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Emissions from Nine Heavy Trucks Fueled by Diesel and Biodiesel Blend without Engine Modification

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Biodiesel, a fuel that can be made from renewable biological sources such as vegetable oils or animal fats, has been recognized recently as an environment friendly alternative fuel for diesel engines. In this paper, we describe a study that compared exhaust emissions from in-use heavy trucks fueled with a biodiesel blend with those from trucks fueled with petroleum diesel. The biodiesel blend tested is a mixture of 35% biodiesel and 65% petroleum diesel, a blend designated as B35. The study is based on the field test results from West Virginia University's Transportable Heavy Duty Chassis Dynamometer Emissions Testing Laboratory and sponsored by the U.S. Department of Energy. The heavy trucks we tested performed well when the originally equipped compression-ignition engine (diesel engine) was fueled with B35 without any engine modifications. Fuel economy (in terms of gallon per mile) of the two fuels was about the same. The emissions test results have shown that the heavy trucks fueled by B35 emitted significantly lower particulate matter (PM) and moderately lower carbon monoxide (CO) and hydrocarbon (HC) than the same trucks fueled by no. 2 diesel (D2). Oxides of nitrogen (NO_x) emissions from B35 and D2, however, were generally in the same level. Emissions variations from two different engine models and two driving cycles were also observed. Although we recommend more tests for biodiesel vehicles, the data obtained in this study indicate that biodiesel has promise as an emissions-reducing alternative fuel for diesel engines.

Introduction

As public concern about environmental pollution and energy security increases, alternative transportation fuels, such as compressed natural gas (CNG), liquefied natural gas (LNG), ethanol, methanol, and propane (also called liquefied petroleum gas or LPG), are receiving more and more attention.

Biodiesel, which can be generated from natural, renewable sources such as new or used vegetable oils or animal fats, may have the potential to reduce our nation's reliance on imported oil and to improve air quality. In addition, it is compatible with petroleum diesel fuel in compression-ignition engines, meaning that an existing diesel engine can be fueled by biodiesel blends.

Vegetable oils have long been used as fuels for diesel engines. As early as the late 1800s, Rudolf Diesel used peanut oil in a diesel engine. But using chemically unaltered vegetable oils directly in diesel engines can cause performance problems because of their high viscosity and low volatility. A feasible solution is to transesterify the oils with methanol (or ethanol) to form esters. Vegetable oils are primarily composed of glycerol esters of fatty acids (triglycerides). In the process of transesterification, the glycerol components of the triglycerides molecules are exchanged for a lighter methanol (or ethanol). The product is composed of fatty acid methyl esters (or ethyl esters), consisting of straight saturated and unsaturated hydrocarbon chains. The most widely used product, soyate methyl ester (SME), is made through a reaction of soybean oil and methanol.

In recent years, an ester-based oxygenated fuel, called biodiesel, has been used in compression-ignited diesel engines without any engine modifications. B20 (a mixture of 20% biodiesel and 80% petroleum diesel) and B35 (a mixture of 35% biodiesel and 65% petroleum diesel) are the most popular biodiesel fuel blends used to date in the United States.

In the last several years, many studies (*1*−*36*) have looked at the potential of biodiesel as an alternative fuel for diesel engines. Schumacher (*1*) and Spataru (*2*) both studied several blends of no. 2 diesel and SME or canola methyl ester (CME) to determine and compare engine emissions from a Detroit Diesel Corporation (DDC) 6V92TA engine (a type of diesel engine widely used in transit buses and heavy trucks) operated on those fuels. They conducted engine and chassis dynamometer testing as well as on-road testing. Similar emissions trends were seen: an increased percentage of SME and CME blended with diesel led to increased emissions of NO_x and decreased emissions of PM, HC, and CO. Schumacher found the optimum ratio between biodiesel blend and petroleum diesel, based on the tradeoff of PM decrease and NO_x increase, to be 20/80. Spataru recommended that certain methyl ester/diesel blends be explored in conjunction with delays in engine timing and technologies that reduce the soluble fraction of particulate emissions.

Grabaski et al. (*3*) also employed a 1991 DDC series 60 engine to determine emissions of NO_x, CO, HC, and PM that result from blending biodiesel (methyl soyester) and conventional diesel. The tests showed that as the percentage of biodiesel blend in the fuel increased, the NO_x increased but HC, CO, and PM decreased.

