Transient Testing of Soy Methyl Ester Fuels in an Indirect Injection, Compression Ignition Engine[1]

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ABSTRACT: An evaluation of the exhaust emissions from a compression ignition engine for fuels composed of 100 and 30% methyl esters of soy oil (SME) is described. These fuels were compared with a low-sulfur, petroleum #2 diesel fuel in a Caterpillar 3304, prechamber, 75 kW diesel engine, operated over heavy- and light-duty transient test cycles developed by the United States Bureau of Mines. More than 60 h of testing was performed on each fuel. The objective was to determine the influence of the fuels upon diesel particulate matter (DPM) and gaseous emissions. The effect of a modern diesel oxidation catalyst (DOC) also was determined in an effort to minimize emissions. Neat SME produced a higher volatile fraction of the DPM, but much less carbon soot fraction, leading to overall DPM reductions of 23 to 30% for the light- and heavy-duty transients. The DOC further reduced the volatile fraction and the total DPM. The SME fuel reduced gaseous emissions of CO by 23% and hydrocarbons by over 30% without increasing NO_x. The DOC further reduced CO and hydrocarbon levels. Mutagenicity of the SME exhaust was low. Results indicate that SME fuel, used with a proper DOC, may be a feasible emission reduction technology for underground mines.
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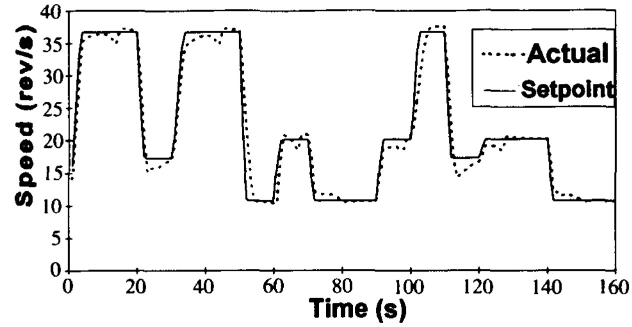
KEY WORDS: Diesel, diesel exhaust, emissions, methyl esters, soy oil, vegetable oil.

Diesel-powered equipment is used in underground mines because it is more powerful and mobile than electric-powered equipment. However, diesel exhaust pollutants in the enclosed environments of underground mines may pose a significant health hazard to mine workers. The National Institute for Occupational Safety and Health (1) and the International Agency for Research on Cancer (2) have declared whole-diesel exhaust to be "potentially" or "probably" a human carcinogen.

The Mine Safety and Health Administration (MSHA), the regulatory agency overseeing air quality and safety concerns in United States mines, has set permissible exposure limits for some of the primary diesel exhaust pollutants. Currently, MSHA is proposing to lower these limits and to establish a new limit for diesel particulate matter (DPM) (3,4). Compliance with a low permissible exposure limit for DPM will pose a significant challenge for diesel-equipped mines. In an attempt to improve air-quality levels in underground mines, the United States Bureau of Mines (USBM) (Minneapolis, MN) develops and evaluates emission control technologies and conducts technology transfer to the mining industry. This paper describes the results from a laboratory evaluation of soy methyl ester fuels that have the potential to reduce exhaust emissions in underground mines.

Methyl ester diesel fuels. The primary benefit from using ester fuels instead of petroleum diesel fuels is DPM emission reduction. Previous investigations have shown that oxygenated fuels may reduce DPM emissions (5–7). Neat vegetable oils, however, have a significant glycerol component and have much higher viscosities than #2 diesel fuel (8,9), causing combustion problems (8,10) or requiring engine modifications.

