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Neill, W. Stuart; Chippior, Wallace L.; Mitchell, Ken; Fairbridge, Craig;
Pigeon, René; McCormick, Robert L.; Van Heyst, John

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THE INFLUENCE OF HIGH CETANE BLENDING COMPONENTS ON EMISSIONS FROM A HEAVY-DUTY DIESEL ENGINE WITH EGR

W. Stuart Neill and Wallace L. Chippior
National Research Council Canada

Craig Fairbridge
National Centre for Upgrading Technology

Robert L. McCormick
National Renewable Energy Laboratory

Ken Mitchell
Shell Canada Products

René Pigeon
Natural Resources Canada

John Van Heyst
Suncor Energy Inc.

ABSTRACT

The exhaust emissions from a single-cylinder version of a heavy-duty diesel engine with exhaust gas recirculation (EGR) were measured with eight high-cetane components blended into an ultra-low sulphur diesel base fuel. The blending components evaluated were conventional nitrate and peroxide cetane improver additives, paraffins from two sources, three ethers, and soy methyl ester. The blending components were used to increase the cetane number of a base fuel by ten numbers, from 44 to 54. Exhaust emissions were measured using the AVL eight-mode steady-state test procedure. PM and NO_x emissions from the engine were fairly insensitive to ignition quality improvement by nitrate and peroxide cetane improvers. Soy methyl ester and two of the ethers, 1,4 diethoxybutane and 2-ethoxyethyl ether, significantly reduced PM emissions, but increased NO_x emissions. The two paraffinic blending components reduced both PM and NO_x emissions.

INTRODUCTION

Since 1990, increasingly stringent government regulations have been adopted to reduce pollutant emissions from mobile diesel engines. These regulations are forcing major changes in engine design. More recently, energy security and greenhouse gas emissions have become important issues in North America. Although mobile source emissions are determined primarily by engine design, fuel properties do play a role. For example, new diesel fuel sulphur content regulations in North America will enable advanced emission control technologies to be introduced in the 2007 to 2010 timeframe. The reduction in fuel sulphur content will also lower sulphate emissions. It is expected that

further emission reductions may be possible by burning "cleaner" fuels.

Cetane number is an important property that relates to fuel quality. The fuel specifications for cetane number are established to meet the requirements for satisfactory engine performance and reliable operation. In Europe, the Comité Européen de Normalisation (CEN) establishes the diesel fuel standard for members of the European Union. Currently, the specifications call for a minimum cetane number of 51. In North America, the minimum cetane number is 40, although California regulations have tended to produce diesel fuels with much higher cetane numbers. The current exploratory investigation was performed to compare several options for improving the ignition quality of an ultra-low sulphur diesel fuel in a modern, heavy-duty diesel engine with EGR.

Cetane improver additives are one of the options employed by fuel refiners to improve the ignition quality of diesel fuels. McCarthy et al. [1] studied the effects of cetane number changes on emissions from a prototype 1994 Navistar heavy-duty diesel engine. Raising the cetane number was found to reduce all regulated emissions, but the particulate response to cetane number change was found to be small. Ullman et al. [2] investigated cetane number effects on transient emissions from a prototype 1998 Detroit Diesel Corporation (DDC) Series 60 engine using conventional nitrate and peroxide cetane improvers. The effect of increasing cetane number from 45 to 55 using cetane improver was a decrease in all four regulated composite transient emissions: NO_x by 4%, PM by 6%, CO by 15%, and HC by 40%. Li et al. [3] found that nitrate and peroxide cetane improvers produced similar reductions in NO_x emissions from a Ricardo Proteus engine, tuned to meet 1994

U.S. EPA emission standards, for a given cetane number change. PM emissions were found to increase as cetane number increased. Schwab et al. [4] also concluded that nitrate and peroxide cetane improvers produced similar NO_x emission reductions from a 1993 DDC Series 60 engine.

In 2000, the U.S. EPA Heavy-Duty Engine Working Group produced a series of SAE papers [5-7] describing an investigation of fuel property effects on emissions from a prototype 2004 Caterpillar 3176 engine equipped with exhaust gas recirculation (EGR). Mason et al. [7] concluded that NO_x emissions had statistically significant positive correlations with fuel density, cetane number, mono-aromatics, and poly-aromatics. The engine had a very low NO_x emission sensitivity to cetane number, which differs from the results of similar experiments with engines not equipped with EGR.

