STATUS AND EMISSION IMPLICATIONS OF BIODIESEL FUEL

FINAL REPORT

November 4, 2002

Submitted to:
Technology Advancement
South Coast Air Quality Management District

EF&EE
ENGINE, FUEL, AND EMISSIONS
ENGINEERING, INCORPORATED

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Final Report

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South Coast Air Quality Management District
21865 East Copley Drive
Diamond Bar, CA 91765

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ABSTRACT

"Biodiesel" is a mixture of alkyl esters of fatty acids of biological origin, which can be used as fuel for diesel engines. Common feedstocks for biodiesel production include soy oil, rapeseed (canola) oil, and recycled "yellow" grease from restaurants. Waste grease from restaurant grease traps and mustard seed oil as a co-product with "organic" insecticides are potential future sources. In general, use of 100% biodiesel in place of petroleum diesel increases NOx emissions slightly, while sharply reducing NMHC, CO, polynuclear aromatic hydrocarbons, and other toxic species. The solid carbon fraction of the PM emissions is greatly reduced, while the soluble organic fraction of the PM emissions increases. The effect on total PM mass depends on the operating conditions. Under typical heavy-duty truck duty cycles, the solid carbon effect dominates, and PM emissions are reduced by 20 to 60%. Under lightly-loaded duty cycles (such as a diesel pickup truck or SUV) the effect on SOF dominates, so that total PM emissions increase. The NOx increase with biodiesel may also be reversed at light loads. Biodiesel emissions also depend on the feedstock used: saturated fats give lower NOx and better PM reductions, but the product tends to congeal in cold weather. For practical biodiesel feedstocks, the estimated NOx increase in a heavy-duty truck cycle would be about 5%. Overall, the emission effects of 100% biodiesel compare unfavorably to natural gas as a substitute for diesel fuel.

EXECUTIVE SUMMARY

"Biodiesel" is the name that has been given to mixtures of alkyl esters of fatty acids of biological origin. These mixtures can be used as fuel for diesel engines, either alone ("neat") or in mixtures with diesel fuel derived from petroleum. Biodiesel is produced by reacting methanol, ethanol, or other alcohols with vegetable oils and/or animal fats in the presence of a catalyst. Commonly used feedstocks include soy oil, rapeseed (canola) oil, and recycled "yellow" grease from restaurant operations. Waste grease from restaurant grease traps and mustard seed oil as a co-product from "organic" insecticides are potential future sources.

Biodiesel has recently been proposed as an "alternative" fuel potentially meeting the requirements of the SCAQMD's 1190-series rules. To assess the emissions impacts of biodiesel, the SCAQMD requested Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) to research the issues and prepare this report on the status and emission implications of current biodiesel fuels.

Different oil and fat feedstocks contain different fatty acids in varying ratios, and this can affect the properties of the resulting biodiesel. The principal fatty acid properties affecting emissions are the degree of saturation and the molecular weight. Animal fats such as lard and tallow are high in saturated fats, while vegetable oils tend to be higher in unsaturated compounds. Yellow grease, being composed of partly hydrogenated vegetable oils, is intermediate in saturated fat content.

The effects of biodiesel use on pollutant emissions are complex, and depend substantially on the engine technology and operating conditions as well as the fatty acid composition of the biodiesel. These effects can be summarized as follows.

NOx. The use of neat biodiesel (B100) fuel tends to increase diesel NOx emissions under high-load engine operating conditions, but reduces NOx from direct-injection engines at light loads. The increase is greater for the types of high-pressure unit injection systems commonly used in heavy-heavy duty engines, and less for pump-line-nozzle or common-rail injection systems. NOx emissions from heavy-duty engines are lowest from biodiesel containing mostly saturated fatty acids, and increase as the degree of unsaturation increases. Thus, biodiesel made from tallow, lard, or soy oil hydrogenated to saturate the fatty acid compounds produces lower NOx than biodiesel made from yellow grease, which in turn produces lower NOx than biodiesel made from virgin soy or canola oils. Biodiesel made entirely from saturated fats can give NOx emissions comparable to those from CARB diesel. However, this fuel has poor cold-flow properties, making it impractical as a vehicle fuel, except possibly in summer. Practical biodiesel blends would likely result in about a 5% NOx increase compared to CARB diesel. Some work is under way on technologies to reduce or reverse the NOx impacts of biodiesel. Water-biodiesel emulsions appear promising in this regard.

Comment [n1]: You did not define what is practical. A blend of soybiodiesel at 20% with CARB diesel increases emissions by 2.8 % while a yellow grease B20 with CARB diesel increases NOx by about 2.5%.

Particulate matter. The use of neat biodiesel dramatically reduces the solid carbon (soot) portion of the particulate matter. This is attributable to the oxygen content of the fuel, which interferes with the chemical conditions needed to form soot. On the other hand, biodiesel use tends to *increase* the soluble organic fraction (SOF) portion of the diesel particulate matter – often increasing these emissions several-fold. At high loads, and in the heavy-duty transient test procedure, the reduction in solid carbon tends to dominate, so that biodiesel use reduces the total mass of PM emissions - typically by 20 to 60%. At light loads, and in light-duty vehicles, the effect of the SOF increase tends to dominate, so that the total mass of PM emissions increases with biodiesel use. Long-chain, saturated compounds appear to result in more SOF emissions compared to monounsaturated species and common vegetable oils.

PM emissions using B100 differ greatly in composition from those produced using petroleum diesel, and this could mean that the health effects might be different as well. Our present understanding of these health effects and their mechanism(s) is inadequate to predict what these differences might be. Research and testing are needed to assess the relative toxic effects of diesel and biodiesel PM.

Comment [n2]: You might be better off discussing the results of Tier II health Effects studies on live animal populations to support your speculation..

Carbon monoxide. The use of neat biodiesel tends to reduce the already-low CO emissions from diesel vehicles by around 40 to 60%. Given the low level of diesel CO emissions, however, these emission reductions are of little significance for air quality.

Non-methane hydrocarbons. The use of neat biodiesel tends to reduce non-methane HC, as measured by flame ionization detection (FID) by 40 to 90%. A substantial part of this reduction may be due to the condensation of biodiesel vapors in the sampling system, however.

Toxic air contaminants. The most important toxic air contaminant from diesel engines is diesel particulate matter, discussed above. Of the other toxic air contaminants of significance, biodiesel appears to reduce formaldehyde and acetaldehyde emissions. PAH emissions with neat biodiesel are greatly reduced compared to U.S. certification fuel or CARB diesel, but still higher than those produced by ultra-clean diesel fuels such as Fischer-Tropsch or Swedish EC1 diesel fuels.

Comparison to natural gas. Given the emission control technologies used in the mid to late 1990s, the use of natural gas engines in place of diesel engines reduced in-use PM emissions by 86 to 96%, compared to a reduction of about 20 to 60% for the use of B100. NOx emissions with natural gas engines were reduced by 32 to 73%, compared to an estimated 5% increase for engines running on B100. Emissions of NMHC and CO from diesel, biodiesel, and natural gas vehicles are all low in absolute terms. Compared to engines burning petroleum diesel, NMHC and CO emissions will tend to be lower for biodiesel and higher for natural gas engines.

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1. INTRODUCTION

"Biodiesel" is the name that has been given to mixtures of alkyl esters of fatty acids of biological origin. These mixtures can be used as fuel for diesel engines, either alone ("neat") or in mixtures with diesel fuel derived from petroleum. Biodiesel is produced by reacting methanol, ethanol, or other alcohols with vegetable oils and/or animal fats in the presence of a catalyst. Commonly used feedstocks include soy oil, rapeseed (canola) oil, and waste grease from restaurant operations.

Biodiesel has attracted attention and governmental support as an alternative, renewable, and potentially "cleaner" fuel for diesel engines. Since biodiesel is derived largely from renewable biological resources, its substitution for petroleum diesel reduces fossil fuel dependence and net emissions of carbon dioxide (CO_2) that may contribute to global climate change. Biodiesel use has also been promoted as reducing emissions of diesel particulate matter (PM), hydrocarbons, and carbon monoxide from diesel engines; although NOx emissions are acknowledged to increase somewhat. As this report will show, the actual emissions effects of biodiesel are complex, depending on both the engine technology and the duty cycle experienced by the engine.

Diesel PM has been identified as a toxic air contaminant by the State of California. To reduce emissions of diesel PM and associated toxic compounds, the South Coast Air Quality Management District (SCAQMD) has adopted its "1190" series rules. These rules require owners and operators of specified classes of vehicles to purchase alternative fuel vehicles rather than diesel vehicles when adding to or replacing vehicles in their fleets. At the time these rules were adopted, the principal alternative fuels used in these replacement vehicles were expected to be natural gas and alcohols. However, neat biodiesel meets the legal definition of an "alternative" fuel contained in these regulations, and has attracted attention as a possible compliance option for the affected fleets.

To aid it in evaluating the suitability of biodiesel as an alternative fuel under the 1190-series rules, the SCAQMD commissioned Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) to research the issues and prepare this report on the status and emission implications of current biodiesel fuels. EF&EE was asked to address the following specific issues: what biodiesel fuels are currently being marketed, their possible sales volume, their chemical properties, and their probable emissions and toxics impacts compared to CARB diesel and natural gas. To address these issues, EF&EE carried out a survey of the applicable technical literature, contacted biodiesel marketers, and reviewed data available on the Internet. This report presents the results of this evaluation.

2. BIODIESEL FEEDSTOCKS AND PRODUCTION

In chemical terms, biodiesel is made up of alkyl esters of various fatty acids of biological origin. It is produced from the reaction of alcohols with vegetable oil or animal fat through a process known as "transesterification". The alcohols most commonly used are methanol and ethanol, producing methyl and ethyl esters, respectively. Isopropyl and butyl alcohols have also been used for biodiesel production.

Comment [n3]: Laboratory experiements only.

Typical animal and vegetable fats are triglycerides, comprising three fatty acid chains linked to a single glyceryl group. The transesterification process works by separating these triglyceride compounds into their component fatty acids, which then react with the alcohol to produce the corresponding ester. The glyceryl group is released as glycerol (a by-product of the process).