Engine efficiency for biodiesel blends proved to be the same as that of diesel fuel. Marshall et al. (*4*) selected a Cummins L-10E engine on which to conduct tests, using the Federal Test Procedure (FTP). The results showed that as the concentration of biodiesel increased, the L-10E engine produced lower levels of HC, CO, and PM but a higher level of NO_x. When fueled with B20 and B35, the L-10E engine's power during the FTP was nearly equal to its power when fueled with baseline diesel (no. 2 diesel). The results also showed that retarding injection timing on either a DDC 6V92TA engine (*1*) or a Cummins L-10E engine (*4*) fueled with B20 can successfully reduce NO_x emissions.

Schumacher (*5*) and Peterson (*6*) both conducted about 100 000 mi of road tests on Cummins B5.9L engines running on 100% biodiesel in Dodge pickups. No fuel-related problems were noted during the tests on the unmodified trucks. Both emissions test results showed that CO, HC, and smoke exhaust emissions from biodiesel tend to be lower. Although Schumacher found that NO_x emissions increased

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FIGURE 1. Class 8 tractor secured to the chassis dynamometer of the WVU transportable emissions testing laboratory. The exhaust can be seen entering the full-scale dilution tunnel located in the analytic trailer.

13% and PM decreased nearly 20% on biodiesel, Peterson observed the opposite results: an 11.8% NO_x reduction and a 10.3% PM increase.

Chang et al. (*7*) studied the effects of using blends of methyl and isopropyl esters of soybean oil with no. 2 diesel at several steady-state operational conditions in a four-cylinder turbocharged John Deere 4276T engine. Both methyl and isopropyl esters provided significant reductions in PM emissions as compared with no. 2 diesel fuel. Emissions of CO and HC were also reduced significantly, but NO_x increased by about 12%.

To evaluate biodiesel emissions as compared with those of commercial low-sulfur diesel fuel, McDonald (*8*) studied a Caterpillar 3304 PCNA (pre-chamber naturally aspirated) diesel engine using oxygenated fuels (including 100% SME and a blend of 30% SME with 70% no. 2 diesel, or B30). The SME fuel and the B30 caused no fuel-related engine performance problems. Emissions test results show that NO_x emissions from B30 did not change significantly but that they decreased with the neat SME fuel. Neat SME and the B30 blend fuels increased volatile organic diesel particulate matter (DPM) and decreased nonvolatile DPM resulting in a net decrease in total DPM as compared to no. 2 diesel fuel. Using a diesel oxidation catalyst (DOC) is found to further reduce both volatile and total DPM.

All the above work suggests biodiesel as a promising alternative fuel for diesel engines. Considerable emissions benefit for PM, CO, and HC can be realized without any penalties in terms of fuel consumption or engine performance, but a small NO_x increased was measured in some studies. Although engine modifications were not necessary, some researchers have reported that engine optimum calibrations lowered biodiesel emissions, especially NO_x emissions.

As of today, there is very little data available on emissions from in-use heavy trucks powered by biodiesel blends. This paper presents emissions results based on instantaneous measurement data collected from nine heavy trucks in Sheldon, IA, equipped with two different types of engines. Each vehicle was tested by fueling B35 and no. 2 diesel, separately. Gaseous and particulate matter emissions data from both fuels were analyzed and discussed with the help of suitable plots.

Test Facilities

The tests were conducted by West Virginia University (WVU) researchers using their Transportable Heavy Duty Chassis Dynamometer Emissions Testing Laboratory. Figure 1 shows the laboratory at a test site. The laboratory consists of two major components—a flatbed semi-trailer carrying a chassis dynamometer that is used to simulate vehicle inertia and road load and a second trailer used to house the data acquisition and emissions analysis system. The central computer controls functions of all components, including the dynamometer, the instrument system, and the gas analysis bench.

The emissions measurement system consists of a critical flow venturi-constant volume sampler (CFV−CVS) with a primary dilution tunnel, a secondary dilution tunnel, heated probes, and heated lines. The primary dilution tunnel is used to dilute the exhaust gas with supplemental air. Four analyzers are used in the primary tunnel to measure the regulated gaseous emissions. Nondispersive infrared analyzers (NDIR) measure CO and carbon dioxide (CO_2) emissions. A chemiluminesecent detector (CLD) measures NO_x emissions, and a heated flame ionization detector (FID) measures HC emissions. A secondary tunnel is used for PM sampling by taking exhaust gas samples from the primary dilution tunnel. The central control computer controls all these measurements.

