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ABSTRACT

The effects of fuel properties of both oil-sands-derived and conventional-crude-oil-derived diesel fuels were investigated on a single-cylinder DI research engine. The engine used in this study incorporated features of contemporary medium- to heavy-duty diesel engines and was tuned to the U.S. EPA 1994 emission standards. The engine experiments were run using the AVL 8-mode steady-state simulation of the U.S. EPA heavy-duty transient test procedure. The experimental fuels included 12 fuels blended using refinery streams to have controlled total aromatic levels and 7 other diesel fuels obtained from different sources. The results showed that at a constant cetane number (44) and sulfur content (150 ppm), oil-sands-derived fuels produced similar NOx emissions as their conventional-crude-oil-derived counterparts and total aromatic content and fuel density could be used in a regression model to predict NOx emissions. At the same total aromatic content, the oil sands derived fuel blends produced 5-10% higher PM emissions in the test engine, whereas at the same density, the two kinds of fuel blends produced similar PM emissions. Therefore, the higher PM emissions observed in oil-sands-derived fuel blends could be attributed to the higher densities of these fuels. Regression analysis showed that fuel density was a better descriptor for PM emissions than total aromatic content when the cetane number and sulfur content were kept constant.

INTRODUCTION

Combustion and emission formation processes in diesel engines are very complex in nature. Engine efficiency and exhaust emissions are dependent largely on engine design but influenced by fuel composition. Although low-emission engines that implement new technologies and optimize engine parameters seem to have lower sensitivities on fuel composition, fuel properties still have a measurable impact on exhaust emissions [1-4]. It could be expected that to meet more stringent emission limits, the interaction between engine and fuel composition will become even more important.

In Canada, 21% of petroleum crude is produced from oil sands. This figure is expected to increase as the conventional crude oil resources are depleted. In the diesel boiling range, the oil-sands-derived crude oil is low in sulfur but higher in aromatics (although low in multi-ring aromatics) compared to conventional crude oil. The oil-sands-derived crude also contains more cycloparaffins. Diesel fuels produced from oil-sands-derived crude tend to have relatively poor cetane quality but good low temperature properties. The specific emission behavior of oil-sands-derived diesel fuel is not well documented.

In recent years, more attention has been directed to the effect of aromatic content in the fuel. Unlike sulfur content or cetane number, aromatic content in the diesel fuel is difficult to separate from other fuel properties. Consequently, the results obtained in different research programs are often biased by the specific fuel matrix designs and the correlation between aromatic content and various fuel properties. The matter is further complicated by the different fuel appetites exhibited by different engines.

In a number of fuel matrices designed to investigate various fuel properties, Tamanouchi, et al., showed that NOx emissions from four different engines running both EPA transient and Japanese 13-mode test procedures decrease with the decrease of aromatic content and fuel density [1-2]. The other emissions, however, are more engine dependent, with T90 being the major variable affecting PM emissions on two of the four engines. Using solvents and pure hydrocarbon compounds in four fuel matrices that completely de-correlate various fuel properties, Tanaka, et al., showed that aromatic content influences NOx emissions on two different engines, whereas PM is affected by T10 and T90 for both engines and by multi-ring aromatics for one of them [3]. In other studies, NOx emissions are found to decrease when fuel density decreases [4-5], aromatic content decreases [5-10]], poly-aromatic content decreases [4], and T90 or T95 decreases [4][10]. The PM emissions are found to decrease when total aromatic content decreases [5][8][10-11], poly-aromatic content decreases [4][8][12-13], density decreases [13-15], and T90 decreases [5][8][12].

The focus of this study was to investigate the emission behavior of oil-sands-derived diesel fuels and compare it with diesel fuels derived from conventional crude oil. The main objective was to answer the question whether oil-sands-derived diesel fuel is different from conventional-crude-derived diesel fuel (with the same total aromatic content) as far as the exhaust emissions are concerned.

The use of a single cylinder research engine facilitated the investigation of a large number of test fuels, and enabled a more accurate control of the engine conditions. A steady-state simulation of the EPA transient test procedure was used in the program. The emission test results were therefore linked to the results obtained from the EPA transient test. At the same time, the steady-state engine tests offered detailed information on pollutant formation under different engine operating conditions.

Twelve fuels were blended using refinery diesel components. Six of these 12 fuels originated from oil sands streams and the other 6 were derived from conventional crude. Engine emission results from these two groups of fuels were compared. The influence of fuel properties on exhaust emissions was analyzed. Regression models generated from these fuels were tested using 7 test fuels obtained from various sources.

EXPERIMENTAL

Test Engine and Exhaust Emission Measurement - The engine used in this program was a single-cylinder research version (Ricardo Proteus) of a Volvo TD123 heavy-duty truck engine. The engine was a direct-injection type and had a displacement volume of 2 liters. Major engine configuration data are shown in Table 1. The research engine

Table 1 Research Engine Configuration

Engine Type	Ricardo Proteus (replicates one cylinder of Volvo D123)
Bore	130.2 mm
Stroke	150.0 mm
Number of Cylinders	1
Displacement	1.997 litres
Combustion Chamber Type	Toroidal Bowl
Compression Ratio	17:1
Number of Valves/Cylinder	2
Injection Type	Direct Injection
Fuel Injection Pump	Bosch PE6P 120A 320RS8011
Injection Pressure (Typical)	120 MPa (17,400 psi)
Fuel Injection Nozzle	Bosch DLLA 152 P 285
Maximum Power Output	44.67 kW (60 bhp) @ 1900 rev/min