Most biodiesel is produced using methanol, since methanol is less costly than ethanol. The transesterification reaction between methanol and a triglyceride to give biodiesel (methyl ester) is shown in the following equation.

$$GI(FA)_3 + 3\,MeOH \rightarrow 3\,MeFA + GI(OH)_3$$

where MeOH is methanol, $GI(FA)_3$ is triglyceride, $GI(OH)_3$ is glycerol, FA is fatty acid, and MeFA is methyl ester (biodiesel). The process of producing biodiesel includes cleaning up the oil to remove water and impurities, mixing the oil with an alkali catalyst such as potassium hydroxide or sodium hydroxide, dissolving in "rich" methanol (50% excess), settling and drawing off the glycerine/soap from the bottom, and washing with water or acid to further remove the small amount of soap from the ester and other impurities.

The primary potential feedstocks for biodiesel are vegetable oils such as soybean, rapeseed, sunflower, cottonseed, corn, peanut, palm, and safflower seed oils. The principal biodiesel feedstock used in the U.S. at present is soybean oil; the resulting product is commonly called soy methyl ester (SME) or methyl soyate. According to industry sources, this predominance is due to the low price of soybean oil, which is due in part to agricultural subsidy programs. Waste oil from restaurant operations, known as “yellow grease” is the other main feedstock used in U.S. biodiesel. The U.S. Department of Energy has also identified mustard seed oil (a potential byproduct from “organic” pesticides based on mustard seed) as a potential feedstock for large-scale production of biodiesel[1]. Rapeseed (Canola) oil is the principal feedstock for biodiesel production in Europe, producing rapeseed methyl ester or RME.

Different oil and fat feedstocks contain different fatty acids in varying ratios, and this can affect the properties of the resulting biodiesel. The principal fatty acid properties affecting emissions are the degree of saturation and the molecular weight. Saturated fatty acids contain no carbon-carbon double bonds, mono-unsaturated fatty acids contain a single such bond, and poly-unsaturated fatty acids contain two or more. According to information[2] developed by the National Renewable Energy Laboratory (NREL), NOx emissions in the heavy-duty transient test tend to increase with the degree of unsaturation of the fatty acids in biodiesel. These and other data showing the effects of biodiesel composition on emissions are analyzed in Section 4.5. The fatty acid composition of a number of potential biodiesel feedstocks is summarized in Table 1. For rapeseed and mustard seed oils, C20 and C22 fatty acids make up a substantial fraction of the composition. These are almost all mono-unsaturated species[3].

Table 1: Fatty acid composition of some biodiesel feedstocks

	Fatty Acids: C# carbons: # C=C bonds								
	≤C12	C14:0	C16:0	C16:1	C18:0	C18:1	C18:2	C18:3	≥C20
Soy	0	0	12	0	4	23	55	7	1
YG	0	1	23	1	10	50	15	0	0
Rape	0	0	4	0	1	10	15	10	60
Mustard	0	0	3	0	2	39	15	9	30
Sun	0	0	6	0	4	19	69	0	2
Lard	0	1	25	2	14	46	10	0	3
Tallow	0	2	27	2	25	40	2	0	2

Source: reference 2

According to the U.S. Department of Energy "Approximately 55% of the biodiesel industry can use any fat or oil feedstock, including recycled cooking grease. The other half of the industry is limited to vegetable oils, the least expensive of which is soy oil. The soy industry has been the driving force behind biodiesel commercialization because of excess production capacity, product surpluses, and declining prices. Similar issues apply to the recycled grease and animal fats industry, even though these feedstocks are less expensive compared to soy oils."

DOE further estimates that there is only enough soy oil and recycled grease feedstock available to supply about 1.9 billion gallons of biodiesel per year, even under policies designed to encourage biodiesel use. Approximately 7.7 pounds of oil or grease feedstock are required to produce one gallon of biodiesel. A study[4] done for the DOE in 1998 estimated the production of yellow grease from restaurant operations in urban areas of the U.S. at approximately 9 pounds per person per year. This is enough to produce about 350 million gallons of biodiesel. The remainder of DOE's estimated 1.9 billion gallons per year would presumably come from virgin oils, primarily soy oil. As discussed in detail in Section Four, the NOx emissions characteristics of biodiesel made from yellow grease are somewhat more favorable than those for biodiesel from soy oil, making this feedstock especially attractive for the South Coast.

According to the 1998 feedstock availability study for DOE, 16 pounds of waste grease per person per year is also available in grease traps of restaurants and sewage treatment. This waste grease is similar in fatty acid composition to yellow grease, but is not presently used for biodiesel production, as it is contaminated by sewage and involves greater processing difficulties than other feedstocks. Efforts are under way, however, to develop suitable processing methods to take advantage of the favorable economics of this feedstock source. Unlike recycled yellow grease (which has a market value of around 10-15 cents per pound), grease trap waste has negative value, as it must be disposed of in sewage treatment systems at a significant cost. Nationwide, grease trap waste could be used to produce about 620 million gallons of biodiesel per year if all of it were collected and processed.

Comment [n4]: The trap grease is included in the 1.9 bil gallons of biodiesel protential, mostly because it isn't hard to clean up (it is relatively easy to clean and not highly contaminated) but because esterification technology has never been optimized to deal with feedstocks with 50% Free Fatty acids or more. We have a demo ongoing with Ocean Air Environmental to show that trap greases can be made into biodiesel. There are a number of routes, and Ocean air is attempting the cheapest of these first.

Total diesel fuel sales in California are about 10.5 million gallons per day, of which the South Coast probably accounts for about 45%, or about 1,700 million gallons per year. On-highway diesel sales in the South Coast in 2005 are estimated at 1,000 million gallons per year in ARB's EMFAC 2000 inventory model[5]. The 15 million people in the South Coast region would produce enough yellow grease to make about 18 million gallons of biodiesel per year, and enough grease trap waste for another 31 million gallons. This would total 49 million gallons, or roughly 5% of annual diesel fuel consumption in 2005. If all of the potentially available yellow grease and grease trap waste in the U.S. were converted to biodiesel, this would produce 970 million gallons per year — slightly less than estimated on-highway diesel use in the SCAQMD. Thus, it would theoretically be possible to substitute biodiesel made from recycled or waste grease for nearly all of the present on-highway diesel fuel consumption in the SCAQMD, but to do so would consume essentially all of the potential U.S. production of this fuel, and would likely result in very high transportation costs.

DOE is also evaluating the possibility to use mustard seed oil for biodiesel production. This oil would be produced as a byproduct from the production of mustard seed cake, which is being considered as an organic pesticide. According to DOE estimates, this oil could be supplied for as little as $0.10 per pound, and in sufficient quantity to produce 10 million gallons of biodiesel per year. If this were to develop, biodiesel could conceivably be substituted for as much as 25% of total on-highway diesel fuel consumption. Mustard oil also has more favorable NOx emission properties than soy oil, although not as good as yellow grease.

Presently, biodiesel prices are in the range of $1 to $2 per gallon. In April, 2002, the market price of soy oil stood at $325 per metric ton – equal to 14.7 cents per pound, or $1.08 per gallon of biodiesel for the feedstock cost alone. Yellow grease has a market value somewhat less than that of soy oil. At ten cents per pound, the feedstock cost of biodiesel made from mustard oil could be as low as $0.73 per gallon. With sufficient economies of scale in production and transportation, this could make it possible to provide biodiesel based on mustard oil at prices competitive with current prices for petroleum diesel.

3. BIODIESEL AS A FUEL FOR DIESEL ENGINES

Both neat biodiesel and biodiesel blends have been used successfully in a number of demonstration programs. However, only a few vehicles have operated for any significant time on neat biodiesel, so the effects on engine life and relative frequency of engine problems are not well characterized as yet. Such studies *have* been done on biodiesel blends, and have shown no significant differences in engine maintenance costs.

In general, no engine, fuel system, or fuel injector modifications are necessary for diesel engines to operate on biodiesel. However, older engines with fuel lines and components made of natural rubber or butyl rubber need to have those fuel lines replaced before using neat biodiesel. B20 and B35 blends can usually be used without trouble even with rubber fuel lines.

Biodiesel contains less energy per unit volume than petroleum diesel. The BTU contents of some diesel and biodiesel formulations are compared in Table 2.

Table 2: Energy content of some diesel and biodiesel fuels

	LHV BTU/gal	**% Diff to CARB**
EPA Cert Fuel	130,650	2.2%
Typical CARB Diesel	127,854	0.0%
ECD-1 Ultra-low sulfur	127,593	-0.2%
Biodiesel - Soy	115,832	-9.4%
Biodiesel - Lard	115,506	-9.7%

Studies of biodiesel combustion have shown that the peak cylinder pressure and peak rate of pressure rise are higher for biodiesel powered engines as compared to diesel-powered engines. This suggests that the engine components for biodiesel-powered engines are carrying higher stress than in engines using petroleum diesel, and this could affect their long-term durability and reliability. Biodiesel fuel is somewhat more viscous, on average, than petroleum diesel, and this will mean that mechanical elements in fuel injection systems undergo higher stress. That could also affect long-term reliability and durability. On the other hand, biodiesel has excellent lubricity compared to diesel fuel, especially ultra-low sulfur diesel.

Most major engine manufacturers have published statements on biodiesel fuel, and these are available on-line[6]. In general, these statements indicate that use of biodiesel, whether in blends or as neat fuel, will not affect the manufacturer's warranty on the engine, but they do state that any engine problems resulting from biodiesel use would not be covered under that warranty. Specific potential problems and issues raised in these statements include the following:

- possible need to shorten oil change intervals, due to the potential for biodiesel to dilute the lubricating oil;

- potential incompatibilities between biodiesel and common elastomers used in seals and hoses;
- potential fuel gelling and filter plugging in low-temperature operation, since biodiesel has relatively high cloud and pour point temperatures;
- problems of oxidation stability and potential microbial growth (consequences of biodiesel's biodegradable nature); and
- potential corrosion problems with some metals, and plugging of fuel filters due to deposits loosened by the solvent action of the biodiesel.

Comment [n5]: NOT due to its biological nature, as diesel fuel exhibits similar problems and there are many additive packages manufactured for oxidative stability and microbial growth for DIESEL FUEL. It may be more accurate to say that problems associated with these issues occur more frequently with biodiesel. The oxidative stability is not due to its biological origin, but rather to its unsaturated nature. Its microbial growth potential is probably due to the fact that biodiesel is less toxic to micro organisms than diesel fuel.

4. EFFECTS OF BIODIESEL ON ENGINE EMISSIONS

Reduction in pollutant emissions is one of the principal advantages claimed for biodiesel use. The pollutant emissions of primary concern are the "criteria" pollutants, which include oxides of nitrogen (NOx), diesel particulate matter (PM), carbon monoxide (CO), sulfur dioxide (SO_2), and volatile organic compounds (VOC). In motor vehicle emission measurements, volatile organic compounds are generally represented by non-methane hydrocarbons (NMHC), but emissions of other compounds such as carbonyls (aldehydes and ketones) also contribute significantly to VOC.