The WVU Transportable Heavy Duty Chassis Dynamometer Emissions Testing Laboratory has traveled from coast to coast to test buses and trucks in the last 7 years (*37*). To date more than 1500 vehicle tests have been conducted for 40 fleet owners in 20 states. The chassis dynamometer emissions data for heavy-duty alternative fuel vehicles are available on the World Wide Web through the U.S. Department of Energy's Alternative Fuels Data Center at http://www.afdc.doe.gov.

Vehicle Emissions Tests

Table 1 describes the vehicles tested in this study. Figure 2 shows one of the heavy trucks fueled by B35. The vehicles were powered by two types of engines: six trucks were equipped with Cummins 855 engines and three with DDC series 60 engines. The vehicles ran on both B35 and no. 2 diesel. For comparison, the fuel properties of no. 2 diesel and SME are shown in Table 2. Biodiesel has all the essential properties of diesel fuel but has a higher oxygen content, a lower sulfur and aromatic content, and a higher cetane number than conventional diesel.

Emissions data are acquired from the trucks using the WVU truck driving cycle and the WVU 5-mi driving cycle. Figures 3 and 4 show the two test cycles. The WVU 5-peak truck cycle is designed for general truck chassis testing and was developed by WVU faculty (*38*−*40*). The cycle consists of five segments, each with an acceleration to a peak speed, followed by a brief steady-state operation and then a deceleration back to idle. The five peak speeds are 20, 25, 30, 35, and 40 mph. The WVU 5-mi cycle is basically the same as the 5-peak cycle except that this cycle accelerates to the steady speed using the highest possible acceleration. To make test results comparable to the original WVU 5-peak cycle, the driving distance is kept at 5 mi and the driving duration is 900 s.

Test Results and Discussion

Engine Performance and Fuel Economy. As Table 1 shows, the nine tractor trucks tested were powered by Cummins 855 engines made in the late 1980s and DDC series 60 engines built in the 1990s. No engine or fueling system modifications were made on the vehicles to run on biodiesel. All vehicles performed well when fueled with biodiesel blends, and no fuel-related problems were observed during tests. Figure 5 shows no significant differences in fuel economy (in miles per gallon) between biodiesel blends and diesel.

Many researchers have shown that SME exhibits chemical and thermodynamics characteristics substantially similar to those of diesel. The molecular structure of vegetable oil-derived biodiesel is similar to diesel fuel. Both are made up of long chains that contain the methylene (CH_2) group. In addition, the carbon/hydrogen ratio of the two fuels is about the same.

TABLE 1. Specifications of Tested Tractor Trucks

vehicle ID	vehicle manufacturer	gross vehicle wt (lb)	engine model	engine model year	engine displacement (L)	engine power (hp)	rated speed (rpm)
T-1	Kenworth	50000	Cummins 855	1987	14	270	1700
T-2	Kenworth	50000	Cummins 855	1988	14	270	1700
T-3	Kenworth	50000	Cummins 855	1987	14	315	1800
T-4	Freightliner	48000	Cummins 855	1992	14	350	1800
T-5	Freightliner	80000	Cummins 855	1989	14	350	1800
T-6	Freightliner	80000	Cummins 855	1989	14	350	1800
T-7	Kenworth	80000	DDC series 60	1994	11.1	365	1800
T-8	Kenworth	50000	DDC series 60	1994	11.1	365	1800
T-9	International	80000	DDC series 60	1993	11.1	350	1800

FIGURE 2. One of the tested heavy trucks in this study.