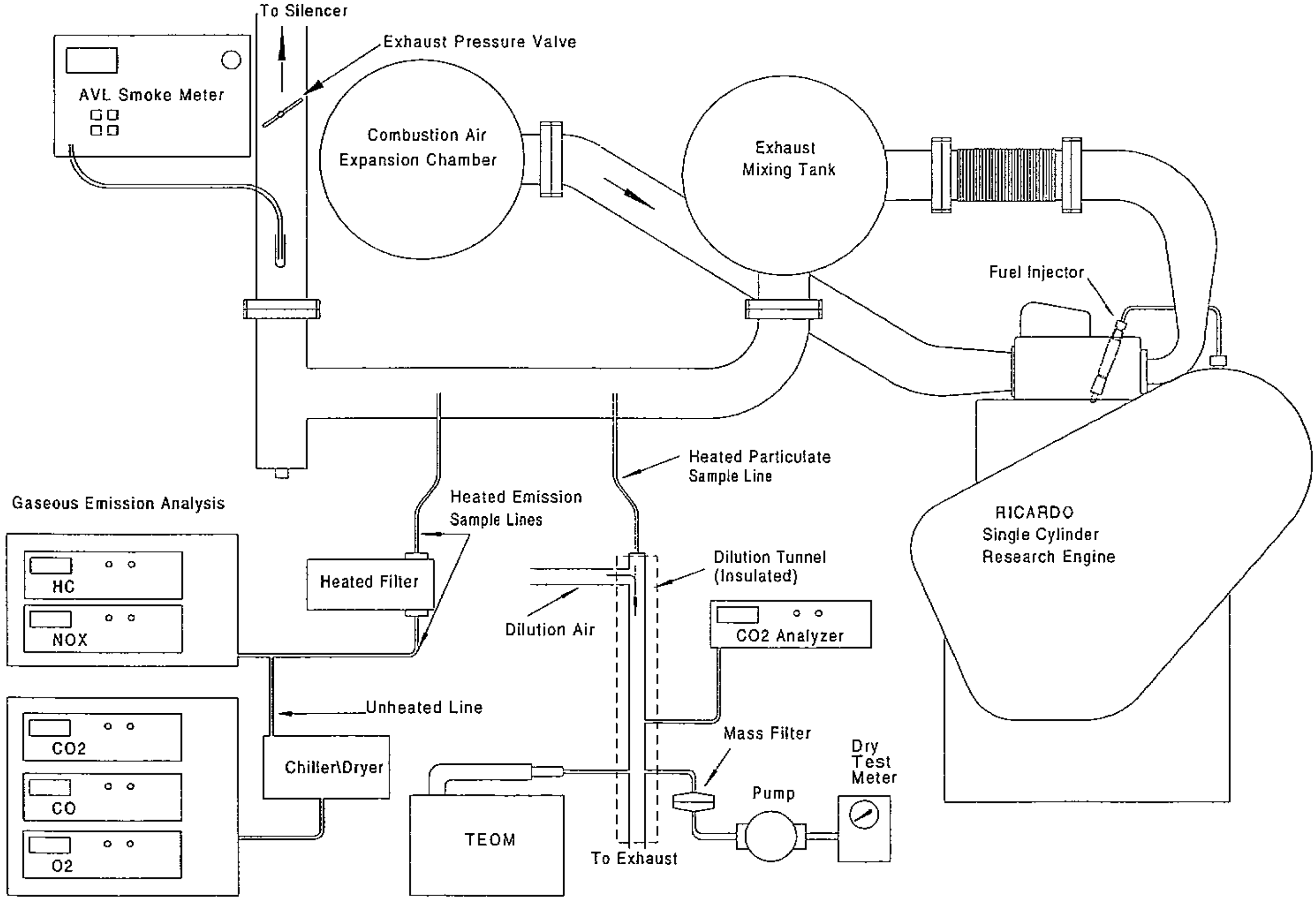

Figure 1 Engine and Exhaust Measurement System

incorporated many features of contemporary medium- to heavy-duty diesel engines. It was tuned to meet the U.S. EPA 1994 emission standards.

Figure 1 shows the schematic of the engine and emission measurement system. The speed and the load of the research engine were controlled independently by a dynamometer and a fuel control system. To simulate a turbo charger, externally compressed and dried air, controllable for temperature and pressure, was supplied to the engine. The exhaust system was fitted with an orifice downstream of the exhaust port, which, together with the exhaust back pressure valve, provided a cylinder pressure pumping loop similar to that of the multi-cylinder parent engine. A mixing tank in the exhaust line reduced the pressure/flow pulsations and provided complete mixing of the exhaust gases before sampling.

Filtered lubricating oil was delivered to the engine by external pump. The temperature of the engine oil was controlled to 80°C. Because the oil reservoir was large, there was no need to change engine oil during the period when a specific fuel matrix was run. The engine coolant temperature was controlled at 80°C.

A Kistler 6121 high-temperature pressure transducer was mounted in the research engine to measure cylinder pressure. The fuel injector was instrumented with a Wolff hall-effect needle-lift sensor so that the start and the end of fuel injection could be determined. The engine crankshaft position was determined by an AVL 360C/720S high-resolution optical crank angle encoder.

A heated probe was mounted after the mixing tank to sample the gaseous emissions in the exhaust. The wet concentration of NOx in the heated sample was measured continuously using a Beckman 955 chemiluminescent analyzer, and the wet concentration of HC in the heated sample was measured using a Beckman 402 flame ionization analyzer. The gaseous sample was then passed through a drying system, and the dry concentrations of CO, CO_2 and O_2 in the exhaust were measured using Beckman 865 and 864 non-dispersive infrared analyzers and a Beckman OM-11EA polarographic analyzer, respectively.

A separate probe was used to sample total particulate matter, shown in Figure 1. The temperature of the probe was maintained at 190°C to prevent condensation of heavy hydrocarbons. The exhaust sample was then diluted in a mini-dilution tunnel using filtered and dried air. The flow rate of the dilution air was regulated, so that the temperature in the dilution tunnel was maintained at 52°C. A PM sample line was connected to a 47 mm particulate filter and a dry test meter. To determine the dilution ratio and thus the actual PM concentration in the engine exhaust, the concentration of CO_2 in the dilution tunnel was measured and compared to the concentration of CO_2 in the exhaust.

Table 2 AVL 8-Mode Steady-State Simulation of EPA Transient Test Procedure

Mode	Speed (rpm)	Load (%)	Weighting Factor
1	600	0	35.01
2	743	25	6.34
3	873	63	2.91
4	1016	84	3.34
5	1900	18	8.40
6	1835	40	10.45
7	1835	69	10.21
8	1757	95	7.34

A computer running PCC software recorded engine control parameters and emission values. A total of 60 data points were recorded in duration of 5 minutes. Averaged values of speed, power, fuel consumption rate, temperatures, pressures and exhaust emission concentrations were used in the calculation of composite emissions.

To establish a link of the results from this program to those obtained with the EPA transient test procedure, the AVL 8-mode steady-state simulation test procedure was adopted [16]. The engine operating conditions and the weighting factors of this test procedure are listed in Table 2. The engine speed in this test procedure varies widely, from low idle speed (600 rpm) to rated speed (1900 rpm). The load also varies widely from 0% to 95%. The low idle condition is weighted heavily in the test procedure.