Comment [n6]: Weird grammar.

Emissions of toxic air contaminants from diesel and alternative fuel engines are also of great concern to SCAQMD. Diesel PM has been identified as a toxic air contaminant by the California Air Resources Board, and extensive test data show that this PM is the principal source of cancer risk due to diesel emissions. Other toxic air contaminants of concern include polynuclear aromatic compounds (PAH) and their nitro-derivatives (NPAH), formaldehyde, acetaldehyde, 1,3 butadiene, and benzene. The mutagenic activity of particulate extracts and vapor-phase compounds is also of interest, as a possible indicator of the carcinogenic properties of pollutant mixtures. Finally, net emissions of greenhouse gases such as CO_2 and methane are of increasing interest from the standpoint of actions to mitigate potential global climate change.

Marketing literature and published summaries of biodiesel emissions effects[7] indicate that biodiesel use reduces PM, CO, NMHC, and aldehyde emissions, while tending to increase emissions of NOx. Our review of the published literature indicates that the situation is more complicated than this, however. The magnitude, and even the sign of biodiesel effects on pollutant emissions depend greatly on the test cycle used, and especially on the degree of engine loading.

Most published data on biodiesel emissions effects in the U.S. are based on the U.S. heavy-duty transient test procedure. Emission measurements based on this procedure are the basis for the published summaries mentioned above, and generally agree with the emission patterns described in those summaries. However, other emission measurements carried out using U.S. and European test procedures for light-duty vehicles show an opposite pattern - with biodiesel tending to increase PM emissions while reducing emissions of NOx. In addition, some limited data are available showing biodiesel effects on heavy-duty vehicle emissions under various on-road driving cycles. These data also show that the emissions effects of biodiesel depend on the driving cycle. Finally, some limited data are available showing the effects of biodiesel blends in a large two-stroke engine of the type used in locomotives. Contrary to what would be expected from the truck engine data, the large engine data show a reduction in NOx and increase in PM emissions with biodiesel use.

4.1 HEAVY-DUTY TRANSIENT TEST DATA

4.1.1 Criteria pollutants

A study[8] by NREL for the U.S. Departments of Energy and Agriculture estimated the life-cycle emissions from buses fueled by conventional diesel, B20, and B100 fuels. This 1998 study analyzed results from four test programs. Three of these test programs used Detroit Diesel Series 60 engines, while one used a Cummins L10. Based on the results of heavy-duty transient tests in these four-stroke, heavy-heavy duty engines, the NREL study developed correlations between biodiesel content in the fuel and changes in emissions compared to EPA 2D certification fuel. These correlations are shown in Figure 1.

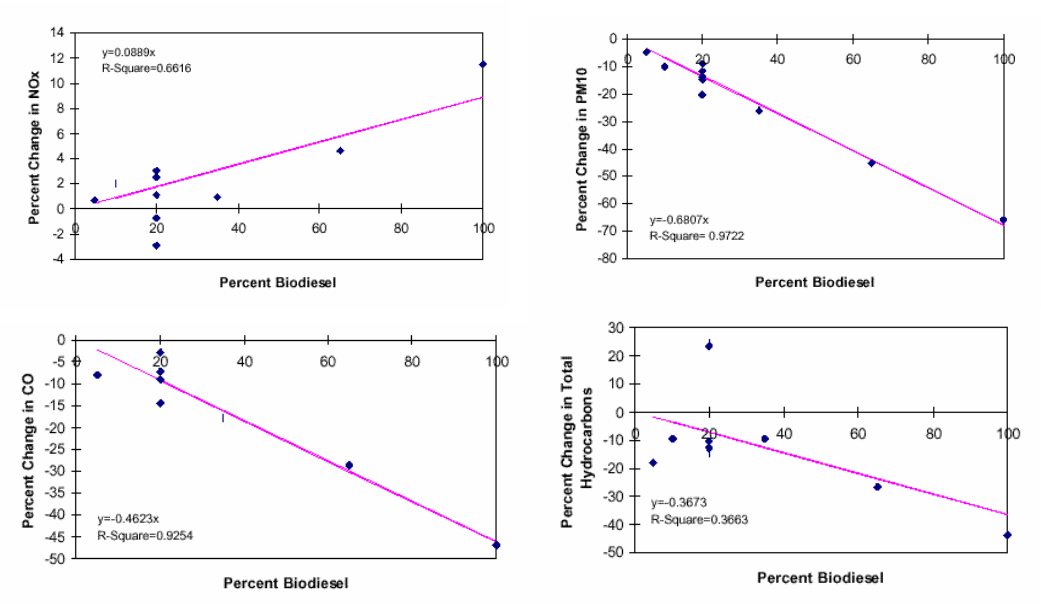

Figure 1: NREL correlation of emissions vs. fuel biodiesel content for four-stroke engines in urban buses (source: ref 8)

Subsequent to the NREL report, very extensive and detailed emission tests[9] were carried out by Southwest Research as part of the requirements for registration of biodiesel as a new fuel under Section 211(b) of the Clean Air Act Amendments of 1990. This test program covered three engines: a 1997 Cummins N14 engine typically used in line-haul trucks, a 1997 Detroit Diesel Series 50 urban bus engine, and a 1997 Cummins B5.9 medium-duty engine of the type used in school buses, medium-duty trucks, and Dodge pickups. The Cummins N14 and DDC Series 50 engines were equipped with high-pressure electronic unit injector systems, while the Cummins B5.9 was equipped with a mechanical pump-line-nozzle injection system. The Series 50 and B5.9 engines had been certified with oxidation catalytic converters for additional PM control, and were tested both with and without these catalysts in place.

The emission test results for the N14 and Series 50 engines must be treated with some caution, as most electronic engines of this vintage made extensive use of software “defeat devices” that were active under most on-road operating conditions, but not in the heavy-duty transient test procedure. These defeat devices advanced the fuel injection timing, improving fuel economy by about 10% at the cost of roughly doubling NOx emissions. Because of the presence of these defeat devices, the transient test data reported here may not fully represent the effects of biodiesel fuel in actual operation on the road.

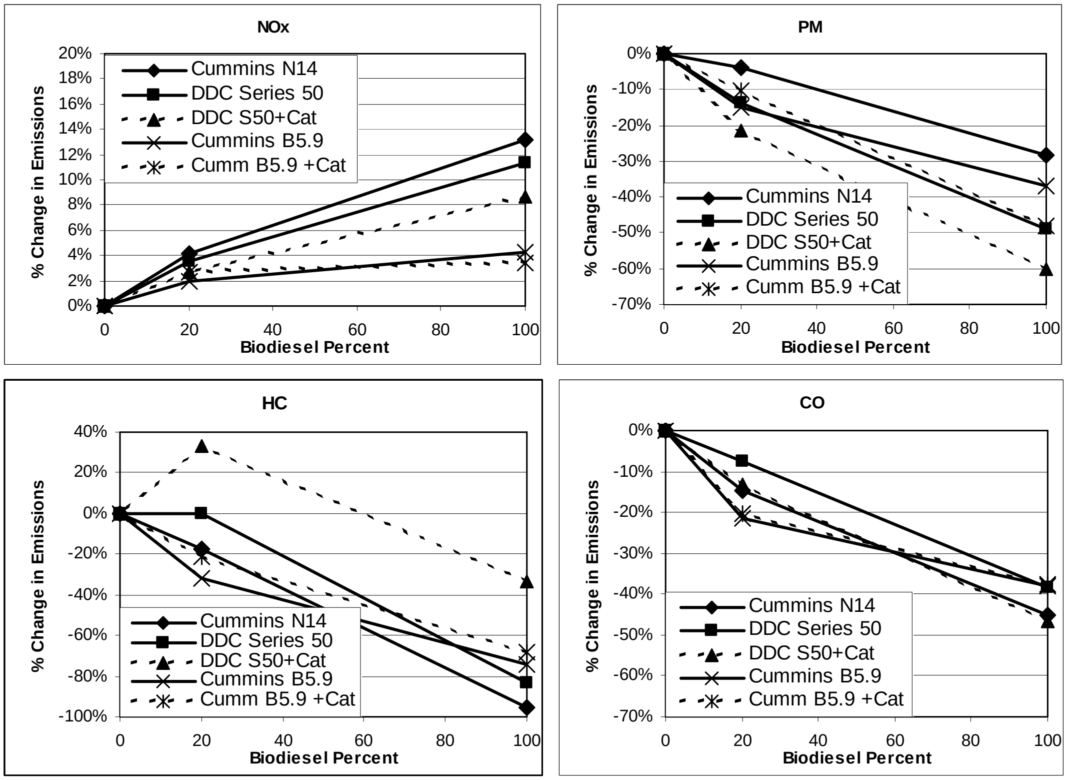

Figure 2: Effect of biodiesel on heavy-duty transient cycle emissions (source: EF&EE analysis of data from reference 9)

The effects of biodiesel on criteria pollutant emissions in the SWRI test program are summarized in Figure 2. These results are generally consistent with those in the earlier NREL study. NOx emissions from the two larger engines increased by 8-12% when running on neat biodiesel, while PM emissions were reduced from 30 to 50%. It is notable, however, that the Cummins B5.9 medium duty engine showed a much smaller increase in NOx emissions, while the PM emissions reduction was comparable to that from the other engines. This engine was equipped with a pump-line-nozzle fuel injection system, as opposed to the unit injectors used in the Cummins N14 and DDC Series 50 engines, and the differences in injection hardware may account for the difference in biodiesel effects.

4.1.2 Unregulated emissions and toxic impacts

The SWRI 211(b) study also examined the effects of biodiesel usage on emissions of aldehydes, PAH, NPAH, and the ozone-forming potential of VOC emissions.[10] Except for the anomalous results from the Series 50 engine with catalytic converter, these data show modest reductions in emissions of formaldehyde, acetaldehyde, and total aldehydes with increasing biodiesel use. PAH emissions were reduced by 50 to 70 percent, and nitro-PAH emissions were reduced by 70 to 90 percent.