Blending normal paraffins into diesel fuel is another option to improve fuel ignition quality and reduce exhaust emissions from diesel engines. Schaberg et al. [8] performed emissions tests with a Sasol Fischer-Tropsch (F-T) diesel fuel in a DDC Series 60 diesel engine that met the 1991 emission standards. It was found that Sasol F-T diesel fuel reduced PM and NO_x emissions by 21% and 27%, respectively, compared to a U.S. No. 2-D diesel fuel. Further studies [9] performed using a 1999 DDC Series 60 engine produced a slightly higher PM emission reduction (47%), but a somewhat lower NO_x emission reduction (11%). In 1999, Atkinson et al. [10] reported 31% and 20% reductions in PM and NO_x emissions, respectively, from a 1994 Navistar T444E engine using F-T diesel fuel with a 74 cetane number. Blends of F-T diesel fuel with No. 2-D diesel fuel produced emissions reductions that were generally in proportion to the amount of F-T components in the blend [8].

The use of oxygenates to produce cleaner burning diesel fuels has been widely studied. Liotta and Montalvo [11] investigated the emissions effects of several oxygen-containing fuels in a 1991 DDC Series 60 diesel engine. Particulate matter reductions were found to be directly related to the oxygen content of the fuel. The type of oxygenate appeared to have a role in its effectiveness at reducing PM emissions. The PM reduction was accompanied by a small increase in NO_x emissions at higher blending levels. Ullman et al. [12] investigated monoglyme and diglyme blending components at 2% and 4% oxygen levels in a DDC Series 60 engine calibrated to meet 1994 and 1998 emission standards. Statistical models of the emissions dependency on fuel composition were developed. Variations in PM emissions were primarily explained by oxygen content. Increasing fuel oxygen content by 1% was predicted to reduce transient PM emissions by 7% and 6% for 1994 and 1998 emission calibrations, respectively. Oxygen content was found to increase NO_x emissions for the engine calibrated to meet the 1998 NO_x emission standard. Akasaka and Sakurai [13] also concluded that oxygenates reduce PM emissions in proportion to the fuel oxygen content, as well as reducing HC and CO emissions.

McCormick et al. [14] blended several oxygenates with No. 2-D diesel fuel at the 1% and 2% oxygen levels. Emissions

were measured in both two- and four-stroke heavy-duty diesel engines. It was found that PM emission reductions of 10-15% were obtained, regardless of oxygenate chemical structure. The oxygenated fuels affected NO_x emissions differently. Methyl esters of soybean oil increased NO_x emissions by 2-3%, decanoic acid had no effect, and octanol may have slightly decreased NO_x emissions. More recently, Yeh et al. [15] investigated the effect of fourteen oxygenates on emissions from a Caterpillar, single-cylinder diesel engine with advanced fuel injection timing. Oxygenates were chosen to span a range of functional groups, volatility, and oxygen content. Large differences in PM emissions were observed for different oxygenates despite keeping the oxygen content the same.

The objective of this study was to quantify the relative emissions benefits of several high-cetane blending components. The blending components include four oxygenates (three ethers, one soy methyl ester) and two paraffins (F-T diesel fuel, SuperCetane). The high-cetane blending components are compared to conventional nitrate and peroxide cetane improver additives. The emission reductions obtained from the fuel additives/blending components in this study will be compared to the emission reductions from potential changes to the refining processes in future studies.

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.

A cooled EGR system was implemented 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 difference 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. The EGR settings and fuel injection timings were selected to produce 2.5 g/hp-hr NO_x emissions, while minimizing PM emissions. Further details of the experimental conditions are provided in [16].

Table 1 – 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
Max. Power Output	74.6 kW (2100 rpm)

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).

Engine exhaust 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 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 [17].

Test fuel design

The base fuel was a 50/50 blend of distillates derived from oil sands sources of commercial quality. The fuel has a density of 837.7 kg/m^3 , 44.2 cetane number, 9.6 ppm sulphur content by mass, and 15.1% total aromatics. Additional fuel properties are provided in Table A-1.

A total of nine high-cetane components were blended with the base fuel. The blending components covered a range of

options including conventional cetane improvers, paraffins, ethers, and soy methyl ester. The components were blended to increase the cetane number of the base fuel by ten numbers. Other fuel properties will be affected by the addition of blending components in percent quantities. A summary of the additive/blending components is provided in Table 2.