TABLE 2. Properties of No. 2 Diesel and SME

fuel	no. 2 diesel	SME
cetane no.	46.2	56.4
LHV (MJ/kg)	43.0	37.1
mole mass	182	308.7
specific gravity	0.85	0.88
mass % sulfur	0.04	0.002
mass % carbon	87	78
mass % hydrogen	12.4	11.5
mass % oxygen	0.006	11
mass % aromatics	30	0
flashpoint (°C)	64	169
viscosity at 400 °C	2.7Cst	4.7Cst

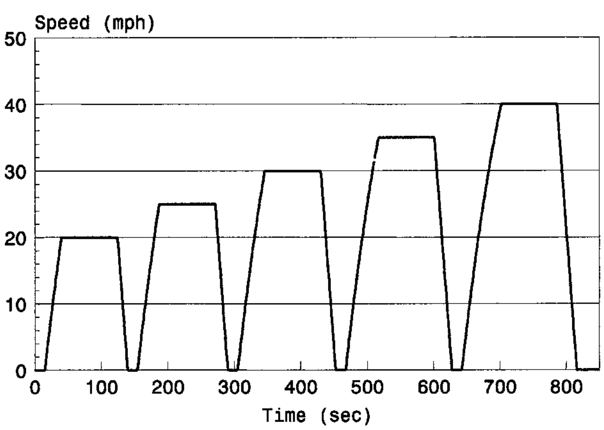

FIGURE 3. WVU truck cycle.

Transient Emissions Analysis. Figure 6 shows the transient emissions traces from vehicle T8 fueled with biodiesel blend and no. 2 diesel along with vehicle horsepower. Because the truck was equipped with a 9-speed manual transmission, the effect of gear shifting during the truck acceleration period is distinctly reflected in the vehicle horsepower curve. All the emissions trace signals were adjusted for measurement delay time to align with horsepower signals. This ensures that emissions measurements correspond to the instantaneous vehicle horsepower at the same time.

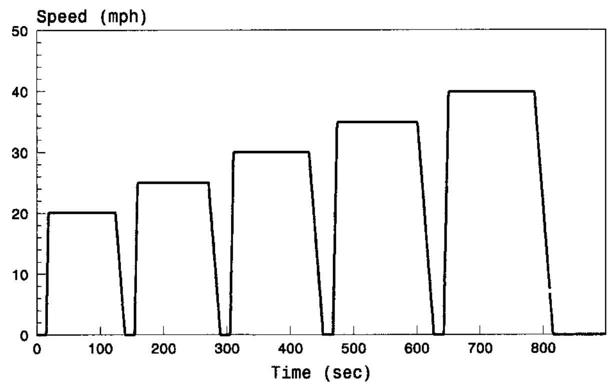

FIGURE 4. WVU 5-mi route cycle.

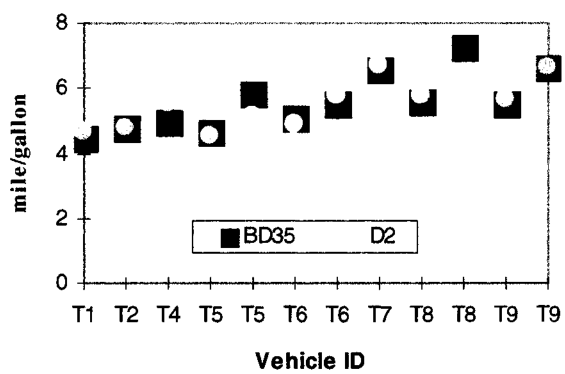

FIGURE 5. Fuel economy comparisons between two fuels for nine tested trucks.

Biodiesel and no. 2 diesel have similar CO emissions trends, which seem to follow vehicle horsepower curves. When the engine is accelerating, CO emissions increase sharply. When the engine is in cruise, emissions decrease and stay at about the same level at different cruise speeds. When the engine is decelerating, CO emissions drop with the deceleration curve. This can be explained by the fact that CO emissions from internal combustion engines are primarily determined by fuel/air equivalence ratio. During acceleration, more fuel is injected, and the transient fuel/air ratio is high. This causes incomplete combustion, which emits more CO. During cruise and deceleration, combustion is more complete, and CO emissions are much lower. Because CO emissions levels of B35 are generally lower than those from no. 2 diesel over the whole cycle, the overall emissions level is lower.