In calculating the composite brake specific emissions, the weighting factor (WF) at each mode is used in the following equation:

$$BSE = \frac{\sum (Emission\,Rate)_i \times WF_i}{\sum (Brake\,Power)_i \times WF_i} \qquad (1)$$

The emission rates in the equation are calculated from measured emission concentrations and fuel consumption rates.

To make the engine experimental results relevant to multi-cylinder production engines, an effort was made to run the research engine at operating conditions as closely as possible to the "parent" production engine. The research engine manufacturer supplied the speed and load mapping of the multi-cylinder "parent" engine. Using this information, engine speed, torque, intake manifold temperature, intake manifold pressure, intake airflow, engine brake torque and exhaust back pressure were determined.

For all test fuels, the speed and the load at each mode were kept the same. Therefore, discrepancies in the amount of fuel per cycle supplied to the engine should be eliminated for fuels having different densities. Nevertheless, fuels having different densities still had slightly different injection timing and duration.

To determine the repeatability of the emission measurements, the reference fuel Ref2 (see Appendix for its properties) was run in the engine periodically. The repeatability results from Ref2 are shown in Table 3. Both the standard deviation and the range of data spread are shown (in percentages of the mean) as measures of experimental repeatability. It is apparent that changes in exhaust emissions were random. Therefore, the experimental data obtained with all other test fuels were not adjusted for engine or experimental system drift.

Table 3 Experimental Repeatability Using Ref2

Test Date	PM filter g/hp.h	NOx g/hp.h	CO g/hp.h	HC g/hp.h	Fuel Cons. g/hp.h
03/10/96	0.081	4.72	-	0.30	45.40
11/10/96	0.076	4.76	-	0.29	45.57
27/10/96	0.076	4.80	0.88	0.28	45.66
01/11/96	0.078	4.71	0.89	0.32	45.52
06/02/97	0.083	4.66	0.88	0.34	45.51
18/02/97	0.085	4.76	0.93	0.30	45.41
27/02/97	0.082	4.78	0.87	0.28	45.49
14/03/97	0.079	4.74	0.88	0.28	45.99
Std. Dev./ Mean (%)	4.35	0.92	2.46	7.28	0.41
Max-Min/ Mean (%)	12.30	2.84	7.26	22.39	1.29

The results of repeatability tests indicate that if single tests were run on two fuels, the smallest differences the system can detect between the emissions from the two fuels are: for PM, around 13%; for NOx, around 3%; for CO, around 7.5%; and for HC, around 22%. However, the ability to detect emission changes caused by a certain fuel property can be increased by measures such as running repeated test on the fuels and properly designing fuel matrix so that some of the random test errors can be reduced.

Test Fuels - The 12 fuels blended in this program (fuels C10A to S30B, see Appendix for their properties) were blended by Shell Canada using refinery streams produced in Canada. Two groups of fuels were blended, one group from refinery components derived from conventional crude oil, the other from refinery components derived from oil sands crude. The intention was to blend fuels from the two sources that had matching properties, and their properties were within the range of typical commercial diesel fuels in Canada.

One of the challenges to blend fuels using refinery component streams is the availability of components. In this program, 11 components that were produced from oil-sands-derived crude were obtained from 3 refineries or plants. Another 11 components that were produced from conventional crude were obtained from 4 refineries.

The following are the parameters controlled in the fuel blending:

- Have total aromatics in three levels, 10, 20 and 30%

- Keep sulfur less than 500 ppm by weight

- Target cetane number in low forties, and allow the use of 2-ethyl hexyl nitrate to adjust cetane number to within the range of 42 to 46

- Have low and high mid-boiling point for each pair of fuels at the same aromatic level from the same source

- Keep other fuel properties (such as viscosity, cloud point and distillation) within the typical range of current commercial diesel fuel in Canada.

The fuels were coded as S or C (oil Sands or Conventional crude derived); 10, 20, or 30 for the nominal total aromatic level; and A or B for the two blends of different properties.

It was noted that the conventional-crude-derived fuels tended to have lower densities than their equivalent oil-sands-derived fuels. This was unavoidable if the other fuel properties (specifically total aromatic content) were to be matched. Two solvent blends had to be used to blend the conventional-crude-derived fuels with nominally 10% total aromatics, since no conventional-crude-derived component of less than 12% total aromatics was available. In each blend, three solvents were back-blended together so that the distillation range of the mixture would more resemble that of a typical diesel component.

The cetane numbers of three fuels, S20B, S30A and S30B, were found to be lower than the desired range. Appropriate amounts of cetane improver (Ethyl HiTEC 4103, 2-ethyl hexyl nitrate) were added into the blends to bring the cetane numbers to within the range of 42 to 46. New codes were given to these cetane number corrected fuels, which were S20Bn1, S30An5 and S30Bn1, respectively.

In addition to the 12 fuels blended for the program, 7 other fuels were also tested in this program. The properties of these fuels are listed in the Appendix.

Aromatic Content Measurement - Since the effect of aromatics on exhaust emissions was the major objective of this study, to measure aromatic content accurately is indispensable. In reality, aromatics, especially the breakdown of different types of aromatic contents, are difficult to measure. Different methods will give different results. The agreement can be quite poor between the results reported by different laboratories using the same methods on the same sample. To minimize the uncertainty associated with the aromatic measurement, four different methods were used to characterize the test fuels.

The four methods include Supercritical Fluid Chromatography (SFC, CGSB 15.0-94), performed by Syncrude Canada Ltd.; High Performance Liquid Chromatography (HPLC, IP391/95) and Hot Fluorescent Indicator Analysis (FIA, UOP 501-83) performed by Shell Canada Ltd.; and Gas Chromatography/Mass Spectroscopy (GC/MS) performed by National Centre for Upgrading Technology. The SFC, HPLC and GC/MS identify aromatic type in terms of single ring compounds, double ring compounds and triple ring (and up) compounds on mass basis. The GC/MS method provides more detailed breakdown of compounds by mass percent. The FIA gives volume concentrations of aromatics, olefins and saturates.

For total aromatic content, the four methods yielded results that correlated well with each other, with correlation coefficients of 0.996 to 0.999. Using total aromatic content measured by any of the four methods should yield the same conclusion when the impact of total aromatic content on engine emissions is assessed.