The conventional cetane improvers were 2-ethylhexyl nitrate (EHN) and di-tert butyl peroxide (DTBP). These additives are commercially used to increase the cetane number of diesel fuels.

Two paraffinic blending components were selected. The first component was a Fischer-Tropsch diesel fuel with a 75 cetane number. This fuel consists of normal- and iso-paraffins in the diesel boiling range. The production process for this component is described in [18]. The second component, called SuperCetane, was a middle distillate produced by hydroprocessing renewable feedstocks [19] to form normal-paraffins. SuperCetane has a cetane number of 100.

The ether blending components were dipentyl ether, 1,4-diethoxybutane, and 2-ethoxyethyl ether, containing one, two and three oxygen atoms, respectively. These components were selected to investigate the role of increasing oxygen in the blending component. The tri-ether was blended at 15.0% mass to increase the cetane number by 10 and at 11.1% mass to have similar oxygen content to the di-ether, 1,4-diethoxybutane. In the latter case, EHN was added to achieve the desired 10 cetane number boost.

The final oxygenated fuel was a B20 biodiesel produced by blending 20% soy methyl ester by volume into the base fuel. Since the B20 biodiesel had a 46 cetane number, 2000 ppm EHN was added to increase its cetane number to 54.

Test procedure

The AVL eight-mode steady-state simulation [20] of the U.S. EPA Transient Test Procedure was used. The emissions were measured at eight speed/load conditions, multiplied by the modal weights and summed to produce composite 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 [21].

Table 2 – Fuel Additives and Blending Components

Test Fuels	Type	Chemical Formula	Blend	Cetane Number
Base fuel + 2-ethylhexyl nitrate (EHN)	Cetane improver	$\text{C}_8\text{H}_{17}\text{NO}_3$	0.2 %v	53
Base fuel + di-tert butyl peroxide (DTBP)	Cetane improver	$\text{C}_8\text{H}_{18}\text{O}_2$	0.5 %v	55
Base fuel + Fischer-Tropsch (F-T) diesel fuel	Paraffin	n- + iso- C_{10-22}	20.0 %m	55
Base fuel + SuperCetane	Paraffin	n- C_{14-18}	14.0 %m	55
Base fuel + dipentyl ether	Oxygenate (mono-ether)	$\text{C}_{10}\text{H}_{22}\text{O}$	8.0 %m	55
Base fuel + 1,4-diethoxybutane	Oxygenate (di-ether)	$\text{C}_8\text{H}_{18}\text{O}_2$	15.4 %m	55
Base fuel + 2-ethoxyethyl ether	Oxygenate (tri-ether)	$\text{C}_8\text{H}_{18}\text{O}_3$	15.0 %m	55
Base fuel + 2-ethoxyethyl ether + 0.05%v EHN	Oxygenate (tri-ether)	$\text{C}_8\text{H}_{18}\text{O}_3$	11.1 %m	54
Base fuel + Soy methyl ester + 0.2%v EHN	Oxygenate (biodiesel)	n- C_{16-18} esters	20.0 %v	54

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-1. The reference fuel was tested a total of 15 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 emission measurements. Statistical analyses were performed using Systat® (Systat Software Inc.).

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 3.6% for PM, 1.0% for NO_x, 6.6% for HC, and 2.6% for CO. There were no systematic trends in the emissions data.

Table 3 – Emissions Repeatability with 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	0.072	2.40	0.062	0.65	170.8
s.d.	0.003	0.02	0.004	0.02	0.7
c.v. (%)	3.6	1.0	6.6	2.6	0.4

Composite emissions of test fuels

The composite PM, NO_x, HC, and CO emissions, as well as brake specific fuel consumption (BSFC) data, are provided for the base fuel and nine test fuels in Table 4. The BSFC of the engine is higher for the oxygenated fuels. However, only the PM and NO_x emissions results will be discussed in this paper.

Conventional cetane improvers

Cetane improver additives are one option available to refiners to improve the ignition quality of diesel fuels. They are often a more cost-effective way to increase the cetane number than by making changes to the refining process. The effect of conventional nitrate and peroxide cetane improvers on PM and NO_x emissions from the research engine are shown in Figures 1 and 2, respectively. The mean and standard deviation of the emissions obtained with the reference fuel is also plotted in the two figures for comparison purposes.