Methyl and ethyl esters of various vegetable oils and animal tallow have been proposed as possible alternatives to diesel fuels or as fuel extenders. These are produced by transesterification, a chemical process in which one alcohol component of an ester is chemically replaced by another. For vegetable oils, the glycerol components of the triglyceride molecules are exchanged for lighter alcohols such as methanol or ethanol (Scheme 1). For methyl esters of soy oil (SME), this can be accomplished (11) by heating the oil to 80°C and adding 1.6 molar excess of methanol and methanolic solution of 0.5% KOH. A molar ratio in excess of 3:1 (methanol/veg-



SCHEME 1

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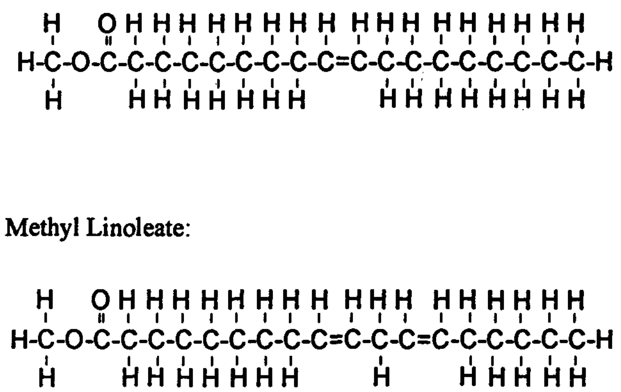
[1] References to specific products do not imply endorsement by the U.S. Bureau of Mines, a now defunct agency.

[2] Present address: Calgene Chemical, Skokie, IL 60076.

Methyl Oleate:

Methyl Linoleate:



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SCHEME 2

etable oil) could also be used in some situations. The mixture is agitated for 30 min and allowed to settle. After about 4 h, the glycerine layer is separated, and the ester layer is acidified with 0.1% phosphoric acid. The ester is washed with water until the wash water is neutral. In this operation, the ester layer is heated to about 85°C with nitrogen bubbling through the oil and then washed with hot water (90°C). This operation is repeated a few times until the wash water is neutral. The ester layer is then dried under a vacuum to remove the last traces of moisture. Other transesterification processes are also used (12,13).

The transesterification process used by the fuel supplier for these tests typically resulted in methyl esters of 97% purity. The remaining impurities can be removed by distillation. Methyl esters have a kinematic viscosity of 3 to 6 cSt (5,13–15), which is similar to the American Society of Testing and Materials diesel fuel viscosity limit of 4.1 cSt. Methyl esters are completely miscible in diesel fuel and thus can be blended with current petroleum-based fuels. Methyl oleate and methyl linoleate account for about 75% of the SME (Scheme 2). There are three other esters present in significant amounts (methyl palmitate, stearate, and linolenate). At this time, costs of SME are typically about three times that for petroleum diesel fuel. However, cost reductions could be attained by using a cheaper feedstock, such as waste yellow grease, by increasing the production of SME, and by blending methyl esters with diesel fuel.

MATERIALS AND METHODS

Tests were conducted on a Caterpillar 3304, 7-L, naturally aspirated, indirect injection engine (Mossville, IL). This engine is rated at 75 kW at 37 rev/s, with a peak torque of 380 N-m at 20 rev/s and is representative of engines used in underground mines. The laboratory, equipment, and exhaust sample analysis procedures are described in previous papers (16,17).

To maintain an equivalent intake oxygen concentration in the presence of day-to-day variations in humidity and barometric pressure, the intake pressure was controlled while the intake temperature was maintained at 25°C.

The engine and exhaust system were thoroughly conditioned after fuel and oil changes to limit the presence of residual, adsorbed volatile compounds in the exhaust system and combustion chamber from testing the previous fuel. The engine and exhaust system were conditioned by operating the engine at a high speed and load condition (rated power) for 16 h while concurrently taking exhaust filter samples with the dilution tunnel. Lubrication oil was changed concurrently with each fuel change to minimize the effects of fuel-diluted oil on the chemical composition of the DPM.

Fuels and diesel oxidation catalyst tested. Three fuels were tested: (i) a low-sulfur #2 petroleum diesel fuel (D2) from a single batch; (ii) double-distilled (99.9% purity), neat SME; and (iii) a blend of 30% SME by volume with 70% D2. The fuel-related properties are given in Table 1.

An Engelhard advanced formulation diesel oxidation catalyst (DOC) was installed in the engine's exhaust stream for some of the emissions tests [The part number for the specific catalyst and packaging used for this project was: PTX D390-H329803 (Engelhard Corp., Iselin, NJ), S/N: 3A.] The DOC used a platinum and rare earth-based technology. The monolith was approximately 24.1 cm in diameter, 7.6 cm long, and had a cell density of 46.5 cells per square cm. Specific information about the catalyst washcoat formulation is proprietary, but the catalyst was designed by Engelhard to minimize oxidation of NO to NO_2, and SO_2 to sulfates, when compared to typical DOC formulations.