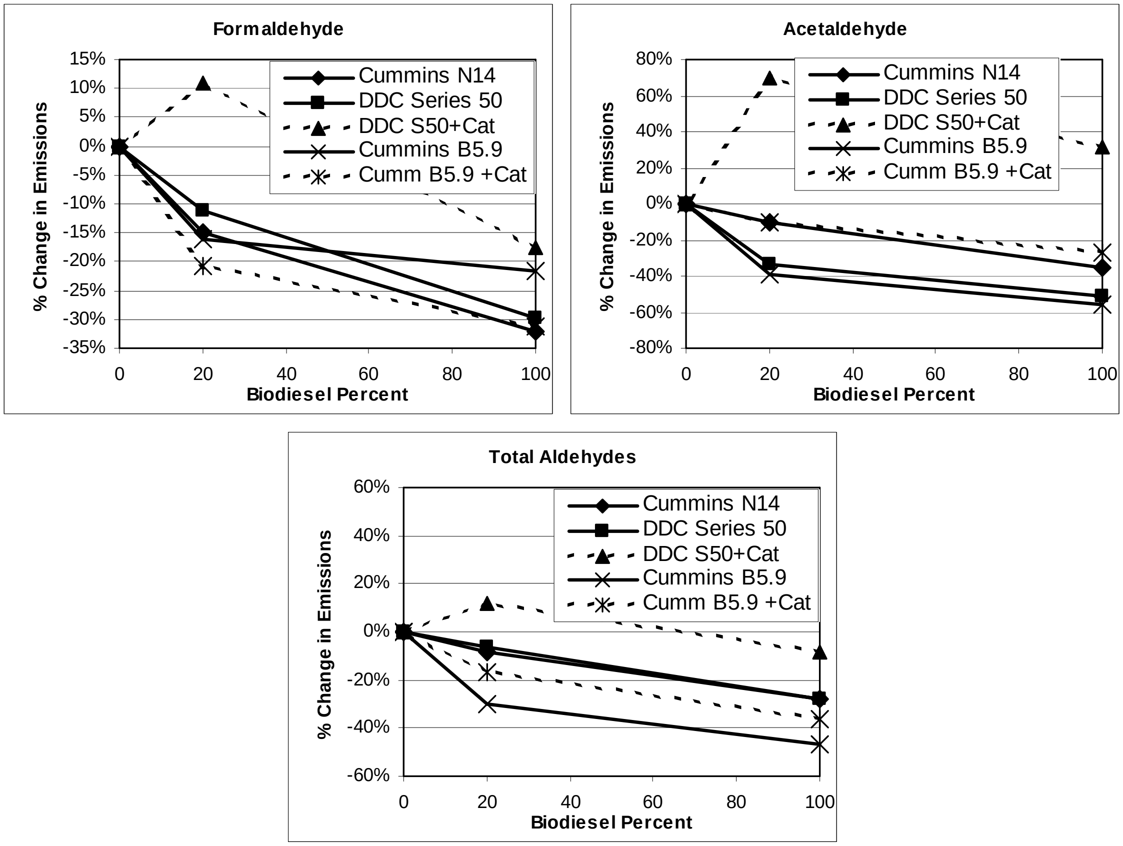

Figure 3: Effect of biodiesel on heavy-duty transient cycle emissions of formaldehyde, acetaldehyde, and total aldehydes (source: EF&EE analysis of data from reference 10)

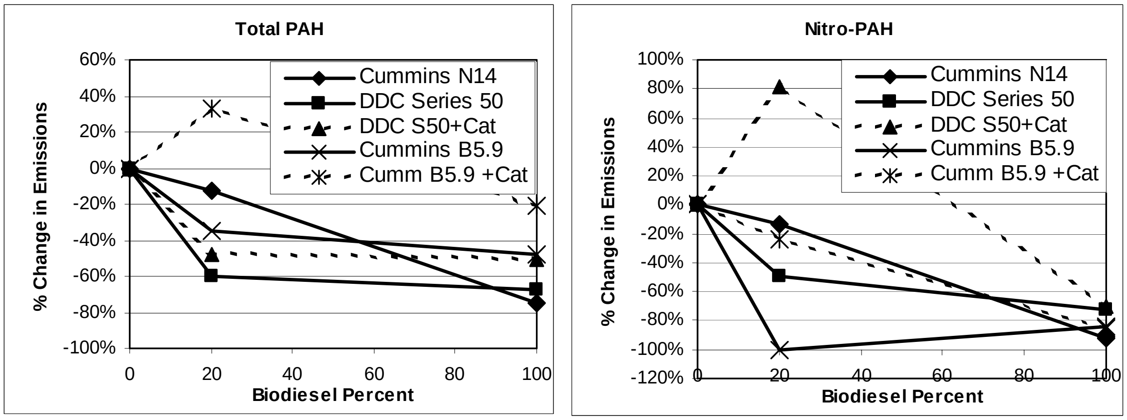

Figure 4: Effect of biodiesel on heavy-duty transient cycle emissions of PAH and nitro-PAH (source: EF&EE analysis of data from reference 10)

4.2 DATA FOR OTHER HEAVY-DUTY EMISSION TEST CYCLES

The U.S. heavy-duty transient test procedure is no longer completely representative of typical in-use operating patterns for heavy-duty diesel vehicles. For this reason, it is of interest to examine the effects of biodiesel use in other driving cycles. One significant test program of this type was undertaken by West Virginia University (WVU), using its portable heavy-duty chassis emissions test facility. The WVU study[11] compared emissions from nine line-haul tractor-trailer trucks using commercial no. 2 diesel fuel and a B35 blend. Six of the trucks were equipped with 1987 to 1992 Cummins N14 engines having mechanical unit injectors, and three trucks had 1993 or 1994 Detroit Diesel Series 60 engines with electronic unit injectors. The biodiesel component of the B35 blend was soy methyl ester.

The WVU study measured emissions from the trucks in two similar driving cycles: the WVU 5-peak cycle, and the WVU 5-mile cycle. Both cycles consist of successive accelerations to 20, 25, 30, 35, and 40 MPH, with a period of cruise at each speed followed by deceleration to back to zero. The cycles differ in that the 5-peak cycle requires only moderate acceleration rates, while in the five-mile cycle the truck accelerates as rapidly as possible.

The results of the WVU study showed mean NOx emissions from the Cummins engines to be 3 to 6% higher with B35 than with no. 2 diesel fuel, which is roughly what would be expected from the transient test data discussed above. However, NOx emissions from the Detroit Diesel engines were 2 to 7% lower with B35 than with no. 2 diesel. PM emissions from the Cummins engines were 21 to 28% lower with B35, while they were 27 to 29% lower for the DDC engines. HC emissions were reduced slightly with B35, while CO emissions were reduced by about 20%.

Two more test programs involving chassis-dynamometer emission measurements were carried out by the Swedish Motor Test Center (MTC). One program[12] compared emissions from a

Scania bus using Swedish Environmental Class (EC) 1 and 2 diesel fuels, as well as 100% biodiesel and a blend of 30% biodiesel with EC2 fuel. The biodiesel used was rapeseed methyl ester (RME). EC1 fuel is an extremely low-emission diesel somewhat comparable to Fischer-Tropsch synthetic fuel. It contained 92% paraffins and less than 5% aromatic hydrocarbons, with virtually zero poly-aromatics and 2 ppm of sulfur. The EC2 fuel tested was somewhat comparable to an alternative CARB diesel formulation, with about 16% aromatics and 5 ppm of sulfur. Several other alternative fuels and blends were also tested, but will not be addressed here. Emissions including criteria pollutants, aldehydes, and PAH were measured in the Braunschweig Bus Cycle, which simulates typical central-city urban bus operation. HC, CO, and NOx emissions were also measured in a chassis version of the European 13-mode steady-state test.

The second MTC test program[13] compared emissions from a Volvo bus using Swedish EC1 diesel fuel and 100% RME. The emission test cycle used was a chassis version of the European Transient Cycle (ETC). This includes a mix of urban, arterial, and expressway driving. Criteria emissions (but not aldehydes or PAH) were also measured over the chassis version of the 13-mode steady-state test.

The results of these two Swedish test programs are summarized in Figure 5. Percentage reductions are calculated with respect to EC2 diesel for the Scania bus, and with respect to EC1 diesel for the Volvo (criteria pollutant emissions from the Scania bus on EC1 were similar to those on EC2). As Figure 5 shows, NOx emissions increased substantially with use of biodiesel in place of EC-diesel for both the transient and steady-state tests. PM emissions were reduced substantially in the heavily loaded, steady-state 13-mode test, but not in the Braunschweig bus cycle or the ETC. Emissions of HC, CO, formaldehyde, and acetaldehyde were reduced significantly with biodiesel use.

The MTC test data showed a 60% reduction in PAH emissions from the Scania bus with B100 compared to EC2 diesel, which is comparable to the results of the Southwest Reseaarch 211(b) study discussed earlier. However, B100 PAH emissions from the Volvo bus were 60% higher than those measured using EC1 diesel. Mutagenic emissions, as measured by the Ames Test, were substantially lower for B100 than for EC2 diesel, but slightly higher than mutagenic emissions using EC1.

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The data on particulate composition from the MTC tests are important to understanding the effects of biodiesel on particulate emissions. These data are summarized in Figure 6. In chassis dynamometer tests on the Scania bus using the Braunschweig bus cycle, the solid carbon (soot) portion of the particulate matter accounted for 57% of the total mass, while oil-derived hydrocarbons were 16.8% and fuel-derived hydrocarbons were only 7.6%. For the 100% RME fuel, solid carbon made up only 14.7% of the particulate matter, while fuel-derived hydrocarbons were 68.1% and oil-derived hydrocarbons were essentially unchanged at 18.9%. Thus, the effect of biodiesel was to decrease drastically the solid carbon content of the PM, but to offset this reduction with a large increase in fuel-derived soluble organic matter. The data on the Volvo bus show the same pattern of a sharp reduction in solid carbon content and a sharp increase in fuel-derived SOF.