The di-aromatic content measured by all three methods correlated well. The correlations between tri-(and plus)aromatics were not as good due to their low concentrations in the test fuels. It is therefore not meaningful to use tri-aromatic content as a separate fuel property. Instead, the lump sum of all the aromatics having two or more ring structures was used as a separate fuel property, and this property was termed "poly-aromatics". The correlations between the poly-aromatic contents measured by different methods correlated well, with coefficients ranging from 0.979 to 0.991.

In this paper, SFC data were used for all the analyses. The SFC data not only were available for all the test fuels, but also correlated well with other measurements.

RESULTS AND DISCUSSIONS

All test fuels were run in the research engine using the AVL 8-mode steady state simulation of the U.S. EPA transient test procedure. The injection timing was also set the same for all the fuels. Three repeated runs at each mode were conducted, yielding 3 composite gaseous emission values. Two filter measurements and one TEOM measurement were performed for PM emissions. The averaged emission results were used in the analyses. To guard against unknown systematic errors, fuels were run in random order. The pair of fuels having the same total aromatic content but derived from different sources (oil sands or conventional crude oil) were run back to back.

Corrections for Sulfur Content, Cetane Number and Injection Timing - The sulfur contents of all the test fuels were lower than 500 ppm by mass. The actual sulfur content of the test fuels varied from 3 to 270 ppm by mass. A "reference" sulfur content of 150 ppm by mass was chosen, which lay approximately in the middle of the sulfur range among the 12 specially blended test fuels. To obtain a sulfur correction factor for PM emissions, four fuels were blended by adding different concentrations of di-tertiary-butyl disulfide into a base fuel and run in the engine. The linear relationship between PM emissions and the sulfur content was used to correct the PM emissions for all the test fuels to the reference sulfur level. The maximum sulfur correction for PM emissions was an increase of 0.0033 g/hp.hr for fuel S10B, which represented a 4.2% correction.

The cetane numbers of the 12 test fuels in the fuel matrix were controlled in a narrow range, within 6.3 cetane number. The "reference" cetane number was chosen as 44. The cetane

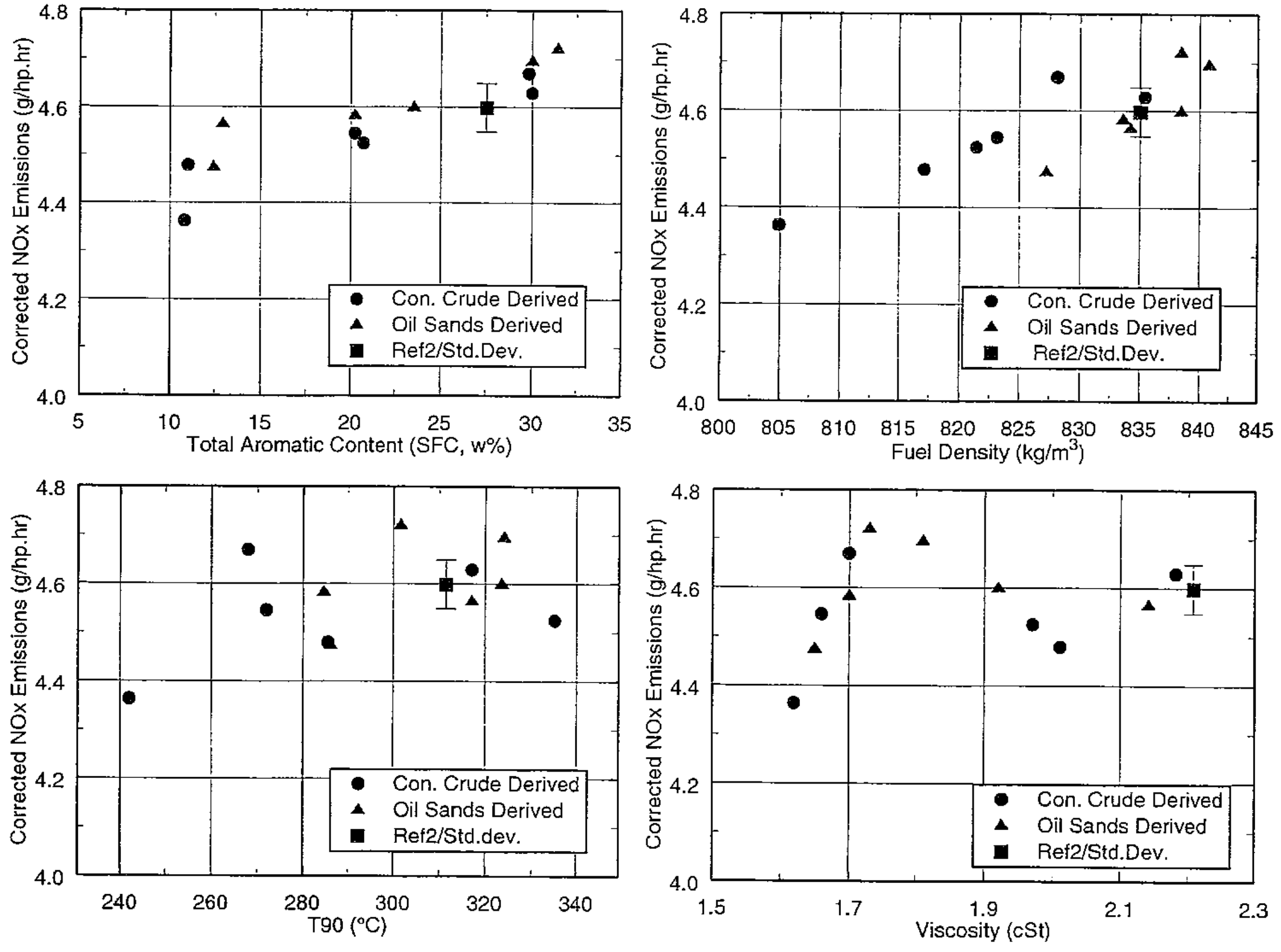

Figure 2 Corrected NOx Emissions versus Different Fuel Properties

number correction factors for NOx and PM emissions were determined from engine emission results that were obtained from fuels blended by adding 2-ethyl hexyl nitrate into a base fuel. The linear relationships between the emissions and the cetane number from this base fuel were used to correct the NOx and PM emissions for all the test fuels to the reference cetane number. The maximum cetane number corrections for NOx and PM emissions were obtained for fuel S20A: a decrease of 0.04 g/hp.hr (0.9%) in NOx emissions and an increase of 0.0017 g/hp.hr (2.2%) in PM emissions.

