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COMPARISON OF OIL-SANDS-DERIVED AND CONVENTIONAL-CRUDE-OIL-DERIVED DIESEL FUELS AT DIFFERENT ENGINE OPERATING CONDITIONS

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INTRODUCTION

In Canada, 21% of annual petroleum crude processed is oil-sands-derived crude oil. 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 fuels is not well documented.

The general approach in fuel property studies is to blend fuels such that a single fuel property can be varied in a large range while maintaining the other fuel properties within a narrow span. This task is always challenging and sometimes impossible. Consequently, most of the studies to investigate the influence of fuel properties on diesel emissions are biased by the specific fuel matrix design and by the inter-correlation between the fuel properties. One way of alleviating this problem is a careful fuel matrix design consisting of a large number of fuels.

One of the disadvantages of running the U.S. EPA heavy-duty transient emission tests is that it is not possible to differentiate the contributions of different operating conditions to exhaust emissions. Some of the engine operating conditions are more sensitive to fuel properties than some others. In this study, the AVL 8-mode steady state simulation of the EPA transient test procedure was used. The composite emissions obtained from steady-state tests simulate the EPA transient results. The emission test results are therefore comparable to the results obtained with EPA transient test. At the same time, the engine test results from different engine modes offer detailed information so that the influence of each fuel property on oxides of nitrogen (NO_x) and particulate matter (PM) formation at different engine operating conditions can be investigated.

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 effects of total aromatic content and fuel density were also investigated. We used two fuel matrices consisting a total of 19 diesel fuels.

EXPERIMENTAL

The engine used in this study is a single-cylinder research version (Ricardo Proteus) of a Volvo TD123 heavy-duty truck engine. The engine is a direct injection type and has a displacement volume of 2 liters. The research engine incorporates many features of contemporary medium- to heavy-duty diesel engines. It is tuned to meet the U.S. EPA 1994 emission standards. Detailed information on the test engine can be found in [1, 2]. The test procedure used in this study is the AVL eight-mode steady-state simulation of the U.S. EPA transient test procedure [3]. The engine speed and load at each of the eight modes are listed in Table I. To check the repeatability of the emission measurements, a low sulfur fuel obtained locally (Table III, fuel Ref2) was run in the engine periodically. The results showed that the standard deviations of NO_x and PM emission measurements were 0.9% and 4.3% of their means, respectively. No engine performance shift was

observed and the experimental data obtained with all test fuels were not adjusted for engine shift or experimental system error.

Among the 19 test fuels, 12 were blended using refinery streams. Six of these 12 fuels were originated from oil sands and the other six were derived from conventional crudes. A total of 22 components obtained from seven refineries were used in this fuel matrix. The parameters controlled in this fuel matrix were:

♦ total aromatics (10, 20 and 30% by mass)
♦ sulfur content (<500 ppm by weight)
♦ cetane number (42 to 46)
♦ viscosity, cloud point and distillation properties (within the typical range of current commercial diesel fuels in Canada).

The major properties of these test fuels are listed in Table II.

Seven other fuels obtained from various sources were run in the engine so that the regression models generated using the 12 blended fuels can be examined. The major properties of these fuels are listed in Table III.

RESULTS AND DISCUSSION

Composite Emissions

Using correction factors generated in the earlier stages of this research program[5], the composite NO_x and PM emission results were corrected to 150 ppm sulfur content and 44 cetane number. The effect of a small change in injection timing caused by the differences in fuel properties was also corrected. The NO_x and PM emission results are shown in Figure 1 and Figure 2 versus total aromatic content and fuel density.

The oil-sands-derived fuels yield NO_x emissions similar to the conventional-crude-oil-derived fuel blends. A good correlation between the composite NO_x emissions and fuel aromatic content and density was observed. The higher the total aromatic content and the density, the higher the composite NO_x emissions. NO_x emissions do not correlate with T90 or viscosity.

Comparing the two fuel groups, oil-sands-derived fuels generated higher composite 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. A modest correlation between composite PM emissions and fuel density was observed. A higher density leads 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.

Regression analyses were performed to examine the correlation between the engine exhaust emissions and various fuel properties. The fuel properties considered in the regression analyses are: density, viscosity, T90, T50, T10, total aromatic content, and poly-aromatic content (di+-aromatics). The regression analysis results are shown in Table IV. Fuel density and total aromatic content were found to be the significant variables for NO_x emissions. These two properties account for 92.8% of the total changes in NO_x emissions ($R^2 = 0.928$). Both factors are highly significant, although total aromatic content is more so.