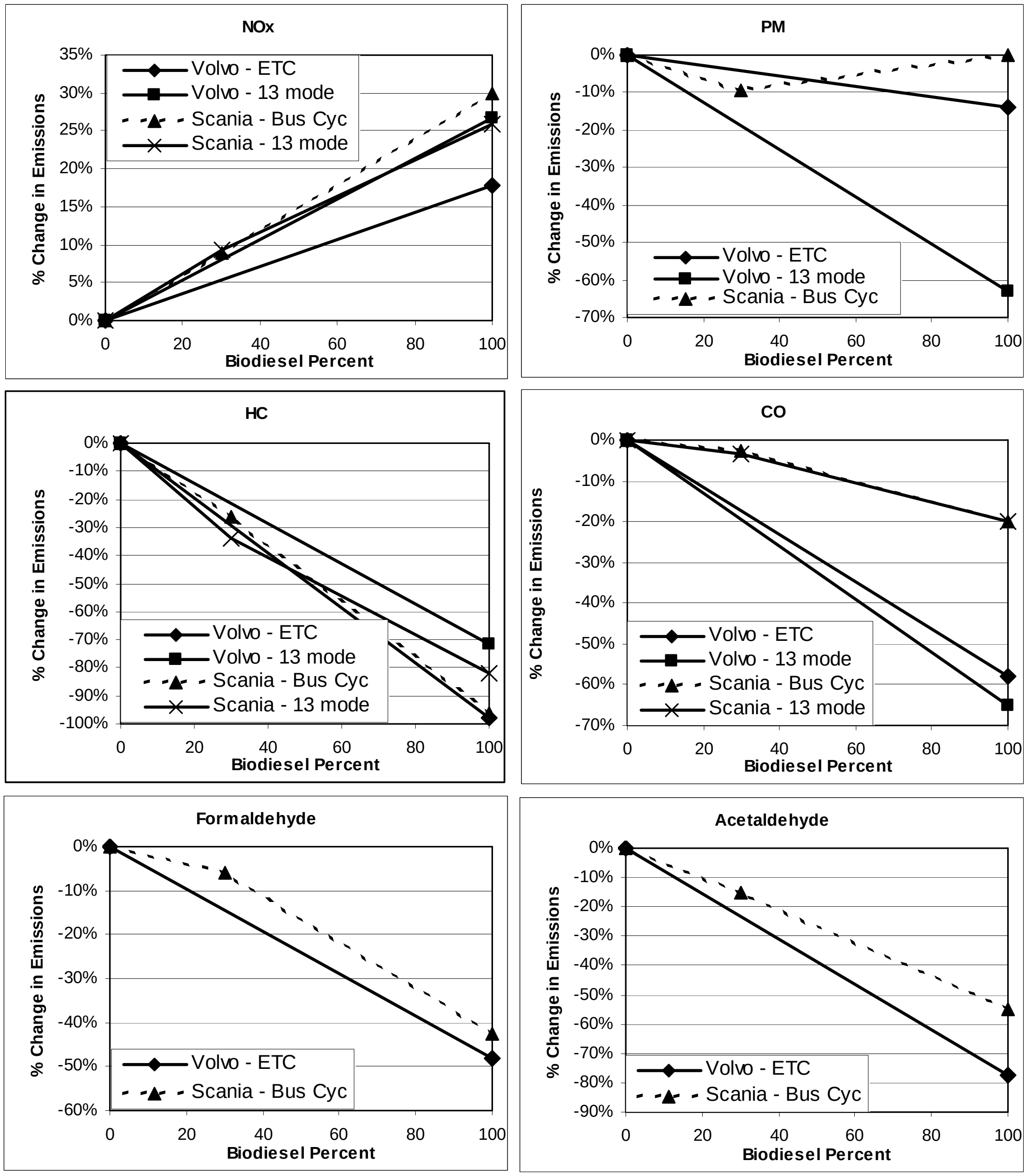


Figure 5: Effect of rapeseed methyl ester (RME) biodiesel on bus exhaust emissions in two Swedish test programs.

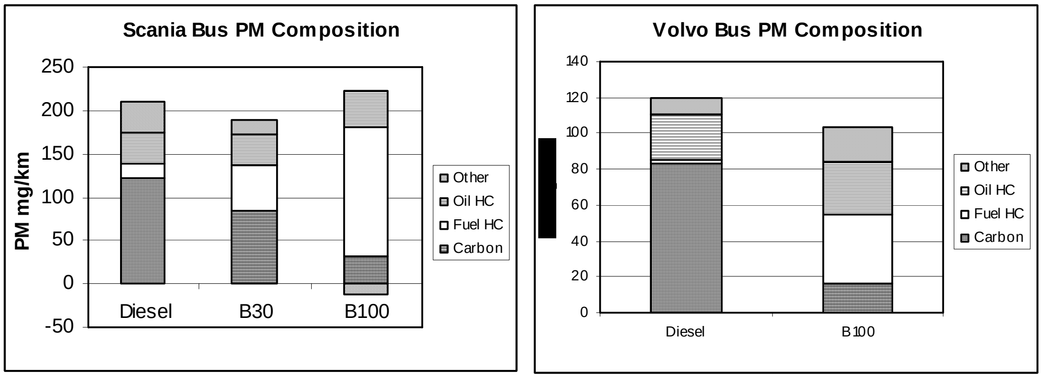


Figure 6: PM composition data from MTC bus tests

The marked difference in PM composition between biodiesel and petroleum diesel could mean that the health impacts of the PM would be different as well. Our present understanding of these health effects and their mechanism(s) is inadequate to predict what these differences might be. Research and testing are needed to assess the relative toxic effects of diesel and biodiesel PM.

4.3 DATA FROM LIGHT-DUTY VEHICLE TESTING

Published emissions data for biodiesel use in light-duty and medium-duty vehicles show a substantially different pattern from the heavy-duty engine and vehicle data discussed earlier. While HC and CO are still reduced, NOx emissions consistently decrease with the use of biodiesel, while PM emissions increase. This is the reverse of the pattern seen in heavy-duty vehicles. For example, researchers at the University of Idaho report[14,15] the results of a series of emission tests performed on two medium-duty Dodge pickup trucks equipped with Cummins B5.9 liter engines. Biodiesel effects shown in these tests are summarized in Figure 7.

The University of Idaho tests were carried out at the Los Angeles MTA heavy-duty chassis dynamometer test facility, using the UDDS test cycle. Although this test cycle is intended to be a chassis version of the heavy-duty transient test, the relatively high power-to-weight ratio of the pickup truck resulted in a much lower average engine load during these tests than during the heavy duty FTP. The test vehicles were model year 1994 and 1995 Dodge pickups. The 1994 vehicle was tested at approximately 5,000 miles, and was apparently equipped with a MY 1993 engine (judging from the emission results and the absence of a catalytic converter). The 1995 vehicle was tested in 1995 at low mileage, and again in 1998 having accumulated more than 86,000 miles. Both times, it was tested both with and without the oxidation catalytic converter installed. As Figure 7 shows, PM emissions from the diesel pickup truck increased by 20 to 40% using neat biodiesel compared to diesel, while NOx emissions were reduced by 10 to 12%.

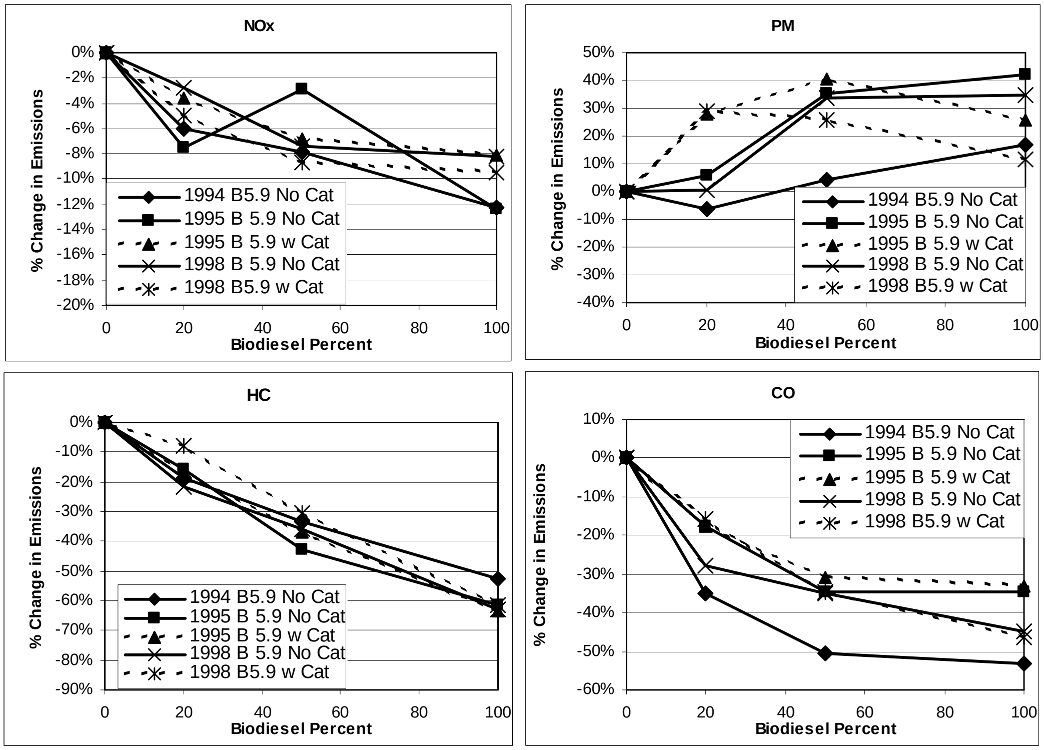


Figure 7: Effect of REE biodiesel on pickup truck exhaust emissions in the University of Idaho program (source: EF&EE analysis of data from references 14 and 15)

Many light-duty diesel vehicles use indirect-injection (IDI) engines. The emissions effects of biodiesel in these engines are be different from those in direct-injection engines. A Danish study[16] tested both RME and a commercial "biodiesel" in a van with a 2.4 liter IDI engine. A number of driving cycles were used, ranging from urban stop-and-go to expressway driving. NOx emissions increased significantly in urban stop-and-go driving, but not in expressway or arterial driving cycles. PM emissions did not show a consistent pattern, being sometimes higher and sometimes lower than with petroleum diesel. Analyses of the PM composition showed that the solid portion of the PM was decreased using biodiesel, while particulate SOF emissions generally increased. The SOF accounted for 50 to 75% of the PM using petroleum diesel, but 80 to 90% when using biodiesel. HC emissions were higher with biodiesel than with petroleum diesel, while CO emission factors were similar between the two fuels.

Another test of biodiesel in an IDI engine was carried out by the Swedish Motor Test Center[17]. The test vehicle was a 1.9 liter turbocharged VW Golf equipped with an oxidation catalyst, and tested over the new European driving cycle (NEDC). NOx emissions in these tests were about 20% higher with RME than with European reference diesel; while PM emissions were about 35% lower. The reduction in PM emissions came during the two urban driving segments of the NEDC; emissions during the extra-urban (expressway) portion were nearly identical. CO and HC emissions were nearly the same between the two fuels over the NEDC.