Fuel injection timing. Preliminary testing by the USBM and others (5,18) found differences in the ignition delay and the NO_x–particulate trade-off with changes in injection timing for SME and D2. Additionally, the stock injection timing of the Caterpillar 3304 was not optimized from the standpoint of emissions with D2. Because it was desirable to test all fuels at their optimum timing with regard to emissions, a sweep of different injection timing settings was performed. This optimization is described in a previous paper (17). A fuel injection timing of 10.5 to 11° was found to be optimum for NO_x, NO_2, and DPM emissions for both D2 and SME. The nominal injection timing was set to 10.5° before top dead center for all fuel evaluations.

Test cycles. Two transient tests were chosen for the test program—a light-duty transient and a heavy-duty transient.

TABLE 1
Fuel Properties[a]

Properties	D2	SME	Blend
Cetane number, D287	43.2	54.7	49.1
Lower heating value, D240	42.8	37.1	40.3
C/H/O (molar ratio)	16:30:0	19:34:2	17:31:05
Mass % sulfur	.01	<0.005	0.005
Mass % oxygen	0	11.0	3.4
Mass % aromatics	39.0	0	27.3
Kinematic viscosity (cSt, 40°C)	2.37	3.05	2.84
Density @ 15°C (g/cm^3)	0.8515	0.8859	0.8618
Cloud point, D2500 (°C)	−21	−2	−17
Flashpoint, D93 (°C)	68	160	77

[a] D2, low-sulfur #2 petroleum diesel fuel; SME, methyl esters of soy oil; C/H/O, molar ratio of atomic carbon, hydrogen, and oxygen.

These tests were devised by the USBM and consist of 16 load/speed segments, each 10 s long, that are continuously repeated during a test. The light-duty transient has a maximum load of 50% of the rated torque. The heavy-duty transient has a maximum load of 90% of the rated torque. Figures 1 and 2 show the speed and torque set-points and actual response for the heavy-duty transient test.

The transient tests were identical for all fuels to allow direct comparisons of brake-specific emissions for different fuels doing identical work. However, by testing each fuel with the same test, possible differences in the equivalence ratios (the stoichiometric fuel-to-air ratios) were not accounted for.

Size distribution measurement. Size distributions of the DPM were made with a TSI electrical aerosol analyzer (EAA) (St. Paul, MN) as described previously (19,20). Others (21–24) have used EAA to measure diesel exhaust size distributions, and EAA correlates well with other methods, such as diffusion battery/condensation nuclei counter combinations (21,22). Size distribution measurements were made while running the engine at four steady-state conditions: rated speed, 100% and 10% loads, and 20 rev/s, and 100% and 50% loads.

Experimental design. The test schedule varied the order of testing for the different fuels and the DOC, but was not random. The schedule was compromised because of the time involved in oil and fuel changes and conditioning. Statistical differences were analyzed by a two-sided *t*-test, with differences considered significant at P-value < 0.05. Error bars in the figures refer to standard errors.

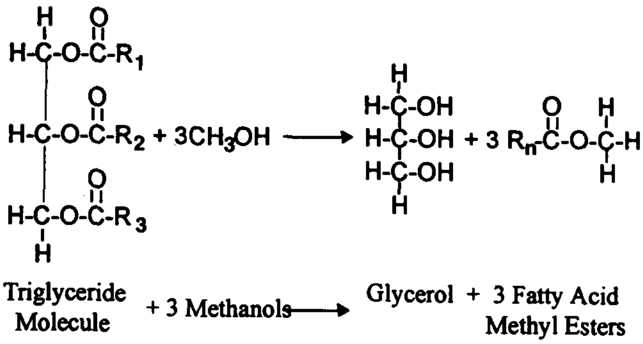

FIG. 1. Speed set-point and response for heavy-duty transient test.