Density is the sole significant variable for PM emissions, accounting for 53.2% of the changes. The total aromatic content was not a significant variable. Considering the low R^2 value, the model can not be viewed as conclusive.

The proposed models were used to predict the NO_x and PM emissions of the 7 test fuels that had not been included in generating the correlations. The NO_x emission model was able to predict the NO_x emission results of six test fuels. The only exception was fuel Ref3 that has properties far away from those represented by the 12 test fuels. This indicates that total aromatic content and density are likely to be two important factors

affecting NO_x emissions. The PM model predictions for 6 of the 7 fuels 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 influencing PM emissions.

Exhaust Emissions at Different Engine Operating Conditions

The eight-mode steady-state test procedure enables us to examine the impact of fuel properties at different engine operating conditions. The effects of cetane number and cetane improvers were significant at low load conditions such as modes 1, 2 and 5. An increase in cetane number from 44 to 64 reduced NO_x emissions by as much as 25% [2][4]. At the same time, PM emissions at low load conditions tended to increase when cetane number was increased. The effects of cetane number on NO_x and PM emissions were not significant at medium to high load conditions. Therefore, the cetane number corrections were performed on NO_x and PM emissions at modes 1, 2 and 5 only using the individual correction formula obtained from engine tests for each corresponding mode.

The sulfur correction formulas were found to be different for different modes. In general, the effect of sulfur appeared to be the largest at the low idle condition, mode 1. Individual correction formulas were used for corresponding modes.

The effects of injection timing on NO_x emissions could be described using second order polynomials for all the modes [5]. This effect was greater at low speed and low load conditions (such as modes 1 and 2). The effects of injection timing on PM emissions were best described using linear relationships. The engine injection timing affected PM emissions more at high load conditions (such as modes 4 and 8).

The corrected brake specific NO_x and PM emissions at each mode were calculated. The results at low idle and the heavy load conditions are plotted in Figure 1 and Figure 2 in comparison with the composite emissions. For NO_x emissions, the oil-sands-derived fuels behaved the same as the conventional-crude-oil-derived fuels at all eight modes. At medium to high load conditions (modes 3,4,6,7 and 8), the NO_x emissions increased with total aromatic content and fuel density. At light load conditions (modes 1,2 and 5), NO_x emissions were not affected by fuel properties.

The PM emissions at individual modes had relatively larger scattering than the composite PM emissions. Consequently, the oil-sands-derived fuels did not show clear difference from conventional-crude-oil-derived fuels in terms of PM emissions at individual modes. The total aromatic content and fuel density impacted on PM emissions differently at different modes. The effects of fuel properties on PM emissions appeared greater at low load conditions (modes 1 and 5); an increase in PM emissions was observed when total aromatic content and fuel density were increased. However, at heavy load conditions (such as modes 4 and 8), the effects of fuel properties on PM emissions were not significant.

The fuel density generally affects the fuelling rate when conducting transient tests. If all the test fuels are run using the same power curve that is generated from a reference fuel, the fuel with a higher density will run at a higher fuelling rate on mass basis. This fuelling discrepancy can bias emission comparison between fuels. In this study, steady-state tests were conducted, and the power outputs of all the fuels were kept the same. This minimized the fuelling discrepancy between the test fuels. The specific fuel consumption changed less than 1% and was not a function of density.

The effect of fuel density on NO_x emissions is likely to be a physical one. A higher fuel density leads to a higher injection rate on a mass basis and therefore shorter injection duration. This effect becomes more significant at heavy load condition due to longer injection duration. Between the heaviest and the lightest fuels, a 4% difference was observed in the mean cylinder pressure that was averaged from the start of mixing controlled burning to the end of fuel injection. This indicates that a higher injection rate

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caused more fuel to be injected into the high temperature region, leading to higher NO_x emissions.

The effect of total aromatic content on NO_x emissions could be a chemical one. At high load conditions, major portion of the fuel was burned at fuel-rich locations where the chemical composition of the fuel is likely to have an impact on the local gas temperature. The fuel with a higher total aromatic content can be expected to generate a higher temperature in these fuel-rich regions because the adiabatic temperatures of the hydrocarbons with ring structures tend to be higher.