It was noticed that fuel properties had an effect on the actual injection timing. At each mode, the start and the end of injection event changed among the test fuels. This change was consistent for all 8 modes. The actual amount of the injection-timing change can be determined from the experimental data. Using the measured injection timing of fuel C20B as a reference (since this fuel has a density that represents the midpoint of the fuel matrix), the injection-timing changes of the test fuels can be determined from the needle lift traces recorded in the experiments.

The relationships between the injection timing and engine emissions were obtained by running the engine in a series of tests using different injection-timing settings. Using these relationships, the effects of injection timing (due to fuel density) on NOx and PM emissions were corrected. The maximum correction occurred for fuel C10A that had the largest timing change of 0.4 crank angle degree. The NOx emissions were increased by 0.13g/hp.hr (2.8%) and the PM emissions were reduced by 0.0019 g/hp.hr (2.4%).

Comparison of Oil-Sands-Derived Fuel Blends with Conventional-Crude-Oil-Derived Fuel Blends - The corrected NOx emission data are plotted in Figure 2 versus total aromatic content, density, viscosity and T90. A correlation between NOx emissions and both total aromatic content and density was observed. The higher the total aromatic content and the density, the higher the NOx emissions. NOx emissions did not correlate with T90 or viscosity. At the same aromatic content, the oil-sands-derived fuels had NOx emissions similar to the conventional-crude-oil-derived fuel blends. At equal densities, oil sands derived fuels had lower NOx emissions.

It should be pointed out that the maximum change in NOx emissions among the 12 fuels was relatively small, about 7%. However, this difference is well above the repeatability of the NOx measurements (standard deviation less than 1%) and can not be attributed to the experimental errors.

The corrected PM emissions are shown in Figure 3

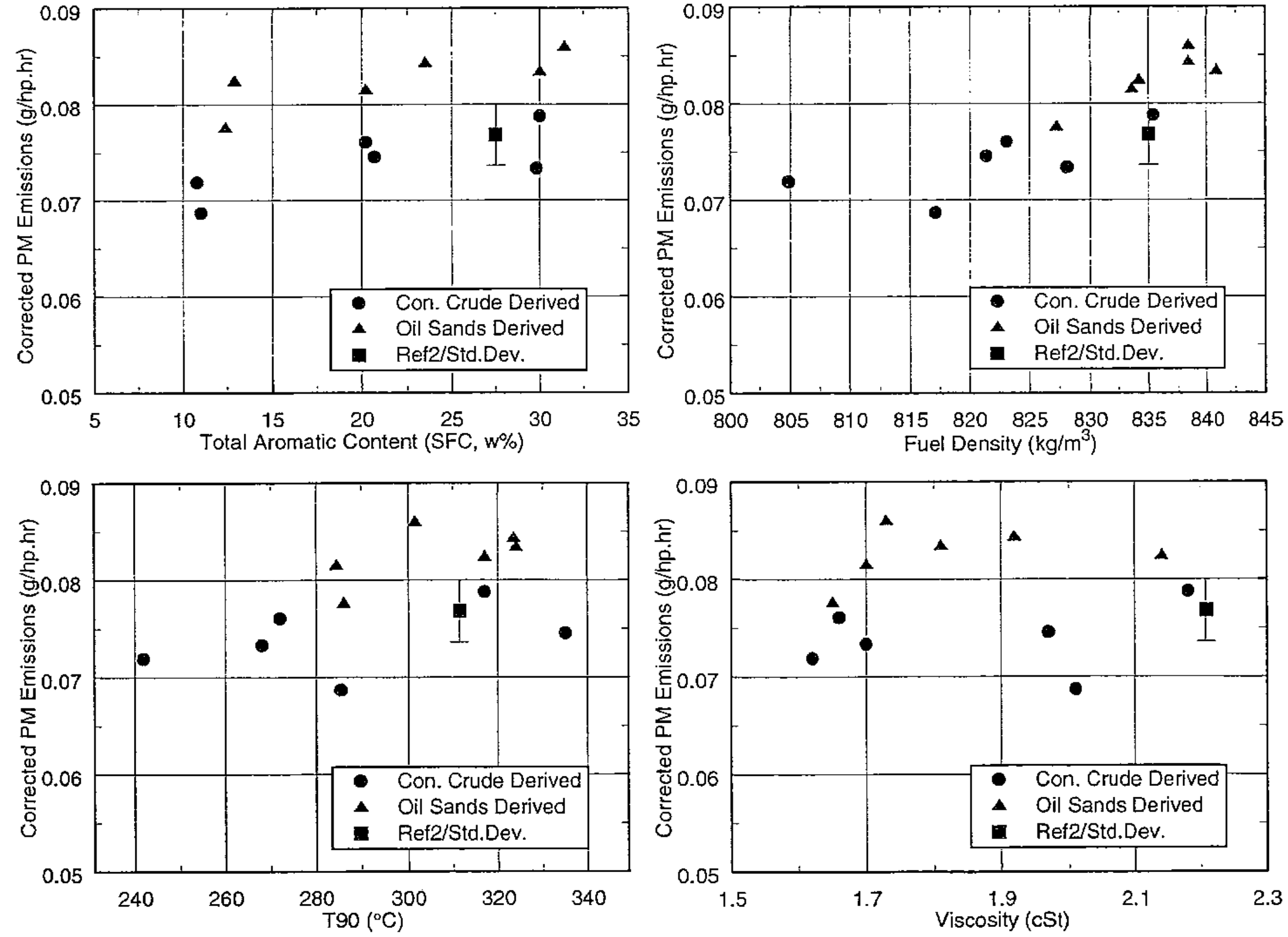

Figure 3 Corrected PM Emissions versus Different Fuel Properties

Table 4 Correlation Coefficient of C&S Fuel Properties

	Dens.	T90	T50	T10	Visc.	Total_ Arom	Poly_ Arom
Dens.	1.000	0.663	0.576	-0.599	0.275	0.670	0.456
T90		1.000	0.531	-0.393	0.679	0.371	0.538
T50			1.000	-0.073	0.776	0.340	0.649
T10				1.000	0.166	-0.063	0.290
Visc.					1.000	0.033	0.607
Total_ Arom						1.000	0.714
Poly_ Arom							1.000

versus total aromatic content, density, viscosity and T90. Again, a correlation between PM emissions and fuel density was observed. A higher density led to higher PM emissions. A slight increasing trend was also observed in PM emissions when total aromatic content was increased. There was no correlation between PM emissions and T90 or viscosity.