Future medium-duty and light-duty engines will increasingly use common-rail fuel injection systems. Biodiesel effects in these engines may also be different. A 1999 study[18] used a common-rail injection system in a single-cylinder engine to examine biodiesel effects. NOx emissions, CO, and smoke were all found to decrease using biodiesel, while PM and HC emissions were not measured. The reduction in NOx was attributed to an increase in the duration of the combustion process. This, in turn, was attributed to higher mean droplet diameter in the biodiesel spray, along with slower droplet evaporation due to the higher boiling point of biodiesel compared to petroleum diesel.

Another study at Southwest Research[19] with a common-rail engine compared a B20 blend with low-sulfur diesel to the low-sulfur diesel base fuel, as well as several other fuels. The test cycle was a relatively highly loaded 13-mode, steady-state cycle. The test engine was an advanced common-rail DI engine being considered as a hybrid vehicle prime mover. The B20 blend gave 3% higher NOx but 15% lower PM than the low-sulfur diesel base fuel. HC emissions increased by 40%, while CO was nearly the same. A review of the mode-by-mode data shows that NOx emissions were increased and PM decreased substantially in the high-torque operating modes of the cycle, while the reverse was true under light-load conditions.

4.4 DATA FOR LARGE DIESEL ENGINES

Published data[20] are available for one set of emissions tests in a large diesel engine used for electric generation. The test engine was a GM Electromotive Division 20-645E4B two-stroke engine rated at 3,600 horsepower. Similar engines are also common in locomotives, offshore oil production, and offshore oil supply boats.

Contrary to the trend with truck engines, emission tests using 0, 5, 10, and 20% biodiesel blends in this large medium-speed engine did not show any clear trends in either NOx or PM emissions. Particulate emissions were relatively high, ranging from about 0.3 to more than 1 g/BHP-hr, and there appeared to be a weak trend toward higher PM and lower NOx emissions with increasing biodiesel concentration at higher loads. NOx emissions with B20 were about 7% lower than with straight diesel fuel at high loads, while PM emissions were 15 to 30% lower. These trends were not visible at low load, and are opposite to the general trend in vehicular engines. PAH emissions were reduced by about 50% with all of the biodiesel blends compared to straight diesel fuel. THC emissions also decreased with increasing biodiesel concentration, while CO emission were little affected, and formaldehyde emissions increased markedly with increasing biodiesel concentration.

4.5 EFFECTS OF BIODIESEL COMPOSITION

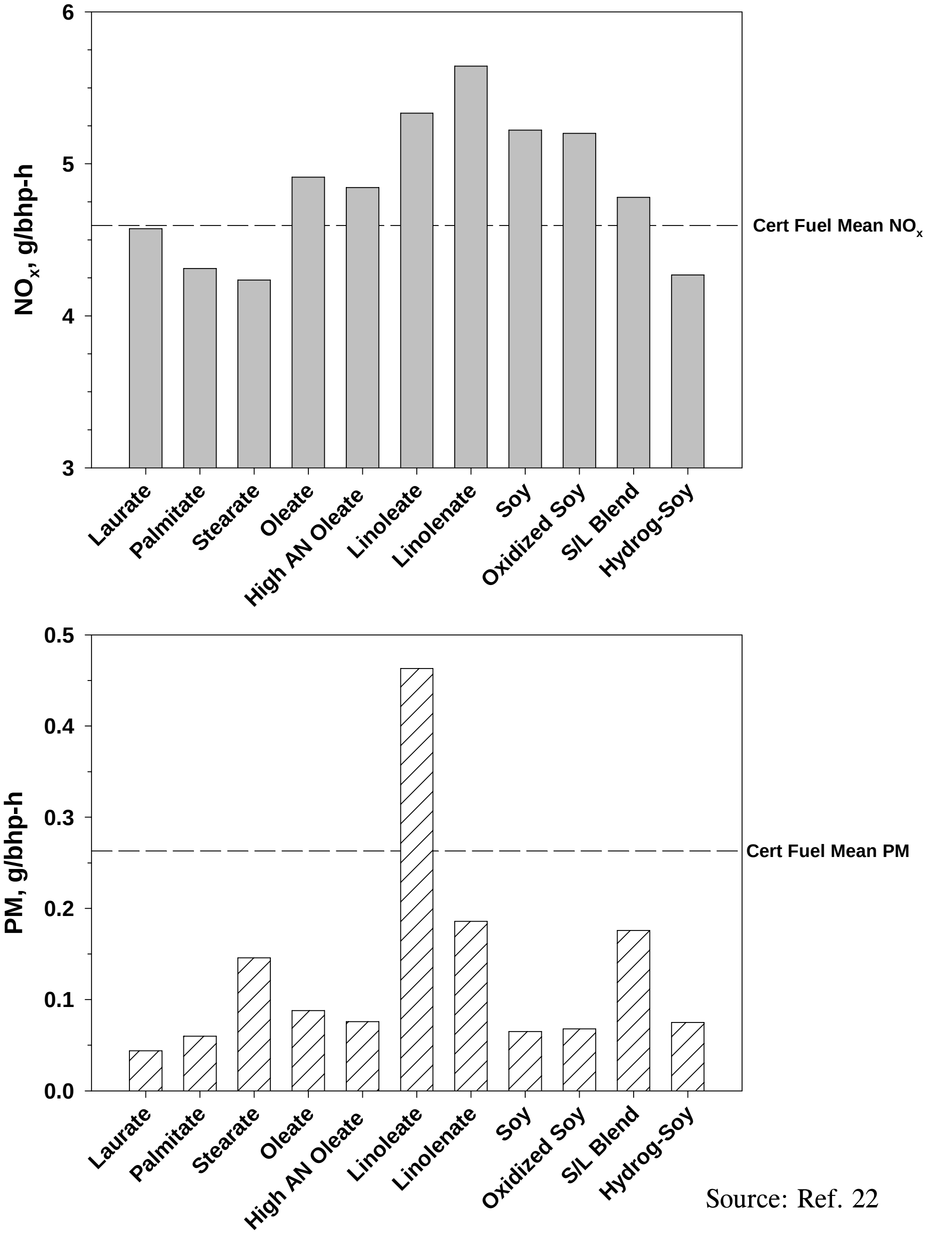
As discussed in Section Two, biodiesel can be produced by the reaction of any of several alcohols with any of a number of types of fats and oils. Most biodiesel emissions data were obtained with methyl esters of soy or rapeseed oil (SME or RME, respectively). However, some data are available comparing emissions results using biodiesel of different formulations. Schmidt and Van Gerpen[21] compared emissions using 20% and 50% blends of seven different biodiesel formulations in a turbocharged, direct-injected tractor engine. The engine was operated near the peak torque point, at 1400 RPM and 100% load. These conditions were selected to maximize PM production, and would have tended to maximize solid carbon PM rather than the soluble organic fraction. Under these conditions, methyl and isopropyl palmitate (a 16-carbon saturate) gave lower PM emissions than methyl and isopropyl stearate (an 18-carbon saturate), or methyl oleate (an 18-carbon mono-unsaturate). The reduction in PM was due to reductions in both solid carbon and the SOF. For a given number of carbon atoms, unsaturated fats were found to give lower SOF emissions than saturates, while solid carbon emissions were similar. The isopropyl esters of stearic and palmitic acids gave higher SOF emissions than the methyl esters, while the solid carbon emissions were similar. NOx emissions were lowest for methyl palmitate and isopropyl stearate, but otherwise did not show a clear trend.

A study done at CIFER[22] also examined the effects of biodiesel source and composition on emissions. This study tested a wide variety of biodiesel compositions, including pure fatty acids as well as commercial blends. Emissions from a 1991 DDC Series 60 engine were measured in the federal heavy-duty transient test procedure. The results for different methyl esters are summarized in Figure 8, while those for ethyl esters are summarized in Figure 9. As these figures show, saturated C12 (lauric), C16 (palmitic) and C18 (stearic and hydrotreated soy) fatty acids gave the lowest NOx emissions - lower even than certification diesel fuel. There is a trend toward increasing NOx with increasing unsaturation of the fatty acids.

Among the saturated fatty acids, the CIFER data show NOx decreasing with increasing carbon chain length from lauric to stearic acids, while PM emissions show the reverse trend. Methyl laurate gave the lowest PM emissions of any of the fuels, while methyl stearate (C18:0) gave higher PM than methyl oleate (C18:1) or methyl soyate. Based on the results of Schmidt and van Gerpen, this increase was likely due to grater condensation of SOF from the methyl stearate. Methyl linoleate (C18:2) and linolenate (C18:3) fuels gave higher PM emissions than methyl stearate - in this case, the effect may have been due to a reduction in combustion quality with these low-cetane fuels.

The results of the CIFER study for different commercially available biodiesel feedstocks are shown in Figure 10. These results are consistent with those for the pure fatty acids. Biodiesel made from tallow and lard, which are high in saturated C16 and C18 fatty acids, gave NOx comparable to that for certification diesel, while the more unsaturated feedstocks such as soy and canola gave higher NOx. Biodiesel made from recycled grease gave intermediate results. PM emissions were similar for all of the biodiesel feedstocks, but slightly lower for the grease and tallow-derived fuels

In a follow-on study[23], CIFER compared emissions produced by soy-derived and yellow grease-derived biodiesel with those produced by EPA certification diesel fuel, diesel fuel meeting CARB specifications, and a Fischer-Tropsch diesel fuel. Those results are summarized in Figure 11.