CONCLUSIONS

In this work, we compared the emission behaviors of fuels derived from oil sands and from conventional crude oil at different engine operating conditions. We also investigated the effects of total aromatic content and density of diesel fuels on NO_x and PM emissions. Our results lead to the following conclusions:

- Oil-sands-derived diesel fuels behave similarly as conventional-crude-oil derived diesel fuels in terms of NO_x emissions at all engine operating conditions.
- Oil-sands-derived diesel fuels exhibit higher composite PM emissions than their conventional-crude-oil-derived counterparts at the same total aromatic content. This can be attributed to the higher densities of the oil-sands-derived fuels. However, this trend was not clear at each individual engine operating mode.
- Different fuel properties influence NO_x and PM emissions at different engine operating conditions. Fuel density and total aromatic content influence NO_x emissions at medium to heavy load conditions, whereas the effects of fuel density and total aromatic content on PM emissions appear to be greater at low load conditions. It is therefore important to investigate the interaction between fuel properties and engine operating conditions.

ACKNOWLEDGEMENTS

REFERENCES

[1] Li, X., Chippior, W. L. and Gülder, Ö. L., "Effects of Fuel Properties on Exhaust Emissions of a Single Cylinder DI Diesel Engine", 1996 SAE Transactions, Paper No. 962116, 1996.

[2] Li, X., Chippior, W. L. and Gülder, Ö. L., "Effects of Cetane Enhancing Additives and Ignition Quality on Diesel Engine Emissions", 1997 SAE Transactions, Paper No. 972968, 1997.

[3] Cartellieri, W. P. and Herzog, P. L., "Swirl Supported or Quiescent Combustion for 1990's Heavy-Duty DI Diesel Engines - An Analysis", SAE Paper No. 880342, 1988.

[4] Li, X. and Gülder, Ö. L., "Effects of Fuel Cetane Number, Density and Aromatic Content on Diesel Engine NO_x Emissions at Different Operating Conditions", Fourth International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines, July 20-23, Kyoto, Japan, 1998.

[5] Li, X., Chippior, W. L. and Gülder, Ö. L., "Canadian Diesel Fuel Composition and Emissions – I", NRC Report No. 37645, 1997.

TABl

FUEL II
Density
Viscosit
Cloud P
IBP, C
T10, C
T50, C
T90, C
EP, C
Cetane I
Cetane :
Sulphur.
Hy. Con
Nitroger
Total ar
1-Ring
2-Ring
3+-Rine

FUEL I
Source
Density
Viscosi
Cloud I
IBP, C
T10, C
T50, C
T90, C
EP, C
Cetane
Cetane
Sulphu
Hy. Co
Nitroge
Total ar
1-Ring
2-Ring
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NO_x

PM

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TABLE I 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

TABLE II PROPERTIES OF BLENDED TEST FUELS

FUEL ID	Oil-sands-derived						Conventional-crude-oil-derived					
	S10A	S10B	S20A	S20B	S30A	S30B	C10A	C10B	C20A	C20B	C30A	C30B
Density	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	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
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 Index	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.	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	13.2	2.4	28.8	31.1	84.7	3.0	8.1	131	31.4	134.0	270.0	202.0
Hy. Cont. 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	27.9	0.3	56.4	1.5	24.8	2.5	1.0	17.5	4.7	19.7	41.2	21.8
Total arom. %	12.4	12.9	20.2	23.5	30.0	31.4	10.8	11.0	20.7	20.2	30.0	29.8
1-Ring	10.9	9.5	17.9	2.02	25.2	27.4	9.6	7.8	16.0	16.8	22.1	25.1
2-Ring	1.5	2.9	2.2	2.7	4.3	3.6	1.1	2.9	4.3	3.2	7.1	4.4
3+-Ring	0.0	0.5	0.1	0.5	0.6	0.3	0.1	0.3	0.3	0.3	0.8	0.3

TABLE III PROPERTIES OF OTHER FUELS

FUEL ID	Ref1	Ref2	Ref3	A	C	E	F
Source	Conven.	Conven.	Conven.	Both	Both	Both	Both
Density	836.2	835.0	842.0	829.7	841.0	836.8	857.3
Viscosity	2.135	2.207	4.03	1.752	1.723	1.439	2.464
Cloud Point C	-22	-19	-6				
IBP, C	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 Index	46.6	49.7	55.5	40.7	38.0	34.2	39.5
Cetane No.	43.9	46.2	55.4	45.8	43.5	40.3	43.1
Sulphur, ppm	287.0	351.0	9.2	466	460	374	299
Hy. Cont. m%	13.38	13.37	13.95	13.78	13.28	13.29	13.19
Nitrogen, ppm	54.1	42.9	2.5				
Total arom. %	27.3	27.5	4.8	10.8	24.5	25.2	23.5
1-Ring	21.8	19.9	4.0	6.5	17.8	20.4	11.4
2-Ring	4.9	6.7	0.7	3.6	6.2	4.7	8.6
3+-Ring	0.5	1.0	0.1	0.7	0.5	0.1	3.6