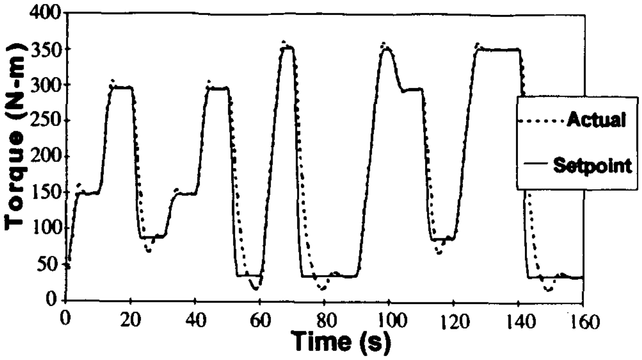

FIG. 2. Load set-points and response for heavy-duty transient test.

DPM sampling. DPM was collected with a partial-flow dilution tunnel (16). Exhaust backpressure was set to 4 kPa above atmospheric pressure at high idle for each test to help maintain adequate sample flow in the partial-flow dilution tunnel. Sampling times varied typically from 16 to 30 min, and 300 mg of DPM was targeted for each sample. Eight to nine samples were taken for each transient test, and each test was repeated four to six times. Also, XAD-2 resin (Supelco, Inc., Bellefonte, PA) was used to collect some of the vapor-phase material that was not adsorbed on DPM (this is referred to as XOC material). One XAD-2 sample was collected per test, simultaneously with a DPM filter, and the samples were retained for solvent extraction and chemical and biological analysis. One DPM sample was also used for sulfate analysis.

Chemical and biological analysis of samples. Selected DPM and XOC material samples were analyzed at Michigan Technological University (MTU) (Houghton, MI) for mutagenicity and *n*-alkane equivalent carbon number (#) distribution. Soxhlet extraction for 24 h with dichloromethane was used to extract the organic material from the particulate filters and XAD-2 resin. Alkane equivalent carbon number distributions were determined by gas chromatography on a Hewlett-Packard (Avondale, PA) 5880 with capillary column and flame-ionization detector. The column was DB-5, 0.25 mm × 30 m with a film thickness of 0.25 micron (J&W Scientific, Folsom, CA). Temperatures were: detector, 325°C; injector, 325°C; column, 50–325°C at 10°C/min; then isothermal at 325°C for 25 min. The carrier gas was He at a flow rate of approximately 1.8 mL/min. Characterization of samples proceeded by comparison of the unknowns to *n*-alkane reference standards, obtained as commercially produced mixtures, covering a practical range of approximately C_8–C_{40}. Comparisons were made to *n*-alkanes only. Other types of compounds were present in the unknowns, which give rise to flame-ionization detector peaks as well. Mutagenic activity was determined by the Ames mutagenicity bioassay (25).

Additional tests were performed to determine the gas-chromatographic spectrum of emissions that contained SME, and to determine the partition of the emissions between the soluble organic fraction of DPM and the gas-phase material. Neat SME was injected into the exhaust stream of the engine when it was run on both neat SME fuel and #2 diesel fuel. DPM and XAD-2 samples were collected in the partial-flow dilution tunnel. The samples were analyzed at MTU for carbon number distribution for comparison with extractions of particulate and XOC material generated with SME fuel combustion without injection into the exhaust.

Gaseous emissions. Gaseous emissions were measured as per Society of Automotive Engineers recommended practice (26). Nondispersive infrared analyzers were used to measure CO and CO_2. Total vapor-phase hydrocarbons were measured with flame-ionization detection. Chemiluminescence detection was used to measure NO_x. In addition, NO, NO_2, and formaldehyde were measured with a Nicollet Fourier transform infrared analyzer (Madison, WI).

RESULTS AND DISCUSSION

The following results are brake-specific cycle-averages and are compared to the diesel fuel (D2) baseline with no DOC, unless otherwise noted. Results are based on more than 60 h of testing on each fuel.