Source: Ref. 22

Figure 8: NOx and PM effects of different methyl ester fuels

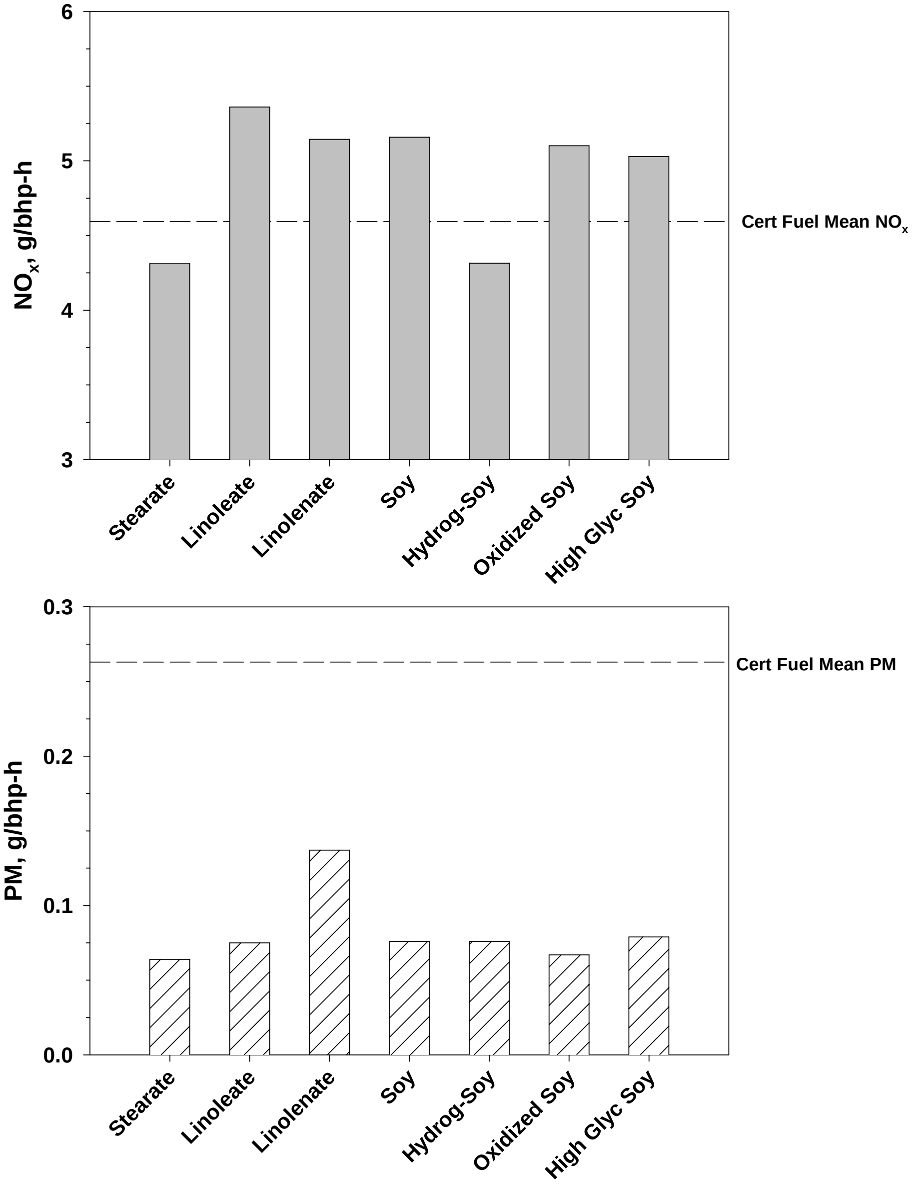
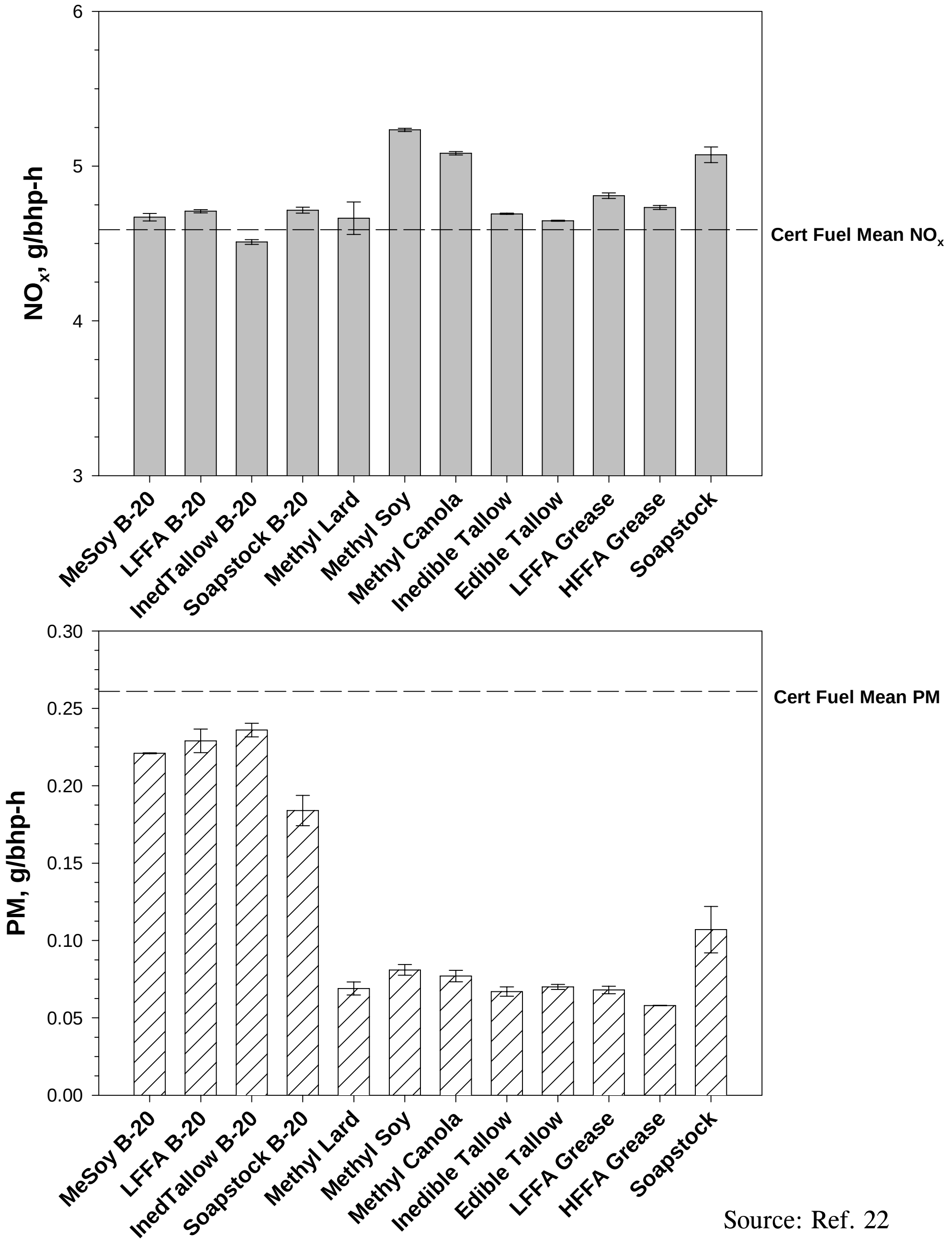


Figure 9: NOx and PM effects of different ethyl ester fuels



Source: Ref. 22

Figure 10: NOx and PM effects of biodiesel made from different feedstocks

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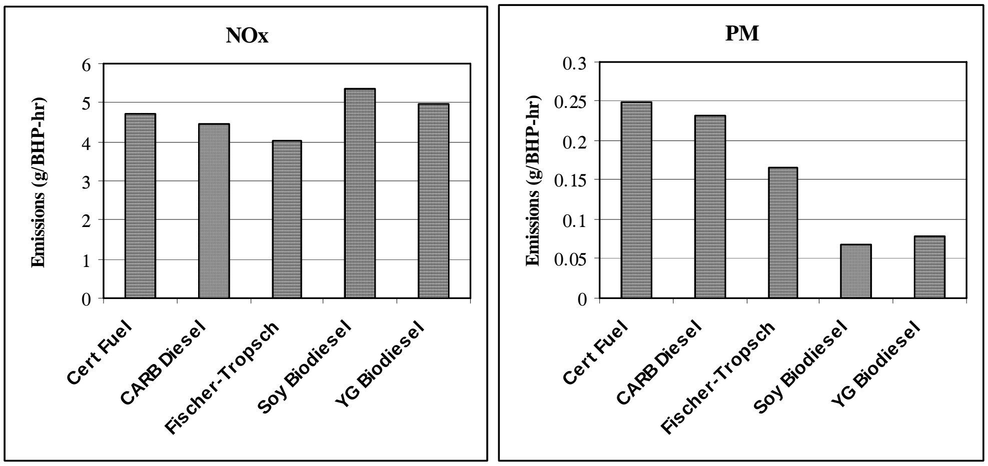

Figure 11: Emissions with two biodiesel formulations compared to certification fuel, CARB diesel, and Fischer-Tropsch diesel (EF&EE analysis of data from ref 23).

4.6 GREENHOUSE GAS EMISSIONS

Substituting biodiesel for conventional diesel fuel reduces net emissions of the greenhouse gases carbon dioxide and methane. Most of the carbon in biodiesel is contained in the fatty acid component. The ultimate source of this carbon is from atmospheric CO_2, which is sequestered and converted into biomass by green plants. After accounting for fossil energy inputs in agriculture, biodiesel processing, and transportation, the NREL life-cycle inventory study calculated that the use of B100 fuel reduces net CO_2 emissions by 78.45% compared to the use of petroleum diesel. There is also a modest reduction in methane emissions. This calculation was based on unfavorable assumptions about the sources of the energy inputs to agricultural production, transport, and electric generation used to produce the biodiesel. If the farm equipment used to grow the feedstock and the trucks used to transport it were assumed to use B100 as well, the net reduction in CO_2 emissions would be even greater.

4.7 EMULSIONS AND ADDITIVES

As the preceding discussion has shown, most heavy-duty diesel engines experience an increase in NOx and a reduction in PM emissions using biodiesel fuel. A technology or additive that could offset or reverse the NOx increase while preserving or enhancing the PM reduction could increase the attraction of biodiesel use as an air pollution control measure. Some work to develop such technologies is under way. The 2001 CIFER study[23] for NREL measured the effect of adding 5% by volume of the cetane improver di-tertiary butyl peroxide to B100, but even this very high concentration gave a NOx reduction of only 2 to 4%. Blending of an anti-oxidant - tertiary butyl di-quinone at 0.2% weight reduced NOx emissions by 1%, but PM emissions increased by 9%. While developing this report, EF&EE was in contact with two other organizations that are working on NOx reduction technologies for use with biodiesel, but neither was prepared to supply data on their effectiveness at this time.

One promising approach to reducing NOx emissions with B100 would be the use of water-biodiesel emulsions. Water-diesel emulsions have already been shown to be effective in reducing NOx and PM emissions - for example, a 20% water-in-diesel macroemulsion has been verified by ARB as reducing NOx by 14%. Researchers in Japan[24] compared the effects of water emulsions with biodiesel and with petroleum diesel. Without the emulsion, NOx emissions with the biodiesel were higher than with the petroleum diesel; but a 30% water emulsion gave lower NOx with biodiesel than with petroleum diesel. The addition of water reduced the NOx concentration at full load from about 1100 ppm to about 650 ppm, with proportional benefits at lower loads down to about 40% load.