Comparing the two fuel groups, oil-sands-derived fuels generated higher PM emissions at the same aromatic level. This difference can be attributed mostly to the density difference between the two fuel groups in the test fuel matrix – the oil-sands-derived fuels having higher densities than the conventional-crude-oil-derived fuels at the same aromatic level. This suggests that fuel components other than total aromatics could play a role in particulate formation.

The standard deviation of repeated PM measurements in the test was 4.35%. The maximum change in PM emissions among the 12 fuels was about 18%. The PM measurement repeatability was not good enough to detect small changes in PM emissions. However, trends displayed by the 12 fuels should be valid since the number of test fuels was relatively large.

For fuels having 20 to 30 % total aromatics, the CO emissions stayed the same. All four fuels having about 10% total aromatics showed higher CO emissions. There was no correlation between CO emissions and the other fuel properties. There was no substantial difference in CO emissions from the two fuel groups.

The HC emissions did not correlate with any of the fuel properties. Also, no difference was found between the HC emissions from the two fuel groups. If there were any difference in HC emissions of the two fuel groups, this difference must be smaller than the experimental error in measuring HC emissions.

Since density has been shown to correlate with both NOx and PM emissions, it is necessary to examine the fuelling rates. Figure 4 shows the fuel consumption rates of the 12 fuels versus density. The variation in fuel consumption rates was small, less than ±1% deviation from the mean. The fuel consumption rate did not correlate with density. It is evident that fuelling rate was not a major factor causing the emission differences among the test fuels.

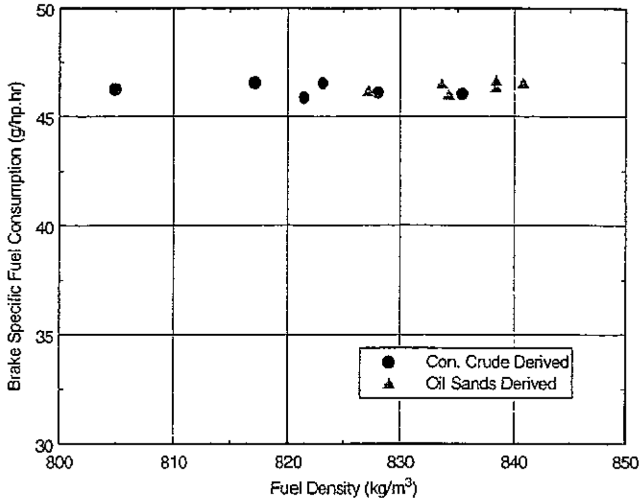

Figure 4 Fuel Consumption Rate of Fuels Having Different Origin and Aromatic Content

Regression Analysis and Emission Models - As shown previously, the emission data indicated that NOx and PM emissions were related to density and total aromatic content. There was also evidence suggesting that other fuel properties might be linked to PM emissions. Regression analyses were performed to examine the correlation between the engine exhaust emissions and various fuel properties. Generated models were also used to examine their capability in predicting NOx and PM emissions.

The fuel properties considered in the regression analyses were: density, viscosity, T90, T50, T10, total aromatic content, and poly-aromatic content (di+-aromatics). The aromatic content data used were SFC results. The correlation of these fuel properties is shown in Table 4. The highest correlation of 0.776 was between T50 and viscosity. Some degree of correlation between total aromatic content and poly-aromatic content was also observed with a coefficient of 0.714.

Different models were obtained using forward and backward step-wise regression analyses on NOx emissions. Fuel density and total aromatic content were found to be the best variables. These two properties account for 92.8% of the total changes in NOx emissions ($R^2 = 0.928$). Both factors are highly significant, although total aromatic content is more so (see Table 5).

The picture for PM was not as clear. Both backward and

Table 5 Regression Analysis of Corrected Composite Emissions

Emission	Variables	Standard Error	Standard Coefficient	F-Value	Probability	R^2
NOx	Density	0.0012	0.4559	14.3053	0.0043	0.928
	Total Aromatics	0.0016	0.5964	24.4841	0.0008	
PM	Density	0.0004	0.7293	11.3602	0.0071	0.532

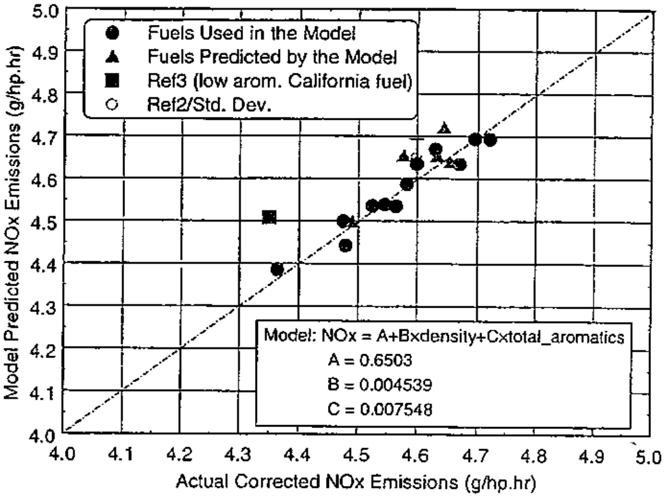

Figure 5 Regression Model for NOx Emissions

forward step-wise regression analyses pick only density as the significant correlating factor, which accounts for 53.2% of the changes in PM emissions. The effect of total aromatic content was not significant. The low R^2 value indicates that density was not the sole determining variable for PM emissions. There should be factors other than density, which affected PM emissions. Because the fuel matrix was not designed to reveal the role of different types of aromatics and some other fuel properties, and also considering the measurement error associated with PM emission measurements, the model can not be viewed as conclusive. In a later study, more fuel matrices will be blended and examined. It is hoped that the results will further reveal the importance of poly-aromatics and possibly other factors such as cycloparaffins.