The continuous NO_x emissions, as seen in Figure 6, demonstrate that transient NO_x emissions also correlate with horsepower. When in acceleration, NO_x emissions increase. When in cruise, the emissions level decreases. Unlike CO emissions, however, NO_x emissions tend to be higher at higher

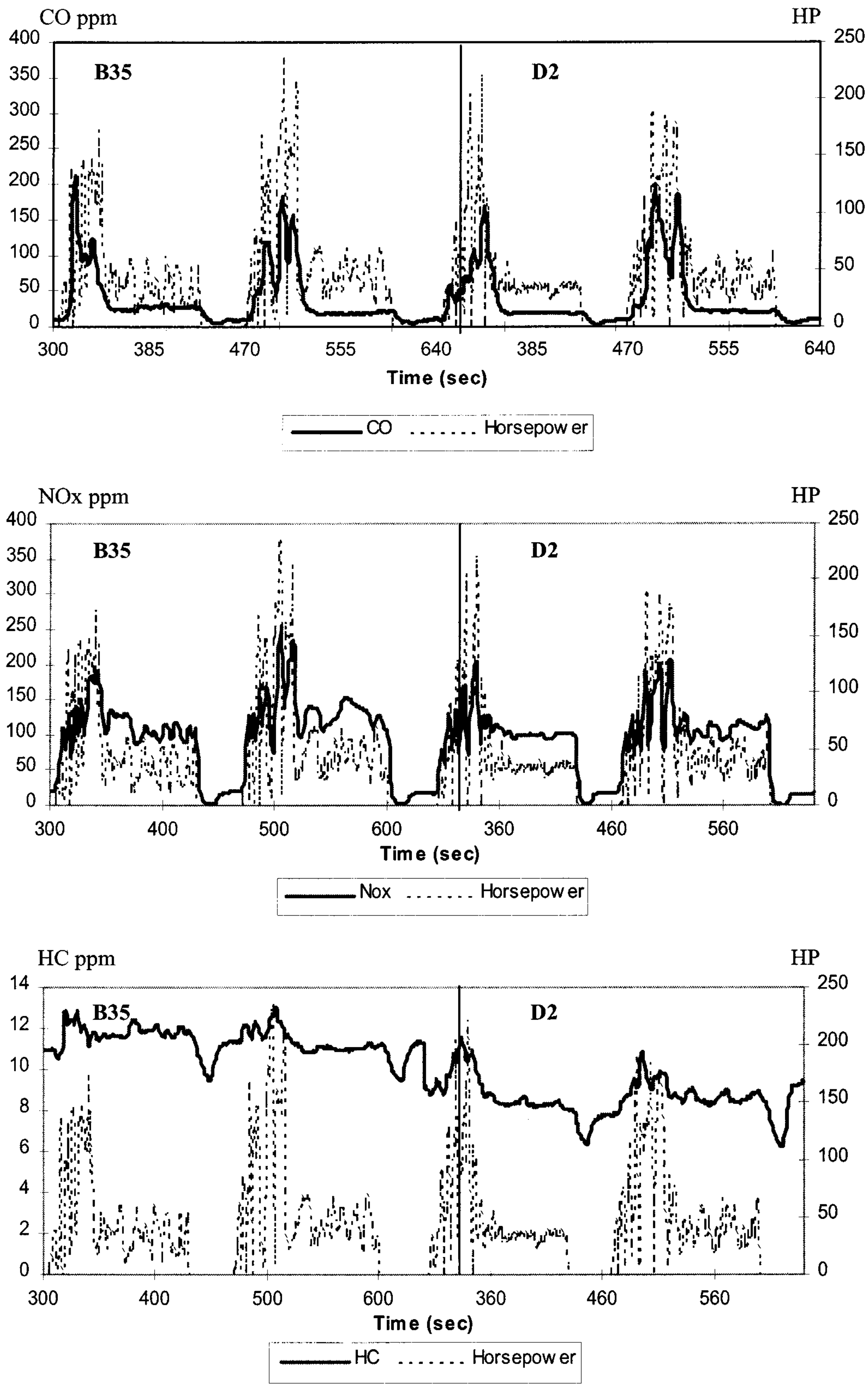

FIGURE 6. Continuous emission traces from B35 and D2 along with vehicle horsepower.

cruise speeds. When in deceleration, NO_x drops to nearly zero. This occurs because NO_x levels increase at high loads, with higher peak pressures, high temperatures, and larger regions of close to stoichiometric burned gas. When in deceleration, very little fuel is injected, resulting in very low NO_x levels. Thus, NO_x emissions are roughly proportional to the mass of fuel injected. BD and no. 2 diesel fuel have similar NO_x emissions trends, but BD NO_x emissions seem to be a bit higher than that of no. 2 diesel.

