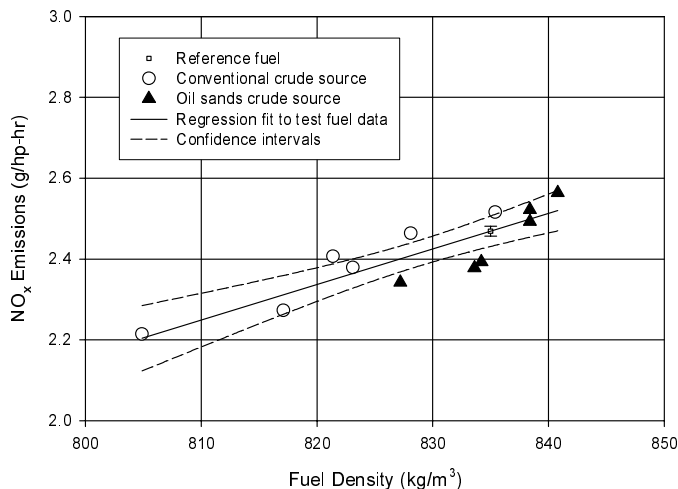


**Figure 4.** Measured Composite $NO_x$ Emissions of the Reference and Test Fuels

**Figure 5.** Composite NO$_x$ Emissions vs. Fuel Density



**Figure 6.** Apparent Mass Burn Rate vs. Crank Angle at Mode 8

incorporating this older technology is known to be affected by fuel density. This may explain the discrepancies in the emissions results between the two engines.

REGRESSION ANALYSES

Regression analyses were performed to develop models that explain the composite PM and NO$_x$ emissions from the engine for the 12 test fuels. The analyses were performed using Systat® (Systat Software Inc.), a statistical and graphical analysis package. The fuel properties listed in Table A-4, with the exception of cetane number, were considered for inclusion in the models. A backward stepwise regression procedure was used to select variables for the model. Variables were removed from the model when the p-values associated with its regression coefficient were greater than 0.01.
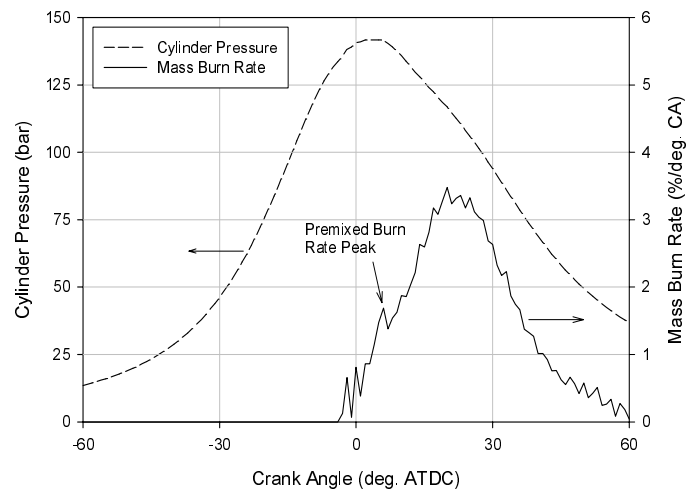
The resultant equations are summarized in Table 5. The PM emissions model has two independent fuel properties, namely total aromatics and sulphur content. The adjusted R$^2$ for the regression equation is 0.82 and the root mean square error (MSE) of the estimator is 0.0024 g/hp-hr. The coefficient of the fuel sulphur variable in the regression model is $3.3 \times 10^{-5}$ g/hp-hr-ppm. This coefficient is significantly higher than the $1.7 \times 10^{-5}$ g/hp-hr-ppm coefficient measured in the sulphur doping experiments. The discrepancy may be due to a correlation between sulphur content and another fuel property, possibly fuel poly-aromatics.

A comparison between the predicted and measured composite PM emissions for the 12 test fuels, the two base fuels, and the reference fuel are provided in Figure 7. The model over-predicted the PM emissions for the three fuels not used to develop the PM regression

**Table 5.** Regression Equations for PM and NO$_x$ Emissions

| Emission | Fuel Effect | Coefficient | p-value | Adj. R$^2$ | Root MSE |
|----------|-------------|-------------|---------|------------|----------|
| PM | Constant | 5.65E-2 | 6.1E-10 | 0.82 | 2.4E-3 |
| | Total Aromatics | 4.19E-4 | 2.7E-3 | | |
| | Sulphur | 3.29E-5 | 6.3E-3 | | |
| NO$_x$ | Constant | -1.89 | 3.3E-2 | 0.95 | 2.4E-2 |
| | Total Aromatics | 7.48E-3 | 1.8E-4 | | |
| | Density | 5.00E-3 | 4.5E-4 | | |