DPM emissions. DPM results for the transient testing are shown in Figures 3 and 4. The methyl ester fuels tend to decrease the nonvolatile fraction of DPM emissions (carbonaceous soot) and increase the volatile organic fraction of DPM. The increases in volatile organic DPM emissions were primarily due to a higher average equivalent carbon number of the SME organic matter. Gas chromatography results indicate that the increases in organic matter in SME exhaust are associated with larger-chain unburned fuel hydrocarbons. The higher the carbon number, the lower the hydrocarbon vapor pressure, and the more likely condensation or adsorption of volatile matter will occur. This is discussed further in the next section. Total DPM decreased with neat SME by 30% for the heavy-duty transient and 23% for the light-duty transient. The blend showed a decrease of 11% in total DPM for the heavy-duty transient, and no statistically significant difference for the light-duty transient.

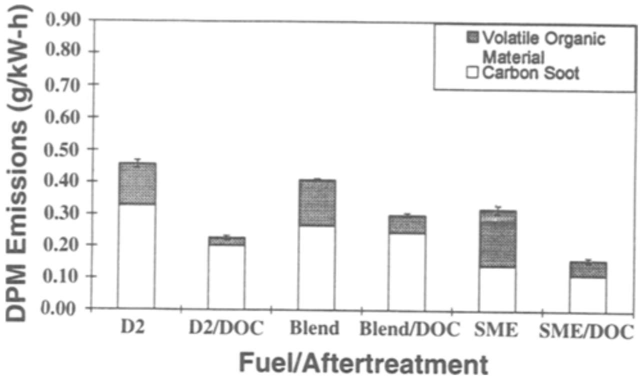

FIG. 3. Brake-specific diesel particulate matter (DPM) results for the heavy-duty transient. Error bars refer to the standard error for total DPM. D2, a low-sulfur #2 petroleum diesel-fuel; DOC, diesel oxidation catalyst; SME, methyl esters of soy oil.

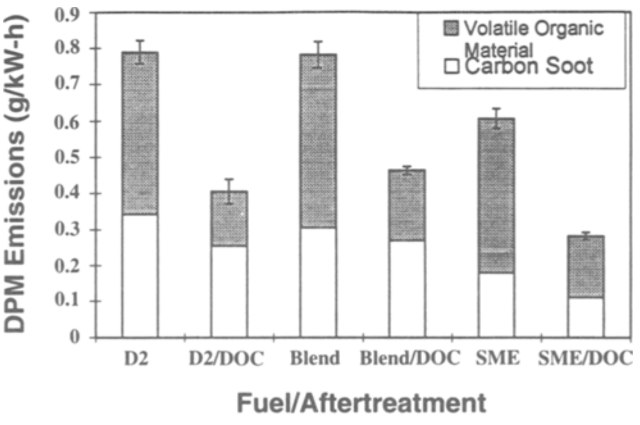

FIG. 4. Brake-specific DPM results for the light-duty transient. Error bars refer to the standard error for total DPM. Abbreviations as in Figure 3.

The DOC reduced the volatile organic fraction of DPM and caused decreases in total DPM. The DOC with SME fuel reduced total DPM by 65 and 64% for the heavy-duty and light-duty transients, respectively. The DOC with the blend fuel reduced total DPM by 35 and 40% for the heavy- and light-duty transients, respectively. The DOC performance with D2 was different than expected. For both transients, the DOC reduced the nonvolatile fraction considerably and was much more efficient at reducing the volatile fraction than it was in other cases, resulting in a 50% decrease in DPM for the heavy-duty transient. This trend has not been explained and was not expected, as others (27) have shown that DOC do not affect the nonvolatile fraction of DPM, and similar testing with this DOC (17) has not shown this trend.

The DPM reductions attained, when using neat SME, indicate that SME fuel could be a potential emission control option in underground mines. The DPM reduction trends are similar to those seen in steady-state testing with the same engine (17) and are large enough to provide significant respirable aerosol reductions in a mine. Also, heavy-duty mining equipment is likely to have more intense duty cycles than the laboratory transient used for these tests, so DPM reductions with SME in a mine situation could be greater than seen in the laboratory tests.

Chemical and biological results. Gas-chromatographic results were available from three types of samples: SME fuel, exhaust emissions from SME fuel, and exhaust emissions from SME fuel and injecting SME fuel into the exhaust stream. The fatty acid composition of the SME fuel is shown in Table 2. Figure 5 is an *n*-alkane equivalent carbon number spectrum of combined DPM and vapor-phase materials collected when the engine was operating with SME fuel and no DOC present. It shows conspicuous peaks at carbon numbers 19 and 21. Similar peaks at carbon numbers were evident from fuel samples and from exhaust samples when neat SME was injected into the exhaust stream of the engine. This indicates that some SME is emitted by the engine with little or no modification (unburned fuel).