Continuous HC emissions in the figure show that the trend for HC transient emissions is more complex than that of CO and NO_x emissions. When the engine is accelerating, HC emissions increase. When in cruise, the level decreases. Emissions peak when the engine begins to decelerate and

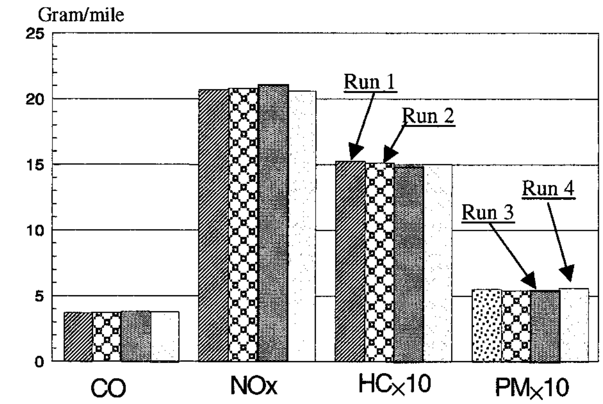

FIGURE 7. Emissions from four test runs of a vehicle.

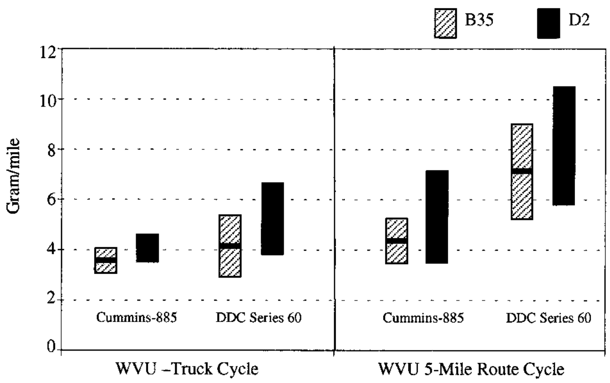

FIGURE 8. Mean and 95% confidence interval of CO emissions.

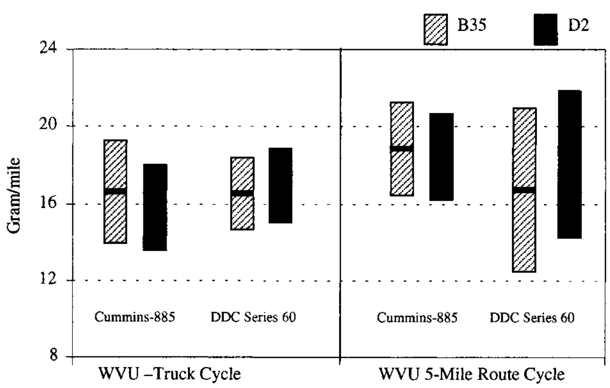

FIGURE 9. Mean and 95% confidence interval of NO_x emissions.

then decrease with deceleration. One reason might be that at the moment when the engine begins to decelerate, much less fuel is injected, and its excessive dilution with air prevents the combustion process from either starting or going to completion. This may cause the unburned hydrocarbon emissions to peak. During deceleration, however, combustion tends to be more stable and HC emissions decrease. BD and no. 2 diesel have similar HC emissions curves, and BD emissions level is lower than that of no. 2 diesel.

Comparative Emissions Analysis. Each vehicle was emissions tested several times to ensure that the tests were accurate. Figure 7 shows the test results of four test runs conducted on vehicle T1, fueled with B35 and running on the 5-mi cycle. The close test results prove the credibility of the emissions testing conducted.

Figures 8–11 show the mean and 95% confidence intervals of regulated emissions from B35- and D2-fueled heavy trucks. The average values and sample size are listed in Tables 3–6. All comparisons made below and shown in the figures are between biodiesel and no. 2 diesel.

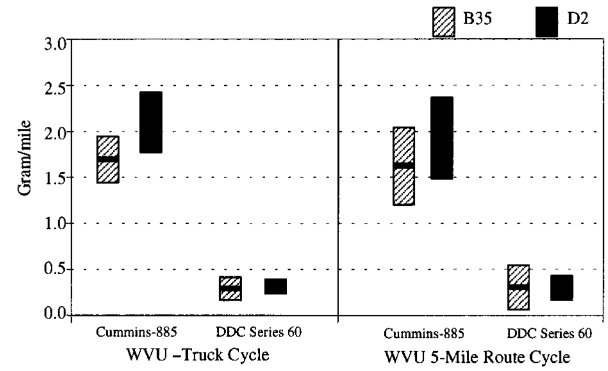

FIGURE 10. Mean and 95% confidence interval of HC emissions.