**Table 6.** Regression Equations for PM and NO$_x$ Emissions with Additional Variable for Crude Source

| Emission | Fuel Effect | Coefficient | p-value | Adj. R$^2$ | Root MSE |
|----------|-------------|-------------|---------|------------|----------|
| PM | Constant | 5.66E-2 | 7.5E-9 | 0.80 | 2.6E-3 |
| | Total Aromatics | 4.29E-4 | 8.6E-3 | | |
| | Sulphur | 3.12E-5 | 5.8E-2 | | |
| | **Crude Source** | **3.69E-4** | **8.7E-1** | | |
| NO$_x$ | Constant | -2.71 | 9.7E-2 | 0.94 | 2.5E-2 |
| | Total Aromatics | 6.69E-3 | 4.9E-3 | | |
| | Density | 6.02E-3 | 9.9E-3 | | |
| | **Crude Source** | **-1.81E-2** | **5.2E-1** | | |

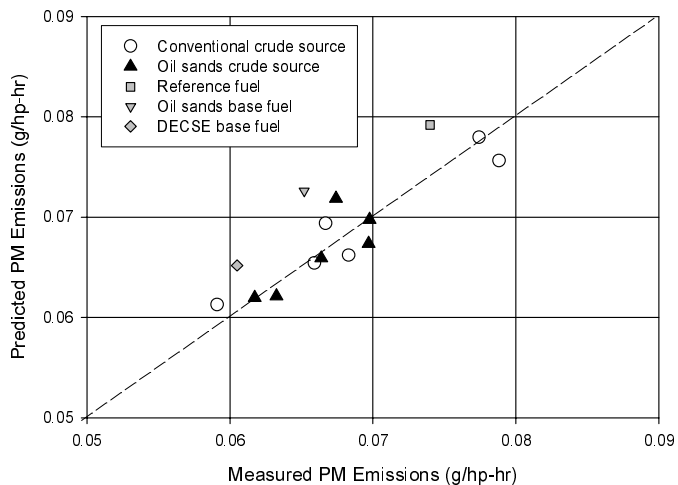**Figure 7.** Comparison of Predicted and Measured Composite PM Emissions



**Figure 8.** Comparison of Predicted and Measured Composite NOx Emissions

model. This may be due to the limited number of fuel properties in the model or uncertainties in the model coefficients. The oil sands base fuel had a higher total aromatic content than any of the test fuels used to develop the model.

The regression analysis of $NO_x$ emissions produced a model with total aromatics and density as the two significant fuel properties. It should be noted that the 90% distillation temperature (T90) would also appear in the model if a 0.05 level of significance were used instead of 0.01. The adjusted $R^2$ for the regression equation in Table 5 is 0.95 and the root mean square error (MSE) of the estimator is 0.024 g/hp-hr. Figure 8 compares the predicted and measured composite $NO_x$ emissions for the same 15 test fuels. The model does a reasonable job of predicting the $NO_x$ emissions for all fuels considered.

The regression models for PM and $NO_x$ emissions were modified by the addition of a predictor variable denoting the crude oil source. The variable was set to zero for the test fuels derived from conventional sources and to unity for the test fuels derived from oil sands sources. The regression coefficients were computed for the modified models and are summarized in Table 6. In both cases, the p-values for the crude source variables exceeded 0.50 and resulted in a regression equation with a slightly higher root mean square error. Thus, the regression models in Table 6 are inferior to those presented in Table 5. This provides strong evidence that the PM and $NO_x$ emissions from the research engine are determined by key fuel compositional properties. Crude oil source did not significantly affect the PM or $NO_x$ emissions from the engine.