Longer-chain organic compounds that remain intact at the end of combustion of SME could cause increased volatile organic matter adsorption, condensation, and self-nucleation. Increases in adsorption of the longer-chain species would account for the increased levels of volatile organic matter in the DPM samples, even with a simultaneous decrease in the total vapor-phase hydrocarbons. Johnson (28) showed that hydrocarbons in diesel exhaust with equivalent carbon numbers

TABLE 2
Fatty Acid Distribution of the SME from Gas Chromatography[a]

Fatty acid	% Mass (average value)
C12:0	0.4
C14:0	0.3
C16:0	10.9
C18:0	4.1
C18:1	23.4
C18:2	52.3
C18:3	8.3
C20:0	0.2

[a] Abbreviation as in Table 1.

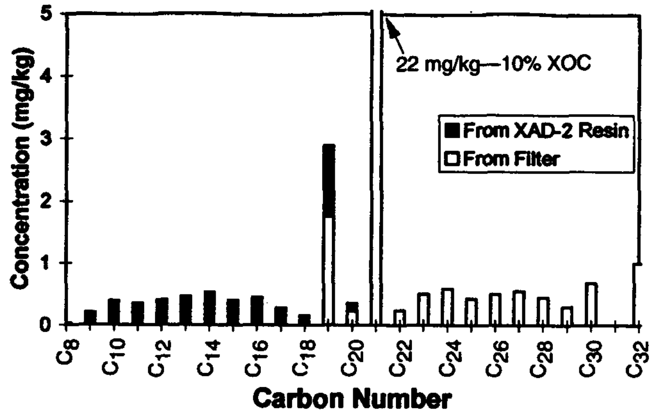

FIG. 5. *n*-Alkane equivalent carbon number distribution of combined DPM and gas-phase materials from gas chromatography. Distribution is from soy methyl ester exhaust. Black columns are from gas-phase (XAD-2 resin; Supelco, Bellefonte, PA) samples; white columns are from DPM samples. XOC, vapor-phase material not absorbed on DPM; other abbreviations as in Figure 3.

above C_{16} are primarily adsorbed or condensed onto the DPM, and hydrocarbons with smaller chainlengths are primarily collected as gas-phase material. The C_{19} and C_{21} peaks that were observed during emissions tests represent 60% of the mass of the total DPM and hydrocarbon emissions. The C_{19} and C_{21} constituents were responsible for 80% of the organic material extracted from the DPM and 47% of the vapor phase organic material. Further analysis is necessary to determine the exact composition of these organic compounds, but the results from the injection tests strongly suggest that the C_{19} and C_{21} components are fuel-related and are probably methyl esters emitted with little or no chemical change.

The mutagenic activity of a limited number of DPM and gas-phase samples was determined. The mutagenicity of the DPM (revertants/kg exhaust) when SME fuel was used with the DOC is approximately 50% of that when D2 was used with the DOC. The DOC was able to reduce the mutagenicity of the DPM emitted with SME fuel by about 40%. Also, the mutagenicity of XOC material is negligible when SME fuel is used with a DOC.

The reduction in mutagenic activity when using SME is probably a result of reduced polycyclic aromatic hydrocarbon (PAH) emissions due to the lack of fuel PAH. Similar results have been found in other research (29). Further chemical analysis with speciation of the extracted organic material will be necessary to understand the observed reduction in mutagenic activity.