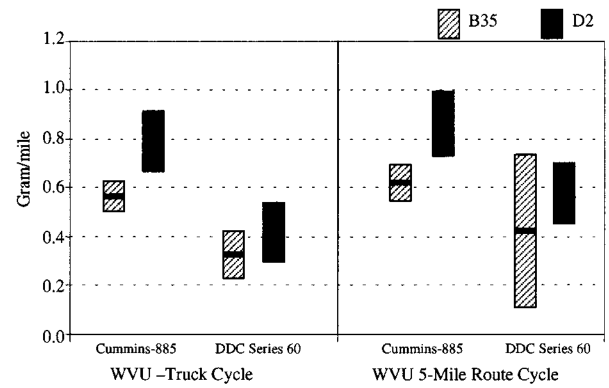

FIGURE 11. Mean and 95% confidence interval of PM emissions.

Carbon Monoxide Emissions. As shown in Figure 8, average CO emissions from trucks fueled with B35 were reduced, regardless of engine type and driving cycle. The 1990s DDC series 60 engines emitted more CO than did the late-1980s Cummins 855 engine.

Biodiesel use reduces CO emissions in the trucks mainly because it has a higher oxygen content than no. 2 diesel. The higher oxygen content encourages more complete combustion. Neat biodiesel generally contains 10–11% oxygen, and B35 contains 4% oxygen. Petroleum diesel contains almost no oxygen. The overall test results showed that B35 reduced CO emissions by an average of about 12%.

Oxides of Nitrogen Emissions. The results showed that for the late 1980s Cummins engines, NO_x emissions levels increased a small percentage from B35 (see Figure 9). But in the later model DDC engines, there was a small average decrease in NO_x emissions from B35. Generally, NO_x emissions variations for different engine type, driving cycle, and fuel type were small.

NO_x emissions formed in an engine are highly dependent on combustion temperature, along with the concentration of oxygen present in combustion products. NO_x emissions from biodiesel are generally slightly higher than those from no. 2 diesel (the results from the DDC series 60 equipped trucks in this study were an exception to this rule). The higher NO_x emissions are mainly because the biodiesel blend has a shorter ignition delay time. The shorter ignition delay, which advances the combustion timing, increases peak pressure and temperature, and enhances NO_x formation, results from biodiesel's higher cetane number. Biodiesel's rich oxygen content is also a factor in high NO_x formation levels. Many researchers have proven that retarding engine timing to lengthen the ignition time is an effective method for controlling biodiesel's NO_x emissions.

Hydrocarbon Emissions. The HC emissions test results (Figure 10) showed that HC decreased moderately when Cummins engines were fueled with biodiesel and was about

TABLE 3. CO Emissions Comparisons (g/mi)

test cycle	WVU truck cycle				WVU 5-mi route cycle			
engine	Cummins 855		DDC series 60		Cummins 855		DDC series 60	
fuel	B35	D2	B35	D2	B35	D2	B35	D2
mean	3.522	4.050	4.182	5.037	4.395	5.244	7.067	8.169
median	3.614	4.215	3.533	5.263	4.782	5.124	6.988	7.998
SD	0.434	0.629	0.943	1.198	0.701	1.761	0.770	1.529
sample variance	0.188	0.395	0.889	1.436	0.491	3.100	0.593	2.339
test run count	30	34	18	22	22	22	11	15
confidence level (95%)	0.363	0.483	1.170	1.258	0.735	1.848	1.913	2.434

TABLE 4. NO_x Emissions Comparisons (g/mi)

test cycle	WVU truck cycle				WVU 5-mi route cycle			
engine	Cummins 855		DDC series 60		Cummins 855		DDC series 60	
fuel	B35	D2	B35	D2	B35	D2	B35	D2
mean	16.647	15.735	16.597	16.957	18.844	18.361	16.631	17.986
median	18.362	16.191	16.884	17.459	19.539	19.219	16.773	18.281
SD	3.173	2.823	1.594	1.903	2.218	1.911	1.732	2.454
sample variance	10.071	7.967	2.541	3.622	4.920	3.652	2.999	6.022
test run count	30	34	18	22	22	22	11	15
confidence level (95%)	2.653	2.170	1.979	1.997	2.328	2.006	4.302	3.905