## SUMMARY AND CONCLUSIONS

The exhaust emissions from a single-cylinder version of a modern heavy-duty diesel engine equipped with
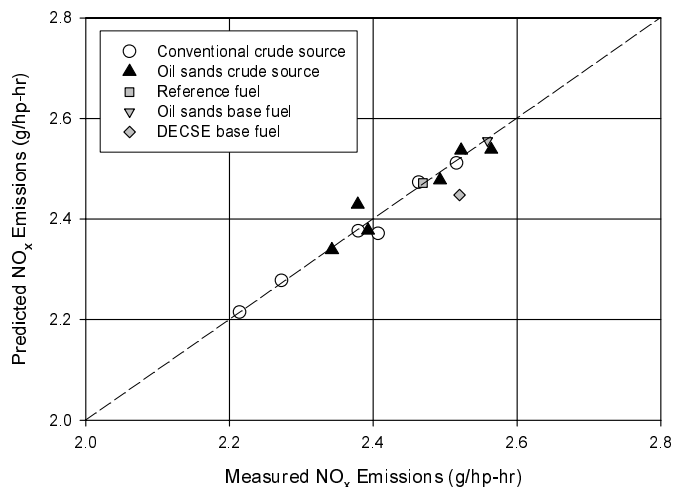
exhaust gas recirculation were measured using 12 diesel fuels derived from oil sands and conventional sources. The test fuels consisted of four fuels, two each derived from oil sands and conventional sources, at three total aromatic levels. Two base fuels were also tested in the engine with various quantities of single- and four-compound sulphur dopants added. The cetane numbers of the test fuels were held constant at 43. The AVL eight-mode steady-state simulation of the U.S. EPA heavy-duty transient test procedure was employed.

A reference fuel was run periodically in the engine to estimate the repeatability of the emissions measurements and to ensure that the engine emissions were not drifting over time. The coefficients of variation of the emissions measurements for seven experiments conducted with the reference fuel were 4.0% for PM and 0.5% for $NO_x$. No systematic drifts in the emissions data were observed.

The following conclusions were drawn based on an analysis of the experimental data for the test fuels investigated in this study:

1. PM and $NO_x$ emissions from the research engine are affected by key fuel compositional properties, but not by the crude oil source.
2. For PM emissions, two fuel properties are statistically significant predictors: fuel total aromatics and sulphur content. The adjusted multiple coefficient of determination (adjusted $R^2$) for the regression model is 0.82.
3. For $NO_x$ emissions, two fuel properties are statistically significant predictors: fuel total aromatics and density. The adjusted multiple coefficient of determination (adjusted $R^2$) for the model is 0.95.
4. The sulphate portion of the PM emissions increase linearly by $1.7 \times 10^{-5}$ g/hp-hr for each ppm by mass of fuel-bound sulphur. The experimental data supports the hypothesis that sulphate emissions are independent of the type of sulphur compound in the fuel.

## REFERENCES

1. Almdal, W., "Investment in the Oil Sands: An Update", presentation to Alberta Chamber of Resources Oil Sands Task Force, Calgary, Alberta, February 19, 2003.
2. Li, X., Chippior, W.L., Gülder, Ö. L., Cooley, J., Richardson, E.K., and Mitchell, K., "Comparison of the Exhaust Emissions of Diesel Fuels Derived from Oil Sands and Conventional Crude Oil", SAE Paper No. 982487, 1998.
3. Mitchell, K., "Effects of Fuel Properties and Source on Emissions from Five Different Heavy Duty Diesel Engines", SAE Paper No. 2000-01-2890, 2000.
4. Cartellieri, W., Kriegler, W. and Schweinzer, F., "Strategies to meet Worldwide Heavy-Duty Diesel Emission Standards", Proc. Istn. Mech. Engrs., Vol. 206, pp. 161-171, 1992.
5. U.S. Code of Federal Regulations, Title 40, Part 86, Section 1312, 1988. (The regulations are available on-line at http://www.access.gpo.gov/nara/cfr/.)
6. Neill, W.S., Smallwood, G.J., Snelling, D.R., Sawchuk, R.A., Clavel, D., Gareau, D., and Chippior, W.L., "Effect of EGR on Heavy-Duty Diesel Engine Emissions Characterized with Laser-Induced Incandescence", ICE-Vol. 39, Paper No. ICEF2002-532, Proceedings 2002 ASME ICED Fall Technical Conference, New Orleans, 2002.
7. Heywood, J.B., Internal Combustion Engine Fundamentals, McGraw-Hill Inc., New York, 1988.
8. Baranescu, R.A., "Influence of Fuel Sulfur on Diesel Particulate Emissions", SAE Paper No. 881174, 1988.
9. Den Ouden, C.J.J., Clark, R.H., Cowley, L.T., Stradling, R.J., Lange, W.W., and Mallard, C., "Fuel Quality Effects on Particulate Matter Emissions from Light- and Heavy-Duty Diesel Engines", SAE Paper No. 942022, 1994.
10. Diesel Emissions Control – Sulfur Effects (DECSE) Program Phase I Interim Data Report No. 1, Appendix A, August 1999. (The report is available on-line at http://www.ott.doe.gov/decse.)