Figure 1 shows that there was a slight trend toward higher PM emissions as the cetane number increases for both nitrate and peroxide additized fuels. The reference fuel had higher PM emissions than the base fuel because of its higher total aromatic and sulphur contents.

Based on previous results with a heavy-duty engine tuned to U.S. EPA 1994 emission standards, the two types of cetane improvers were expected to produce similar PM emissions at a given cetane number [3]. Accordingly, a single regression model was fit to the PM emissions data to determine if the

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)
Base Fuel	0.067	2.33	0.052	0.64	168.8
EHN	0.071	2.38	0.051	0.62	168.5
DTBP	0.069	2.37	0.062	0.62	168.9
F-T diesel	0.063	2.29	0.053	0.60	168.0
SuperCetane	0.064	2.32	0.052	0.61	169.5
Mono-ether	0.067	2.36	0.057	0.61	170.2
Di-ether	0.056	2.44	0.056	0.63	175.8
Tri-ether + EHN	0.050	2.50	0.063	0.55	173.5
Tri-ether	0.045	2.56	0.062	0.56	177.2
Soy methyl ester + EHN	0.053	2.55	0.057	0.56	174.2

linear relationship between fuel cetane number and PM emissions shown in the figure is statistically significant. The results are shown in Table 5. The coefficients and levels of significance (p-values) associated with the fuel effects are provided in the table. The adequacy of the regression fit is measured by the adjusted square correlation coefficient (adj. R²) and the square root of the estimated mean square error (Root MSE). Table 5 shows that there is a 6.6% probability of observing a 5.15×10^{-4} regression line slope if the population slope is zero. Thus, the data does not support the hypothesis that engine PM emissions are significantly affected by the addition of conventional cetane improvers to the base fuel.

Figure 2 indicates that there was a slight trend toward higher NO_x emissions as the cetane number increases for both nitrate and peroxide additized fuels. Again, a single regression model was fit to all the experimental data. The results, provided in Table 5, show that there is a 4.9% probability of observing a 7.41×10^{-3} regression line slope if the population slope is zero. Thus, the data provides some support for the hypothesis that conventional cetane improvers added to the base fuel increase NO_x emissions from the research engine.

Figure 1 – Effect of nitrate and peroxide CI on PM emissions

Figure 2 – Effect of nitrate and peroxide CI on NO_x emissions

In summary, the experimental data provides fairly strong evidence that conventional cetane improvers do not reduce PM or NO_x emissions from 2004 model year, heavy-duty diesel engines with EGR.

Paraffinic blending components

Blending high-cetane paraffinic components into diesel fuels is another way to increase cetane number. Two paraffinic blending components were investigated: SuperCetane and Fischer-Tropsch diesel fuel. Since SuperCetane has a higher cetane number than the Fischer-Tropsch components, only 14% by mass of SuperCetane was blended with the base fuel to achieve a 10 cetane number boost in ignition quality, compared to 20% by mass of Fischer-Tropsch components.

Figure 3 shows the effect of blending SuperCetane and Fischer-Tropsch components into the base fuel. The experimental data has been plotted as a function of the molar hydrogen/carbon (H/C) ratio because the cetane numbers of the three test fuels are similar. The PM emissions reduce linearly as the fuel H/C ratio increases for the three test fuels. The Fischer-Tropsch blending component achieved a larger reduction in PM emissions because more of this component was blended into the base fuel to achieve a 10 cetane number increase in ignition quality, resulting in a larger reduction in aromatic content and a correspondingly larger increase in fuel H/C ratio.

Figure 4 shows that NO_x emissions are also reduced as the fuel H/C ratio increases. The NO_x emission reduction is

Figure 3 – Effect of paraffinic blending components on PM emissions

proportional to the increase in the hydrogen/carbon ratio for the two cases investigated.

Comparison with fuel hydroprocessing option

An alternative to blending high-cetane paraffins into diesel fuels is additional refinery hydroprocessing. Hydroprocessing is used to remove heteroatoms such as sulphur and nitrogen as well as to saturate aromatics. Although the effect of hydroprocessing severity was not directly evaluated in this study, the emission reductions obtained from blending high-cetane paraffins can be compared to the emissions data for a number of diesel fuels blended from refinery streams with different H/C ratios.