TABLE IV REGRESSION ANALYSIS OF CORRECTED COMPOSITE EMISSIONS

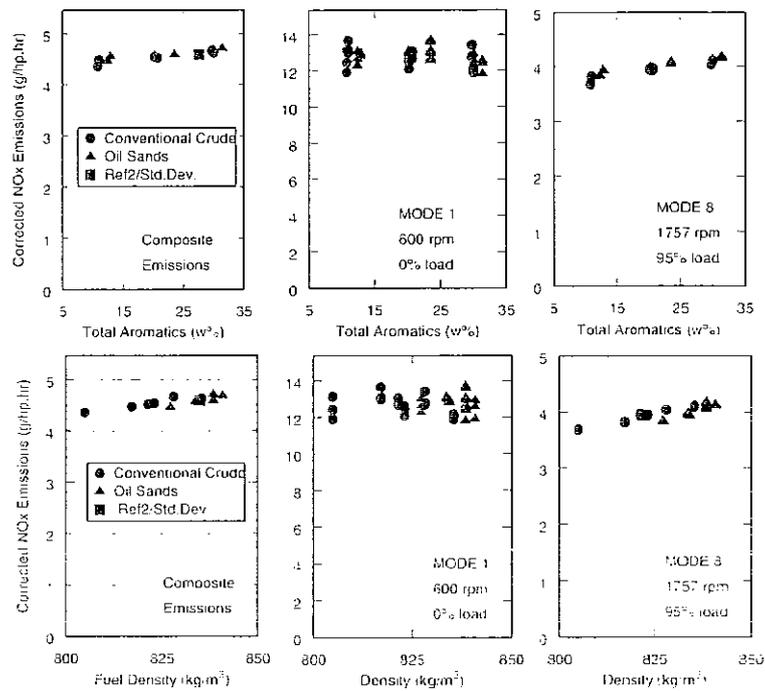| Emission	Variables	Std. Error	Std. Coefficient	F-Value	Probability	R^2
NO$_x$	Density	0.0012	0.4559	14.31	0.0043	
	Total Arom.	0.0016	0.5964	24.48	0.0008	0.928
PM	Density	0.0004	0.7293	11.36	0.0071	0.532

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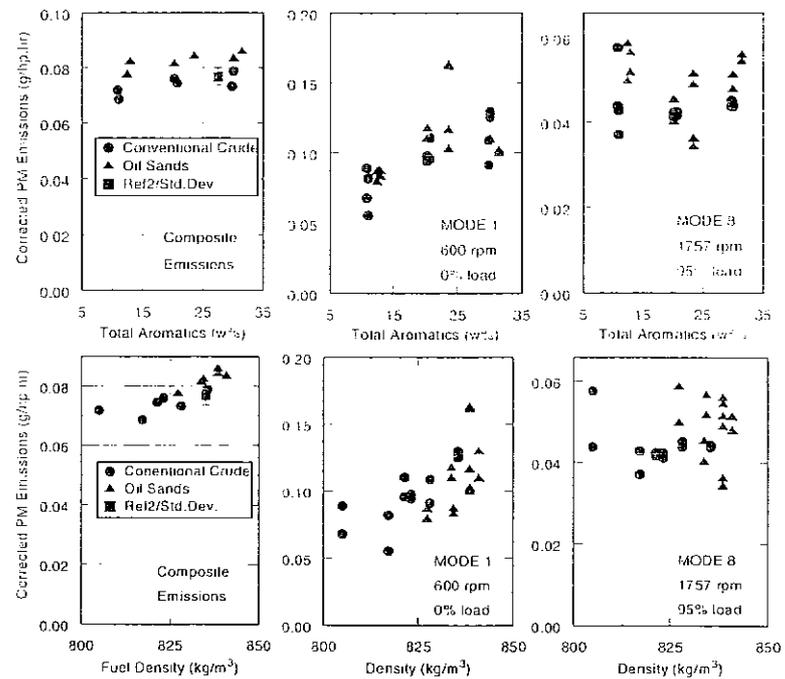Figure 1 Corrected NO$_x$ Emissions versus Total Aromatic Content and Fuel Density

Figure 2 Corrected PM Emissions versus Total Aromatic Content and Fuel Density

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