The proposed models were used to predict the NOx and PM emissions of the 7 test fuels that had not been included in generating the correlations. Fuels Ref1 and Ref2 were obtained locally, and they had cetane number, viscosity and density close to those fuels used in generating the models. Their total aromatic contents were also within the range covered by the test fuel matrix. Fuel Ref3 was obtained from California, and its viscosity, density and cetane number were much higher than the fuels in the test fuel matrix. Ref3 also had a very low aromatic content of about 5% by mass. All three fuels were derived from conventional crude oil. Fuels A, C, E and F (obtained from another program [17-18]) had total aromatic contents, cetane numbers and other fuel properties close to the 12 fuels used in generating the models. These four fuels were blended from Canadian diesel components derived from both oil sands and conventional crude oil.

Figure 5 shows the NOx emission model prediction. The model was able to predict the NOx emission results of the six fuels: Ref1, Ref2, A, C, E and F. The prediction of fuel Ref3 was 3.8% higher than the measured NOx value. Since fuel Ref3 had properties far away from those represented by the 12 test fuels, it was not surprising that the model was not able to predict its emissions. The fact that the regression model was able to predict the NOx emissions for other fuels indicates that total aromatic content and density are likely to be two important factors affecting NOx emissions.

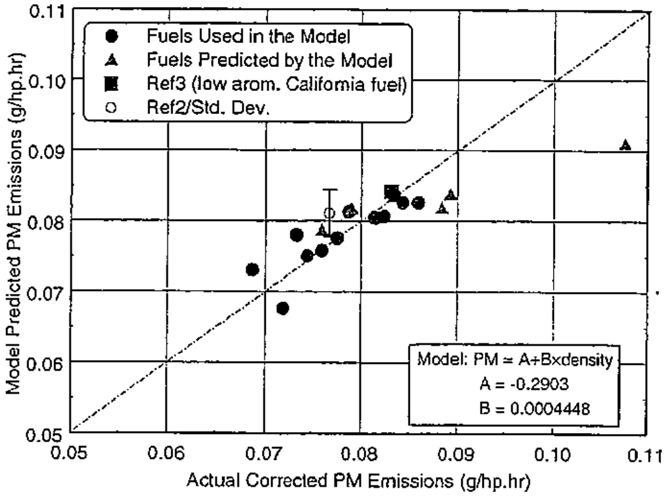

Figure 6 Regression Model for PM Emissions

The PM emission model prediction is shown in Figure 6. The model predictions for the six fuels Ref1, Ref2, Ref3, A, C and E were reasonable. The exception was fuel F. The model prediction was substantially lower than the actual measured PM emission result. Since fuel F had a substantially higher tri+-aromatic content, the result seems to suggest that multi-ring aromatics might be a factor for PM emissions. It is hoped that the role of multi-ring aromatics will become clear after the second stage of this program.

The density of the fuel has been shown by the regression analyses to correlate with both NOx and PM emissions. In conducting the engine experiments, engine power was kept constant at each mode for all fuels. As shown in Figure 4, fuel consumption rates changed little among the test fuels. The effect of injection timing change due to density was also eliminated in the corrected emissions results. One possible reason is that fuel density is a "surrogate" variable that represents the effect of a number of other variables, since density and chemical composition are intrinsically related in commercial diesel fuels (reflected by the correlation between total aromatics and density, Table 4).

SUMMARY AND CONCLUSIONS

A few concluding remarks can be made from this study:

1. The analysis of the emission results with 12 fuels showed that at a constant cetane number (44) and sulfur content (150 ppm), oil-sands-derived fuels produced similar NOx emissions as their conventional-crude-oil-derived counterparts. At the same total aromatic content, the-oil-sands-derived fuel blends produced 5-10% higher PM emissions in the test engine. This could be attributed to higher densities of the oil-sands-derived test fuels.

2. Although the test procedure ensures that the fuelling rate did not change with fuel density, NOx emissions and PM emissions were both found to correlate with fuel density. At the same cetane number and sulfur content, total aromatic content and fuel density could be used in a regression model to predict NOx emissions. Fuel density was also a better defining parameter than total aromatic

content for PM emissions when the cetane number and sulfur content were kept constant.

FUTURE WORK

The results of this study have identified the following areas where further investigation is warranted:

1. The NOx emissions were shown to correlate with the total aromatic content (and density). In addition, one of the fuels tested (fuel F), which had a higher poly-aromatic content (and density), yielded relatively high PM emissions. In view of these results, the roles of mono-aromatics and poly-aromatics (di- and above) will be investigated using fuel matrices that are designed to have the same total aromatic content and density but different mono- and poly-aromatic contents.

2. The non-aromatic fractions in the fuel, particularly naphthenic compounds (cycloparaffins), may have a significant contribution to PM and NOx emissions. Further work is warranted to quantify the effect of cycloparaffins on diesel exhaust emissions. A fuel matrix designed to reveal the influence of cycloparaffins (mono- and/or poly-cycloparaffins) on exhaust emissions should be used for this purpose.

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APPENDIX - PROPERTIES OF TEST FUELS