Figure 5 shows the relationship between sulphate-corrected PM emissions and fuel hydrogen/carbon ratio for 12 Canadian diesel fuels tested recently in the same engine using the same eight-mode test procedure. The diesel fuels were produced by blending refinery streams obtained from conventional and oil sands sources in Canada. The fuels had a target cetane number of 43 and total aromatics ranging from 10 to 30% by mass. Further details about the 12 test fuels and the procedure used to remove the effect of fuel sulphur content may be found in [22].

The results of the regression analyses for the 12 diesel fuels are provided in Table 6. The experimental data supports the hypothesis that sulphate-corrected PM emissions decrease as fuel H/C ratio increases. The experimental data for the paraffinic blending components is also plotted for comparison

Table 5 - Regression equations showing effect of fuel cetane number on PM and NO_x Emissions

Emission	Fuel Effect	Coefficient	p-value	Adj. R ²	Root MSE
PM	Constant	4.48E-2	1.2E-2	0.52	1.9E-3
	Cetane Number	5.15E-4	6.6E-2		
NO _x	Constant	1.95	1.2E-4	0.58	2.4E-2
	Cetane Number	7.41E-3	4.9E-2

Figure 4 - Effect of paraffinic blending components on NO_x emissions

Figure 5 – Effect of fuel H/C ratio on PM emissions

Figure 6 – Effect of fuel H/C ratio on NO_x emissions

purposes. Additional experimental data is needed to make a more definitive statement regarding PM emission reductions obtained by blending paraffinic components compared to those obtained by additional refinery hydroprocessing.

Figure 6 shows that NO_x emissions decrease as fuel H/C ratio increases. The limited data supports the hypothesis that increasing H/C ratio produces a similar decrease in NO_x emissions regardless of whether the hydrogen addition is done at a refinery or by blending high-cetane blending components. The negative slope of NO_x emissions with increasing fuel H/C ratio was found to be statistically significant for the diesel fuels blended from refinery streams.

Oxygenated blending components

The addition of oxygenated components to diesel fuel is another method that has been proposed to reduce PM emissions. Oxygenated components provide oxygen in the core of the fuel jet and counteract the oxygen-reducing aspects of EGR. In this study, four high-cetane oxygenated components were evaluated. Three of the components were ethers and the final component was soy methyl ester.

Table 6 - Regression equations showing effect of fuel hydrogen/carbon content on PM and NO_x Emissions

Emission	Fuel Effect	Coefficient	p-value	Adj. R ²	Root MSE
PM (Sulphate-corrected)	Constant	1.73E-1	8.2E-4	0.40	3.6E-3
	H/C Ratio	-5.67E-2	1.6E-2		
NO _x	Constant	5.85	0.0	0.92	2.9E-2
	H/C Ratio	-1.83	0.0		

Table 7 - Regression equations showing effect of fuel oxygen content on PM and NO_x emissions

Emission	Fuel Effect	Coefficient	p-value	Adj. R ²	Root MSE
PM	Constant	7.01E-2	1.0E-5	0.88	3.5E-3
	Oxygen Content	-5.61E-3	3.6E-3		
NO _x	Constant	2.37	0.0	0.51	6.0E-2
	Oxygen Content	3.95E-2	6.7E-2

Figure 7 – Effect of oxygenated components on PM emissions

Figure 7 shows that PM emissions reduction is roughly proportional to the fuel oxygen content. Table 7 summarizes the results of a regression line fit to the experimental data. The results show that oxygen content has a statistically significant effect on PM emissions because there is only a 0.4% probability of observing a -5.61×10^{-3} regression line slope if the population slope was zero. The adjusted R^2 of 0.88 indicates that the regression model does a reasonable job of explaining the variations in PM emissions.

The test fuels were designed such that two of the ether blends had oxygen contents of 3.3% by mass. One of the test fuels contained 11.1% mass of a tri-ether (2-ethoxyethyl ether), while the second test fuel contained 15.4% mass of a di-ether (1,4-diethoxybutane). A cetane improver, 2-ethylhexyl nitrate, was added to the first fuel to match cetane numbers. The test fuel containing the tri-ether had 11% lower PM emissions than the test fuel containing the di-ether. This provides evidence that the structure of the oxygen-containing molecules may play a secondary role in determining PM emissions.

Figure 8 - Effect of oxygenated components on NO_x emissions

Figure 8 shows that NO_x emissions increase as fuel oxygen content increases. The results of the regression analyses indicate that there is a 6.7% probability of observing a 3.95×10^{-2} slope if the population slope is zero. Thus, the data does not provide strong support for the hypothesis that NO_x emissions increase as fuel oxygen content increases.