TABLE 5. HC Emissions Comparisons (g/mi)

test cycle	WVU truck cycle				WVU 5-mi route cycle			
engine	Cummins 855		DDC series 60		Cummins 855		DDC series 60	
fuel	B35	D2	B35	D2	B35	D2	B35	D2
mean	1.670	2.075	0.277	0.295	1.614	1.893	0.287	0.301
median	1.598	1.955	0.243	0.294	1.463	1.880	0.328	0.324
SD	0.300	0.446	0.083	0.043	0.392	0.396	0.099	0.063
sample variance	0.090	0.199	0.007	0.002	0.154	0.156	0.010	0.004
test run count	30	34	18	22	22	22	11	15
confidence level (95%)	0.251	0.343	0.103	0.046	0.412	0.415	0.247	0.100

TABLE 6. PM Emissions Comparisons (g/mi)

test cycle	WVU truck cycle				WVU 5-mi route cycle			
engine	Cummins 855		DDC series 60		Cummins 855		DDC series 60	
fuel	B35	D2	B35	D2	B35	D2	B35	D2
mean	0.564	0.783	0.320	0.406	0.612	0.859	0.413	0.566
median	0.560	0.757	0.359	0.398	0.595	0.842	0.380	0.578
SD	0.077	0.156	0.078	0.115	0.073	0.121	0.125	0.074
sample variance	0.006	0.024	0.006	0.013	0.005	0.015	0.016	0.006
test run count	30	34	18	22	22	22	11	15
confidence level (95%)	0.064	0.120	0.097	0.121	0.077	0.127	0.311	0.118

the same in the DDC engines. The newer model year DDC engines produced much lower HC emissions than the older Cummins engines on both B35 and no. 2 diesel fuel.

HC emissions generally result from unburned fuel. HC formation is attributed to fuel/air mixtures that are too lean to auto-ignite or to support a propagating flame or attributed to fuel/air mixtures that are too rich to auto-ignite. The longer carbon chains and the absence of aromatic content make cetane number of SME higher than that of no. 2 diesel. SME mixed with no. 2 diesel improves the overall cetane value, promoting complete combustion and reducing the level of unburned fuel.

Particulate Matter Emissions. Figure 11 shows that PM reduction gained with biodiesel blends is significant. We see that B35 normally reduces PM emissions by 25% in the same unaltered trucks. When comparing CO and PM emissions, we note that CO emissions correlate with PM emissions very well, which coincides with the test results of Choi et al. (*41*).

B35 PM reductions can be attributed to two factors. First, SME has no aromatic content and a much lower sulfur content than no. 2 diesel. Aromatic content is widely known to contribute to PM formation. Diluting the sulfur in no. 2 diesel lowers the amount of sulfate and its bonded water, reducing particulate emissions. B35 reduced aromatic content to less than 20%, from 30% in no. 2 diesel.

However, the more important factor is most likely biodiesel's oxygen content. Soot formation, caused by high temperature decomposition, mainly takes place in the fuel-rich zone at high temperatures and pressures, specifically within the core region of each fuel spray. If fuel is partially oxygenated, it could reduce locally fuel-rich regions and limit soot formation, thus reducing PM emissions. Because of its low volatility, any unburned ester will condense on the filter and be measured as soluble organic fraction (SOF). Some studies have shown that neat SME increased volatile organic diesel particulate matter but greatly reduced nonvolatile diesel particulate matter with a net decrease in total diesel particulate matter. Because of the high volatile particulate matter content in exhaust, benefits may be realized through using an oxidation catalyst.

Cycle Effects on Emissions. When comparing cycle effects on emissions levels (Figures 8−11), we see that emissions from the 5-mi route cycle emissions are generally higher than those from the 5-peak cycle, especially for CO and NO_x emissions. The 5-mi route requires that the truck be able to accelerate as fast as possible; the 5-peak cycle requires only moderate acceleration capabilities. The demand for more acceleration means that much more fuel is injected during the test, which causes higher transient or local high fuel/air ratio combustion in the engine cylinder, emitting more CO emissions. The higher power demand also increases the peak temperature and pressure in the cylinder, allowing NO_x to form.

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