## CONTACT

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## APPENDIX

**Table A-1.** Fuel Properties of Oil Sands Derived Blends[1]

| | S10A | S10B | S20A | S20B | S30A | S30B |
|---|---|---|---|---|---|---|
| Density, D4052, kg/m$^3$ @ 15°C | 827.2 | 834.2 | 833.6 | 838.4 | 840.8 | 838.4 |
| Viscosity, D445, cSt @ 40°C | 1.65 | 2.14 | 1.70 | 1.92 | 1.81 | 1.73 |
| Cloud Point, D2500, °C | -44 | -27 | -26 | -25 | -28 | -33 |
| Distillation, D86 | | | | | | |
|   IBP, °C | 155 | 159 | 157 | 157 | 171 | 171 |
|   T10, °C | 176 | 183 | 181 | 179 | 185 | 187 |
|   T50, °C | 218 | 244 | 224 | 232 | 223 | 225 |
|   T90, °C | 286 | 317 | 285 | 324 | 324 | 302 |
|   EP, °C | 314 | 345 | 311 | 349 | 348 | 335 |
| Cetane In., D976 | 41.0 | 46.8 | 40.9 | 41.8 | 37.9 | 39.5 |
| Base Cetane No., D613 | | | | 39.1 | 36.5 | 37.8 |
| 2-EHN cetane improver, % v/v | | | | 0.071 | 0.138 | 0.09 |
| Final Cetane No., D613 | 41.0 | 43.4 | 40.2 | 42.9 | 42.3 | 42.0 |
| Sulphur, D5453, ppm (mass) | 13.2 | 2.4 | 28.8 | 31.1 | 84.7 | 3.0 |
| Hydrogen, D3701, % m/m | 13.8 | 13.7 | 13.5 | 13.4 | 13.1 | 13.2 |
| Base Nitrogen, D4629, ppm (mass) | 27.9 | 0.3 | 56.4 | 1.5 | 24.8 | 2.5 |
| SFC, CAN/CGSB-3.0 No. 15.0 | | | | | | |
|   Total Aromatics, % m/m | 12.4 | 12.9 | 20.2 | 23.5 | 30.0 | 31.4 |
|   Mono-Aromatics, % m/m | 10.9 | 9.5 | 17.9 | 20.2 | 25.2 | 27.4 |
|   Poly-Aromatics, % m/m | 1.5 | 3.4 | 2.3 | 3.2 | 4.9 | 3.9 |
| LC-GC/MS, D2786 | | | | | | |
|   Total Cycloparaffins, % m/m | 68.9 | 66.3 | 61.3 | 57.0 | 47.2 | 47.1 |

[1] Analyses performed by NRC, NCUT, Shell Canada Products and Syncrude Canada Ltd. See [2] for details.

**Table A-2**. Fuel Properties of Conventional Crude Oil Derived Blends[1]

| | C10A | C10B | C20A | C20B | C30A | C30B |
|---|---|---|---|---|---|---|
| Density, D4052, kg/m³ @ 15°C | 804.9 | 817.1 | 821.4 | 823.1 | 835.4 | 828.1 |
| Viscosity, D445, cSt @ 40°C | 1.62 | 2.01 | 1.97 | 1.66 | 2.18 | 1.70 |
| Cloud Point, D2500, °C | <-70 | -27 | 3 | -39 | -10 | -37 |
| Distillation, D86 | | | | | | |
|   IBP, °C | 190 | 202 | 187 | 174 | 179 | 176 |
|   T10, °C | 200 | 208 | 191 | 194 | 199 | 199 |
|   T50, °C | 213 | 222 | 223 | 220 | 244 | 231 |
|   T90, °C | 242 | 286 | 335 | 272 | 317 | 268 |
|   EP, °C | 285 | 321 | 379 | 315 | 352 | 301 |
| Cetane In., D976 | 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, D5453, ppm (mass) | 8.1 | 131.0 | 31.4 | 134.0 | 270.0 | 202.0 |
| Hydrogen, D3701, % m/m | 14.2 | 14.1 | 13.7 | 13.7 | 13.3 | 13.4 |
| Nitrogen, D4629, ppm (mass) | 1.0 | 17.5 | 4.7 | 19.7 | 41.2 | 21.8 |
| SFC, CAN/CGSB-3.0 No. 15.0 | | | | | | |
|   Total Aromatics, % m/m | 10.8 | 11.0 | 20.7 | 20.2 | 30.0 | 29.8 |
|   Mono-Aromatics, % m/m | 9.6 | 7.8 | 16.0 | 16.8 | 22.1 | 25.1 |
|   Poly-Aromatics, % m/m | 1.2 | 3.2 | 4.6 | 3.5 | 7.9 | 4.7 |
| LC-GC/MS, D2786 | | | | | | |
|   Total Cycloparaffins, % m/m | 40.9 | 45.4 | 37.4 | 45.1 | 33.8 | 37.8 |