The U.S. EPA's analysis of the impact of biodiesel on pollutant emissions concluded that, on average, B20 caused a 10.1% reduction in PM emissions and a 2.0% increase in NO_x emissions [23]. This analysis included data from 1997 and earlier model year engines. In the present study using a 2004 compliant engine with EGR, we find a significantly larger PM emission reduction of 21% but also a significantly larger NO_x emission increase of 9%. It has also been shown that in a 1991 engine, the addition of EHN to B20 biodiesel led to a significant reduction in NO_x emissions, however, 5000 ppm of the additive were required to make the NO_x emissions of the B20 blend equivalent to that of the base fuel [24]. In the present study, 2000 ppm of EHN was added to produce a 54 cetane number B20 fuel. The present results suggest that the NO_x emission increase may be larger and less responsive to EHN in EGR engines meeting the 2004 standards, but that a greater PM emission benefit may be gained.

CONCLUSIONS

The exhaust emissions from a single-cylinder version of a modern heavy-duty diesel engine equipped with exhaust gas recirculation were measured with high-cetane components blended into an ultra-low sulphur diesel base fuel. The blending components were used to increase the cetane number of a base fuel by 10 numbers, from 44 to 54. The blending components were compared to conventional nitrate and peroxide cetane improvers. 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 research engine throughout the experiment. The coefficients of variation of the emissions measurements for 15 experiments conducted with the reference fuel were 3.6% for PM and 1.0% 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 fuel blends investigated in this study:

1. Conventional nitrate and peroxide type cetane improver additives did not reduce PM or NO_x emissions.
2. The two high-cetane paraffinic components increased the hydrogen/carbon ratio of the base fuel, leading to lower PM and NO_x emissions. In general, the emissions data from this engine indicates that PM and NO_x emissions are reduced as fuel H/C ratio increases.
3. The high-cetane oxygenated blending components produced the largest reduction in PM emissions, but increased NO_x emissions. The PM emissions reduction and increase in NO_x emissions were roughly proportional to the fuel oxygen content.

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APPENDIX

Table A-1 Properties of base and reference fuels¹

Fuel Property	Base Fuel	Reference Fuel
Density, D4052, kg/m ³ @ 15°C	837.7	833.2
Viscosity, D445, cSt @ 40°C	2.320	1.91
Cloud Point, D2500, °C	-28	-29
Pour Point, D97, °C	-41	-45
Distillation, D86		
IBP, °C	173	160
T10, °C	200	189
T50, °C	249	237
T90, °C	309	298
EP, °C	343	327
Cetane In., D976	47.3	45.1
Cetane No., D613	44.2	43.0
Sulphur, D5453, ppm (mass)	9.6	356
Hydrogen, D3701, % m/m	13.6	13.4
Base Nitrogen, D4629, ppm (mass)	1	22
HPLC, IP 391/95, % m/m		
Total Aromatics	15.1	25.5
Mono-Aromatics	14.5	20.9
Di-Aromatics	0.4	4.2
Tri+-Aromatics	0.3	0.4

¹ Analyses performed by NRC, NCUT and Shell Canada Products.

Table A-2 Carbon, hydrogen and oxygen contents of test fuel blends²

	Base Fuel	Base Fuel + F-T Diesel	Base Fuel + SuperCetane	Base Fuel + Mono-ether	Base Fuel + Di-ether	Base Fuel + Tri-ether	Base Fuel + Tri-ether + EHN	Base Fuel + Soy methyl Ester + EHN
Carbon, D5291, % m/m	85.91	-	-	86.02	82.90	82.40	83.43	-
Hydrogen, D5291, % m/m	13.59	-	-	13.76	13.32	13.30	13.41	-
Oxygen, (100-C-H), % m/m	0.50	-	-	0.22	3.78	4.30	3.16	-
Carbon (calculated), % m/m	86.34	86.01	86.09	85.50	83.16	82.27	83.33	-
Hydrogen, D3701, % m/m	13.66	13.99	13.91	13.69	13.47	13.29	13.39	13.28
Oxygen, (100-C-H), % m/m	-	-	-	0.81	3.37	4.44	3.28	-
Oxygen ^{3,4} , %m/m	0.70	-	-	1.19	3.95	4.66	3.44	2.62

² Analyses performed by NRC, NCUT, University of Alberta, and Shell Canada Products.

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