Gaseous emissions. Brake-specific gaseous emissions are shown in Tables 3 and 4. Results showed decreases or no sig-

TABLE 3
Brake-Specific Gaseous Emissions from the Heavy-Duty Transient Test[a]

Test	NO_x (g/kW-h)	FTIR NO (g/kW-h)	FTIR NO_2 (g/kW-h)	HC (g/kW-h)	CO (g/kW-h)	FTIR HCOH (g/kW-h)
D2 (baseline)	15.2	11.8	0.055	1.100	3.79	0.142
SD	0.9	1.2	0.048	0.187	0.23	0.030
D2-DOC	15.7	12.4	0.128	0.197	0.59	0.043
SD	1.0	0.9	0.063	0.018	0.07	0.011
% change from baseline	3	5	132	−82[b]	−84[b]	−70[b]
SME	13.7	10.5	0.101	0.701	2.90	0.127
SD	0.8	0.5	0.033	0.086	0.14	0.015
% change from baseline	−10[b]	−11[b]	84[b]	−36[b]	−23[b]	−11
SME-DOC	12.8	9.9	0.197	0.161	0.49	0.072
SD	0.4	0.5	0.024	0.025	0.10	0.009
% change from baseline	−16[b]	−16[b]	258[b]	−85[b]	−87[b]	−50*
Blend	13.5	10.7	0.036	0.827	2.92	0.112
SD	0.5	0.6	0.029	0.091	0.23	0.009
% change from baseline	−11[b]	−9[b]	−35	−25[b]	−23[b]	−21[b]
Blend-DOC	13.3	10.0	0.111	0.175	0.42	0.047
SD	0.2	0.4	0.015	0.020	0.07	0.007
% change from baseline	−13[b]	−15[b]	102[b]	−84[b]	−89[b]	−67[b]

[a] FTIR, Fourier transform infrared; HC, hydrocarbon; HCOH, formaldehyde; DOC, diesel oxidation catalyst; other abbreviations as in Table 1.

[b] Statistically significant differences from the diesel fuel baseline ($P < .05$).

TABLE 4
Brake-Specific Gaseous Emissions from the Light-Duty Transient Test[a]

Test	NO_x (g/kW-h)	FTIR NO (g/kW-h)	FTIR NO_2 (g/kW-h)	HC (g/kW-h)	CO (g/kW-h)	FTIR HCOH (g/kW-h)
D2 (baseline)	21.7	15.8	0.235	1.603	4.64	0.193
SD	0.9	1.0	0.033	0.182	0.44	0.034
D2–DOC	22.2	16.7	0.036	0.636	1.09	0.112
SD	0.4	1.1	0.002	0.083	0.22	0.001
% change from baseline	2	6	−85[b]	−60[b]	−76[b]	−42[b]
SME	19.5	14.0	0.284	1.076	3.56	0.152
SD	1.1	0.8	0.069	0.144	0.19	0.013
% change from baseline	−10[b]	−11[b]	21[b]	−33[b]	−23[b]	−21[b]
SME–DOC	18.4	14.0	0.066	0.421	0.84	0.121
SD	1.1	1.0	0.038	0.056	0.10	0.012
% change from baseline	−15[b]	−11	−72[b]	−74[b]	−82[b]	−37[b]
Blend	19.3	14.3	0.204	1.216	3.75	0.166
SD	0.8	0.7	0.045	0.266	0.47	0.034
% change from baseline	−11[b]	−9[b]	−13	−24[b]	−19[b]	−14
Blend–DOC	18.8	14.3	0.052	0.441	0.75	0.083
SD	0.6	0.6	0.018	0.079	0.09	0.022
% change from baseline	−13[b]	−10[b]	−78[b]	−72[b]	−84[b]	−57[b]

[a] Abbreviations as in Tables 1 and 3.

[b] Statistically significant differences from the diesel fuel baseline ($P < .05$).

nificant increases for all of the major exhaust pollutants when SME fuel was used. NO_x was reduced for both the blend fuel and the neat SME fuel by 10 to 11% for both transients. Previous testing and combustion analyses of SME fuel (17) show that a decrease in the premixed burn phase of combustion, lower peak bulk gas temperatures during combustion, and decreased ignition delay may partially explain the NO_x decreases.

CO and total hydrocarbons were reduced significantly with both the blend fuel and the SME fuel. Formaldehyde showed slight decreases with the methyl ester fuels, but the only statistically significant decreases occurred for neat SME during the light-duty transient and for the blend during the heavy-duty transient. NO_2 showed statistically significant increases for the neat SME fuel during both transients, although all NO_2 measurements without the DOC were low (<12 ppm).