**Table A-3.** Fuel Properties of the Reference and Base Fuels[1]

| | Reference Fuel (Ref5) | Oil Sands Base Fuel (Syn3) | DECSE[2] Base Fuel |
|---|---|---|---|
| Density, D4052, kg/m³ @ 15°C | 833.2 | 832.5 | 826.1 |
| Viscosity, D445, cSt @ 40°C | 1.91 | 1.24 | 2.42 |
| Cloud Point, D2500, °C | -29 | -40 | -21 |
| Distillation, D86 | | | |
|   IBP, °C | 160 | 170 | 185 |
|   T10, °C | 189 | 180 | 207 |
|   T50, °C | 237 | 202 | 259 |
|   T90, °C | 298 | 238 | 314 |
|   EP, °C | 327 | 276 | 350 |
| Cetane In., D976 | 45.1 | 33.1 | 53.6 |
| Cetane No., D613 | 43.0 | 41.9 | 44.8 |
| Sulphur, D5453, ppm (mass) | 356 | 7.7 | 3.1 |
| Hydrogen, D3701, % m/m | 13.4 | 13.0 | 13.4 |
| Nitrogen, D4629, ppm (mass) | 22 | 361 | |
| SFC, CAN/CGSB-3.0 No. 15.0 | | | |
|   Total Aromatics, % m/m | 26.2 | 37.9 | 27.8 |
|   Mono-Aromatics, % m/m | 19.9 | 35.5 | 17.9 |
|   Poly-Aromatics, % m/m | 6.3 | 2.4 | 10.0 |
| LC-GC/MS, D2786 | | | |
|   Total Cycloparaffins, % m/m | 26.4 | 34.9 | 29.7 |

[1] Analyses performed by NRC, NCUT, Shell Canada Products and Syncrude Canada Ltd. See [2] for details.
[2] Average of analyses performed by Phillips Petroleum, Core Laboratories, and Southwest Research Institute.

**Table A-4.** Correlation between Fuel Properties and Emissions of Test Fuels

| | Density | Kinematic Viscosity | T10 | T50 | T90 | Final Cetane Number | Sulphur Content | Total-Aromatics | Mono-Aromatics | Poly-Aromatics | Total-Cycloparaffins |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Density | 1.00 | | | | | | | | | | |
| Kinematic Viscosity | 0.28 | 1.00 | | | | | | | | | |
| T10 | -0.60 | 0.16 | 1.00 | | | | | | | | |
| T50 | 0.58 | 0.78 | -0.07 | 1.00 | | | | | | | |
| T90 | 0.66 | 0.68 | -0.40 | 0.53 | 1.00 | | | | | | |
| Final Cetane Number | 0.17 | 0.55 | 0.13 | 0.50 | 0.61 | 1.00 | | | | | |
| Sulphur Content | 0.06 | 0.30 | 0.60 | 0.39 | -0.05 | 0.30 | 1.00 | | | | |
| Total-Aromatics | 0.67 | 0.03 | -0.06 | 0.34 | 0.37 | 0.37 | 0.43 | 1.00 | | | |
| Mono-Aromatics | 0.67 | -0.12 | -0.14 | 0.23 | 0.29 | 0.26 | 0.32 | 0.98 | 1.00 | | |
| Poly-Aromatics | 0.46 | 0.61 | 0.29 | 0.65 | 0.54 | 0.65 | 0.74 | 0.71 | 0.58 | 1.00 | |
| Total-Cycloparaffins | 0.30 | -0.10 | -0.78 | 0.02 | 0.08 | -0.44 | -0.62 | -0.44 | -0.36 | -0.59 | 1.00 |
| PM | 0.44 | 0.22 | 0.24 | 0.49 | 0.24 | 0.52 | 0.76 | 0.80 | 0.73 | 0.78 | -0.53 |
| $NO_x$ | 0.88 | 0.24 | -0.34 | 0.51 | 0.66 | 0.43 | 0.27 | 0.90 | 0.88 | 0.70 | -0.14 |
| HC | -0.15 | -0.41 | -0.07 | -0.35 | -0.12 | 0.10 | -0.19 | 0.10 | 0.18 | -0.25 | -0.13 |
| CO | -0.67 | -0.69 | 0.21 | -0.69 | -0.85 | -0.65 | -0.17 | -0.46 | -0.36 | -0.68 | 0.02 |