The effects of water-biodiesel emulsions on PM emissions at light load would need to be investigated. Like biodiesel, water emulsions strongly decrease the solid carbon fraction of the PM, but can increase emissions of soluble organic PM at light loads. The combination of water plus biodiesel might give even higher light-load PM. The Japanese study showed the expected reduction in black smoke due to the water emulsion, but did not measure mass PM emissions. Thus, it gives no insight on this question.

4.8 SUMMARY AND ANALYSIS: BIODIESEL VS. PETROLEUM DIESEL

As the preceding sections have shown, the effects of biodiesel on pollutant emissions are complex, and depend substantially on the engine technology and operating conditions, as well as the fatty acid composition of the biodiesel itself. These effects can be summarized as follows.

NOx. The use of neat biodiesel tends to increase diesel NOx emissions under high-load engine operating conditions, but may reduce NOx from direct-injection engines at light loads. The increase is greater for the types of high-pressure unit injection systems commonly used in heavy-heavy duty engines, and less for pump-line-nozzle or common-rail injection systems. NOx emissions from heavy-duty engines are lowest from biodiesel containing mostly saturated fatty acids, and increase as the degree of unsaturation increases. Thus, biodiesel made from tallow, lard, or soy oil hydrotreated to saturate the fatty acid compounds produces lower NOx than biodiesel made from yellow grease, which in turn produces lower NOx than biodiesel made from virgin soy or canola oils.

In tests on a Detroit Diesel Series 60 engine, biodiesel made from pure saturated fatty acids resulted in NOx levels less than those obtained with diesel certification fuel, and comparable to those experienced with CARB diesel. However, this fuel has poor cold-flow properties, making it impractical as a vehicle fuel, except possibly in summer. For winter use, it would be necessary to add significant amounts of mono-unsaturates, which would likely increase NOx emissions by 5 to 10% compared to CARB diesel.

Some work is underway on technologies to reduce or reverse the NOx increase due to biodiesel. Water-biodiesel emulsions are one promising approach to this goal.

Particulate matter. The use of neat biodiesel dramatically reduces the solid carbon (soot) portion of the particulate matter. This is attributable to the oxygen content of the fuel, which interferes with the chemical conditions needed to form soot. On the other hand, biodiesel use tends to *increase* the soluble organic fraction (SOF) portion of the diesel particulate matter – often increasing these emissions several-fold with neat biodiesel use. The additional SOF consists almost entirely of unburned biodiesel fuel. The net effect on particulate emissions depends on the balance between reducing solid PM and increasing SOF. At high loads, and in the heavy-duty transient test procedure, the reduction in solid carbon tends to dominate, so that biodiesel use reduces the total mass of PM emissions. At light loads, and in light-duty vehicles, the effect of the SOF increase tends to dominate, so that the total mass of PM emissions increases.

The effects of biodiesel use on PM emissions also appear to depend on the biodiesel composition. Long-chain, saturated compounds appear to result in more SOF emissions compared to monounsaturated species and common vegetable oils. Polyunsaturated fatty acids may also increase PM emissions compared to other biodiesel formulations, but in this case it is not clear whether the increase is due to increased SOF or increased carbon PM.

PM emissions using B100 differ greatly in composition from those produced using petroleum diesel, and this could mean that the health effects might be different as well. Our present understanding of these health effects and their mechanism(s) is inadequate to predict what these differences might be. Research and testing are needed to assess the relative toxic effects of diesel and biodiesel PM.

Carbon monoxide. The use of neat biodiesel tends to reduce the already-low CO emissions from diesel vehicles by around 40 to 60%. Given the low level of diesel CO emissions, however, these emission reductions are of little significance for air quality.

Non-methane hydrocarbons. The use of neat biodiesel tends to reduce non-methane HC, as measured by flame ionization detection (FID) by 40 to 90%. A substantial part of this reduction may be due to the condensation of biodiesel vapors in the sampling system, however.

Toxic air contaminants. The most important toxic air contaminant from diesel engines is diesel particulate matter, discussed above. Of the other toxic air contaminants of significance, biodiesel appears to reduce formaldehyde and acetaldehyde emissions. PAH emissions with neat biodiesel are greatly reduced compared to U.S. certification fuel or CARB diesel, but still higher than those produced by ultra-clean diesel fuels such as Fischer-Tropsch or Swedish EC1 diesel fuels.

4.9 COMPARISON OF BIODIESEL AND NATURAL GAS FUELS

In comparing emissions from different fuels, it is important to compare similar levels of emission control technology. It is also important to consider in-use emissions, which can be much higher than those measured during the engine certification process. Different fuels and technologies experience different levels of emissions degradation in use, and this has important effects on emission levels in the real world.

Table 3: Average in-use emissions from heavy-duty natural gas and diesel vehicles

	Average Mileage	Average Emissions (g/mile)					
		CO	THC	NMHC	NOx	PM	CO_2
Heavy-Heavy Trucks (WVU 5 mile / 5 peak cycles)							
Ded. Natural Gas/No Cat	32,639	7.86	N/A	N/A	5.17	0.058	1,787
Dual-Fuel Nat. Gas	N/A	19.04	N/A	N/A	10.27	0.446	1,489
Diesel	120,727	4.53	N/A	N/A	18.93	0.697	1,726
Urban Buses (CBD Cycle)							
Ded Natural Gas/No Cat	29,798	8.14	27.06	N/A	19.54	0.070	2,307
Medium-Heavy LEV w Cat	13,240	2.40	17.26	1.57	10.20	0.033	1,665
Diesel	45,978	4.91	0.26	N/A	28.56	0.510	2,368
Medium-Heavy Trucks/Buses (Heavy Duty Truck Cycle)							
Ded. NG LEV w Cat	11,042	3.03	15.90	1.70	9.03	0.032	1,355
Ded. NG w/o Cat	15,605	6.75	41.91	1.60	10.25	0.079	1,617
Diesel	19,746	8.59	0.20	N/A	22.22	0.740	2,111

In a study[25] for the Sacramento Council of Government in 2001, EF&EE analyzed available in-use data to compare emissions from diesel and natural gas trucks and buses using engines and technologies from the mid- to late- 1990s. The results of that analysis are shown in Table 2. Most of the data included in this analysis were obtained by WVU using their transportable chassis dynamometer system. These data are contained in the heavy-duty vehicle emissions database maintained by the National Renewable Energy Laboratory. EF&EE also included published data from a series of measurements carried out by Colorado School of Mines[26,27] in cooperation with WVU. The results of this analysis were reviewed by ARB staff, and approved for use in estimating the emission benefits of the Sacramento Emergency Clean Air and Transportation (SECAT) project.

Based on these in-use emission data, average NOx emissions from dedicated natural gas heavy-heavy duty trucks, medium-heavy duty trucks, and buses were 73%, 54%, and 32% less, respectively, than from diesel vehicles. These percentages compare natural gas vehicles without aftertreatment to diesel engines without particulate filters (although some buses were equipped with catalytic converters). For particulate matter, the corresponding reductions are 92%, 96%, and 86%, respectively. The very high NOx emissions from diesel heavy-heavy duty trucks compared to natural gas trucks appear to be linked to the widespread use of "defeat devices" in diesel truck engines of that era, and are probably not representative of engines produced after 1998.

The NREL database includes only very limited results for hydrocarbon emissions from natural gas or diesel buses. In general, mass emissions of NMHC from natural gas buses without aftertreatment are higher than those from diesel or biodiesel buses. However, the bulk of the NMHC from natural gas buses are made up of unreactive and non-toxic species such as ethane and propane, so that these emissions have little effect on air quality.

Recent emission tests on diesel and CNG transit buses in New York City[28] at the ARB laboratory in Los Angeles[29] showed similar results to those contained in the NREL database. These data are summarized in Table 3. NOx emissions with CNG were reduced 37% in the Los Angeles study, and 45% in the New York City test program. PM emissions were reduced 69% compared to ultra-low sulfur diesel in Los Angeles, and 92% compared to ordinary diesel in New York City.

Table 4: Diesel and natural gas bus emissions from recent test programs in Los Angeles and New York City

		Average Emissions (g/mile)				
	Mileage	**CO**	**THC**	**NMHC**	**NOx**	**PM**
ARB Test Program - CBD Cycle						
Diesel w Cat & ULSD	15,169	1.35	0.08	N/A	30.21	0.119
Ded. NGV no Cat	19,629	11.07	11.96	1.91	19.04	0.037
New York City Test Program (CBD Cycle)						
Diesel w Cat & ULSD	N/A	3.0	0.14	0.14	30.1	0.24
Ded. NGV w Cat	N/A	0.6	15.2	0.60	25.0	0.02
Ded. NGV w Cat	N/A	12.7	20.6	3.15	14.9	0.02
Ded. NGV w Cat	N/A	10.8	26.1	2.36	9.7	0.02
Avg. NGV w Cat	N/A	8.0	20.6	2.04	16.5	0.02

The NREL database includes only two comparable test records for 1994 and later model year heavy-duty trucks operating on B100 - too few to form a valid comparison with the averages in Table 2. However, the NREL database also includes emission results for the same trucks operating on petroleum diesel. These results are compared in Table 4. The PM and NOx effects in these tests are less than would have been expected, based on heavy-duty transient test results. This is probably due to the relatively light engine loading experienced in these tests, due to the limited dynamometer capacity.

Table 5: Emissions with B100 vs petroleum diesel for 1994 and later trucks in the NREL database

		Average Emissions (g/mile)			
	Mileage	**CO**	**THC**	**NOx**	**PM**
1994 Trucks - WVU Truck Cycle					
Biodiesel Trucks	85,763	4.40	0.21	15.10	0.235
Same Trucks w Diesel	85,459	6.05	0.26	14.70	0.325
Percent Difference		-27.3%	-19.6%	2.7%	-27.7%

Summary: given the emission control technologies used in the mid to late 1990s, the use of natural gas engines in place of diesel engines burning petroleum diesel fuel reduced in-use PM emissions by 86% to 96%, compared to a reduction of about 20 to 60% for the use of B100 biodiesel. NOx emissions with natural gas engines were reduced by 32 to 73%, compared to an increase of about 5% for engines running on biodiesel. Emissions of NMHC and CO from diesel, biodiesel, and natural gas vehicles are all low in absolute terms. Compared to engines burning petroleum diesel, NMHC and CO emissions will tend to be lower for engines burning B100, and higher for natural gas engines.

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