Properties of Blended Diesel Fuels

FUEL ID	**S10A**	**S10B**	**S20A**	**S20Bn1**	**S30An5**	**S30Bn1**	**C10A**	**C10B**	**C20A**	**C20B**	**C30A**	**C30B**
Source	Oil-sands-derived refinery streams						Conventional-crude-oil-derived refinery streams					
Density, kg/m^3 @15°C	827.2	834.2	833.6	838.4	840.8	838.4	804.9	817.1	821.4	823.1	835.4	828.1
Viscosity @40°C, cSt	1.65	2.14	1.7	1.92	1.81	1.73	1.62	2.01	1.97	1.66	2.18	1.70
Cloud Point, °C	-44	-27	-26	-25	-28	-33	<-70	-27	3	-39	-10	-37
Distillation, D86, IBP, °C	155.0	158.5	156.5	156.5	170.5	170.5	189.5	201.5	187.0	173.5	178.5	175.5
T10, °C	175.5	183.0	181.0	179.0	185.0	186.5	200.0	207.5	191.0	194.0	198.5	198.5
T50, °C	217.5	244.0	224.0	232.0	222.5	224.5	212.5	221.5	223.0	219.5	244.0	231.0
T90, °C	286.0	317.0	284.5	323.5	324.0	301.5	242.0	285.5	335.0	272.0	317.0	268.0
EP, °C	313.5	344.5	310.5	348.5	347.5	334.5	284.5	320.5	379.0	315.0	352.0	301.0
Cetane In., D976-80	41.0	46.8	40.9	41.8	37.9	39.5	47.4	46.1	45.0	43.2	46.5	45.1
Cetane No. D613	41.0	43.4	40.2	42.9	42.3	42.0	40.4	41.6	46.5	41.9	43.9	44.2
Sulphur, ppm (mass)	13.2	2.4	28.8	31.1	84.7	3.0	8.1	131	31.4	134.0	270.0	202.0
Hydrogen Content m%	13.75	13.73	13.49	13.42	13.08	13.16	14.18	14.13	13.72	13.68	13.28	13.40
Nitrogen, ppm (mass)	27.9	0.3	56.4	1.5	24.8	2.5	1.0	17.5	4.7	19.7	41.2	21.8
SFC												
Total Aromatics, %m	12.4	12.9	20.2	23.5	30.0	31.4	10.8	11.0	20.7	20.2	30.0	29.8
Mono-Aromatics m%	10.9	9.5	17.9	2.02	25.2	27.4	9.6	7.8	16.0	16.8	22.1	25.1
Di-Aromatics m%	1.5	2.9	2.2	2.7	4.3	3.6	1.1	2.9	4.3	3.2	7.1	4.4
Tri+-Aromatics m%	0.0	0.5	0.1	0.5	0.6	0.3	0.1	0.3	0.3	0.3	0.8	0.3
HPLC												
Total Aromatics, %m	11.7	12.0	20.0	22.8	32.1	31.3	10.4	10.2	20.0	19.8	29.6	30.2
Mono-Aromatics m%	11.2	10.0	19.0	20.9	29.6	28.8	9.7	8.2	16.8	17.4	24.0	26.9
Di-Aromatics m%	0.5	1.5	1.0	1.3	1.9	2.2	0.7	1.7	2.8	2.2	5.0	3.0
Tri+-Aromatics m%	<0.1	0.5	<0.1	0.6	0.6	0.3	<0.1	0.3	0.4	0.2	0.6	0.3
Hot FIA												
Aromatics, %v.	10.3	10.6	17.3	20.8	27.8	27.6	8.7	9.2	17.4	17.7	25.0	25.4
Olefins, %v.	2.0	2.0	1.9	2.3	2.9	2.3	1.9	2.4	1.8	2.4	1.6	2.7
Saturates, % v.	87.7	87.4	80.8	76.9	69.3	70.1	89.4	88.4	80.8	79.9	73.4	71.9
GC/MS												
Total Aromatics m%	11.1	12.3	19.7	22.3	30.5	30.2	10.2	10.2	19.9	19.4	28.8	28.8
Mono-Aromatics m%	9.8	9.3	17.6	19.2	26.4	26.2	9.1	7.3	15.5	15.7	21.6	24.5
Di-Aromatics m%	1.2	2.7	2.0	2.8	3.8	3.9	1.1	2.8	4.3	3.6	6.9	4.2
Tri+-Aromatics m%	0.0	0.2	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.3	0.1
Aromatic Sulphur m%	0.1	0.1	0.1	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Paraffins m%	20.0	21.3	19.0	20.6	22.2	22.7	48.9	44.4	42.7	35.5	37.4	33.4
Mono-Cycloparaffins m%	33.3	32.0	28.2	25.8	19.9	21.0	21.3	23.1	18.9	17.8	16.6	18.7
Di-Cycloparaffins m%	24.1	21.0	22.4	18.7	16.1	16.0	13.1	15.4	9.9	17.3	9.7	13.1
Poly-Cycloparaffins m%	11.5	13.3	10.7	12.5	11.2	10.1	6.5	6.9	8.6	10.0	7.5	6.0

Properties of Other Test Fuels

FUEL ID	**Ref1**	**Ref2**	**Ref3**	**A**	**C**	**E**	**F**
Source	Conventional	Conventional	Conventional	Both	Both	Both	Both
Density, kg/m^3 @15°C	836.2	835.0	842.0	829.7	841.0	836.8	857.3
Viscosity @40°C , cSt	2.135	2.207	4.03	1.752	1.723	1.439	2.464
Cloud Point, °C	-22	-19	-6				
Distillation, D86, IBP,	178.5	172.9	175.5	166	170	170	170
T10, °C	205.6	198.9	244.8	183	185	183	189
T50, °C	245.5	255.9	297.8	220	224	209	245
T90, °C	306.1	311.4	333.8	284	284	251	344
EP, °C	343.3	336.7	352.6	317	313	282	378
Cetane In., D976-80	46.6	49.7	55.5	40.7	38.0	34.2	39.5
Cetane No. D613	43.9	46.2	55.4	45.8	43.5	40.3	43.1
Sulphur, ppm (mass)	287.0	351.0	9.2	466	460	374	299
Hydrogen Content m%	13.38	13.37	13.95	13.78	13.28	13.29	13.19
Nitrogen, ppm (mass)	54.1	42.9	2.5				
SFC							
Total Aromatics, %m	27.3	27.5	4.8	10.8	24.5	25.2	23.5
Mono-Aromatics m%	21.8	19.9	4.0	6.5	17.8	20.4	11.4
Di-Aromatics m%	4.9	6.7	0.7	3.6	6.2	4.7	8.6
Tri+-Aromatics m%	0.5	1.0	0.1	0.7	0.5	0.1	3.6
HPLC							
Total Aromatics, %m	25.9	26.6	4.2				
Mono-Aromatics m%	22.3	20.8	4.2				
Di-Aromatics m%	3.2	5.0	<0.2				
Tri+-Aromatics m%	0.4	0.8	<0.1				
Hot FIA							
Aromatics, %v.	24.2	23.4	4.7				
Olefins, %v.	1.6	1.9	1.4				
Saturates, %v.	74.2	74.7	93.9				
GC/MS							
Total Aromatics m%	25.4	22.9	4.4				
Mono-Aromatics m%	20.5	16.6	3.6				
Di-Aromatics m%	4.7	5.9	0.5				
Tri+-Aromatics m%	0.2	0.4	0.0				
Aromatic Sulphur m%	0.0	0.0	0.3				
Paraffins m%	29.2	35.0	24.9				
Mono-Cycloparaffins m%	20.8	20.2	23.4				
Di-Cycloparaffins m%	15.8	13.7	22.7				
Poly-Cycloparaffins m%	8.8	8.2	24.6				