The DOC was able to reduce gaseous hydrocarbon and carbon monoxide emissions without significant increases in NO. DOC performance with the methyl ester fuels was similar to the performance with D2, providing overall decreases compared to the D2 baseline of 70 to 90% for hydrocarbons and CO. Formaldehyde was significantly decreased with the DOC. NO_2 increased during the heavy-duty transient, but was decreased during the light-duty transient when DOC was used.

Effects on size distribution. Figure 6 shows the volume size-distribution for the exhaust from the three fuels for the engine setting of 25 revs/s at 100% load. Diesel exhaust can usually be considered to have two modes: a nuclei mode of small particles (.01–.056 μm) and an accumulation mode (.056–1.0 μm) (21,24). The results of this testing show a reduction in the accumulation mode volumes for the methyl ester fuels. The reduction was consistent at all four steady-state engine conditions tested. Some of the reduction is from the reduction in particulate mass when the ester fuels were used. The reduction in the accumulation mode may be due to increased oxygen availability late in combustion. Increased oxidation during late combustion (expansion stroke) could reduce particulate matter emissions. Also, it is possible that volatile material is not entirely surviving the double dilution process. Losses in volatile material would affect the SME size distribution more than the D2 size distribution, because the SME aerosol has a greater fraction of volatile material than the D2 aerosol.

Figure 7 shows the volume fraction in the nuclei mode for the three fuels and two conditions. The SME exhaust has a much greater fraction in the nuclei mode than the D2 exhaust. Because SME has a much greater output of volatile material, the increase in the nuclei mode is likely due to homogeneous

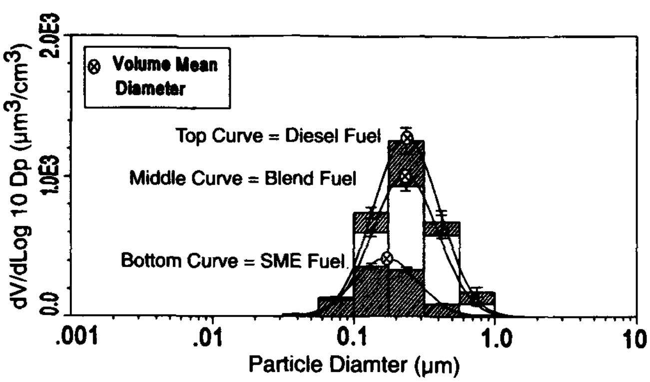

FIG. 6. Volume size-distribution (100:1 dilution ratio) of soy methyl ester, blend, and diesel fuel exhaust aerosols at 25 rev/s and 100% load.

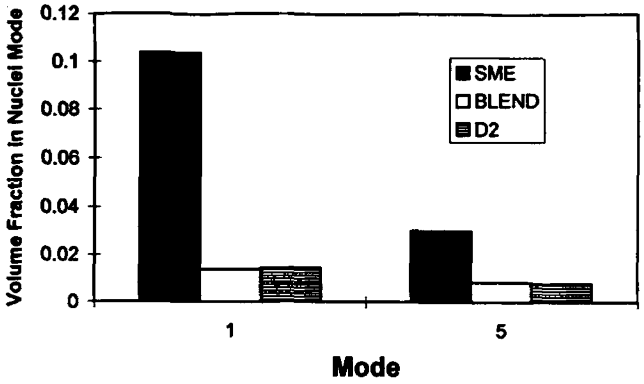

FIG. 7. Volume fraction in the nuclei mode for soy methyl ester, blend, and diesel fuel exhaust aerosol at two modes. Abbreviations as in Figure 3.

nucleation of volatile material. Others (21) have shown that homogeneous nucleation of volatile material into nuclei mode particles may occur when there is an abundance of particulate-phase volatile material. Further research is needed to determine the extent of the size distribution shifts and the mechanisms that could be causing them.

Engine power and performance. No fuel-related problems occurred during more than 60 h of testing on each fuel. The methyl ester fuels provided less power than D2 and had higher fuel consumption due to the lower energy content of the SME fuel. Neat SME had 9% less power and 13% higher fuel consumption. The blend had 4% less power and 4% higher fuel consumption.

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