

Evaluation of the Impacts of Biofuels on Emissions for a California Certified Diesel Fuel from Heavy-Duty Engines

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ABSTRACT

The impact of biodiesel and new generation biofuels on emissions from heavy-duty diesel engines was investigated using a California Air Resources Board (CARB) certified diesel fuel as a base fuel. This study was performed on two heavy-duty diesel engines, a 2006 engine and a diesel particle filter (DPF) equipped 2007 engine, on an engine dynamometer over four different test cycles. Emissions from soy-based and animal-based biodiesel, renewable diesel fuel, and gas to liquid (GTL) diesel fuel were evaluated at blend levels ranging from 5 to 100%. Consistent with previous studies, particulate matter (PM), hydrocarbons (HC), and carbon monoxide (CO) emissions generally showed increasing reductions with increasing biodiesel and renewable/GTL diesel fuel blend levels for the non-DPF equipped engine. The levels of these reductions were generally comparable to those found in previous studies performed using more typical Federal diesel fuels. The DPF-equipped engine THC, CO, and PM emission levels were very low and did not show significant fuel impacts. Carbon dioxide (CO₂) emissions were slightly higher for biodiesel blends, and slightly lower for the renewable/GTL blends. Brake Specific Fuel Consumption (BSFC) was slightly higher for biodiesel and renewable/GTL blends, consistent with their lower energy density.

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INTRODUCTION

There is a global effort to expand the use of renewable fuels in the transportation section. This can have several potential benefits, such as improving air quality, reducing emissions of some of the criteria air pollutants and carbon dioxide (CO₂), which is a greenhouse gas, and reducing dependency on fossil fuels. A number of regulations have been implemented on a multinational, national, and regional level to increase the use of renewable fuels [1,2,3].

Biodiesel is the most popular biofuel for diesel applications. Biodiesel blends can be used in existing diesel engine technologies with no or minor engine modifications [4,5]. Currently, 7% biodiesel is used in diesel fuel throughout Europe [6]. Biodiesel production in U.S has also increased substantially over the past decades and reached 1.1

billion gallons in 2011 [7]. From an air quality perspective, the major benefit of biodiesel blends is that they can reduce the emissions of some of the primary air pollutants [4]. It has also been reported that biodiesel blends can reduce CO₂ emissions when a complete carbon life cycle analysis is performed [8].

Numerous studies of biodiesel emissions have been conducted over the years. In order to better quantify average or typical biodiesel effects, several researchers have done quantitative evaluations in conjunction with comprehensive literature reviews. The U.S. Environmental Protection Agency (EPA) conducted an early assessment of the impact of biodiesel on pre-2002 engines, and more recently updated this study [9,10]. The National Renewable Energy Laboratory (NREL) also published several studies evaluating the biodiesel emissions literature from different perspectives to



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Table 1. Comparison of the percentage differences of the results of several review studies on biodiesel emissions

		EPA, 2002 & 2009[9,10]			McCormick et al., 2006[11]	Yanowitz and McCormick, 2009[12]	Hoekman et al., 2011****[8]
		"Average" Base Fuel, 2002	"Clean" Base Fuel, 2002	"Average" Base Fuel, 2009			
PM	B20	-12%	-8%	-15.6%	0- -31%* Average -12.6%	-14% (SD=13%)** -17% (SD=13%)**	-17.2, -10.5, 1.7
	B50	-26%	-20%				
	B100	-46%	-35%				-44.3, 3.8, 7.9
THC	B20	-21%	-13%	-14.1%	0- -30% Average -10.3%	-16% (SD=18%)** -16% (SD=18%)**	-17.4, -13.3, -7.6
	B50	-45%	-30%				
	B100	-69%	-51%				-48.3, -59.5, -20.1
CO	B20	-12%	-9%	-13.8%	0- -38% Average -12.9%	-15% (SD=10%)** -16% (SD=9%)**	-14.1, -17.3, 1.1
	B50	-27%	-20%				
	B100	-47%	-37%				-34.3, -39, 14.9
CO₂	B100		1-3%				

*Non-DPF equipped engines

** Including new studies to EPA study

*** Including new studies but not two-stroke engine data to EPA study

**** Percentage differences are reported, respectively, over HD/MD engine dynamometer, HD/MD chassis dynamometer, LD Chassis dynamometer

examine differences between engine technologies, between engine and chassis dynamometer tests, and other factors [11]. As part of the Coordinating Research Council's (CRC's) AVFL-17 project, Hoekman et al. also did an evaluation of the literature looking at differences between different engine types (light-, medium-, and heavy-duty) and also between engine and chassis dynamometer studies, as well as other factors [8]. Table 1 shows a comparison between the percentage differences for these different studies. As shown in this table, PM, THC, and CO emissions showed reductions on average for biodiesel for nearly all comparison categories [8,9,10,11,12]. Most of the studies included in these reviews were performed using typical Federal diesel fuels as the baseline test fuel, over a limited number of driving cycles/feedstocks/blend levels, or with older engine technologies without aftertreatment. Therefore, the studies to date have some limitations with respect to their application in California, where more stringent diesel fuel standards are in place. Additionally, although most studies have shown reductions in PM, THC, and CO emissions with biodiesel, some studies have shown less prevalent reductions over some testing conditions, such as low loads, or light/medium duty chassis dynamometer studies [13,14,15,16,17].

The California Air Resources Board (CARB) has conducted one of the most comprehensive studies of biodiesel emissions impacts to date, in conjunction with researchers at

the University of California (UC) at Riverside, UC Davis, and others. The focus of this larger study was to evaluate regulated and toxic emissions from biodiesel and renewable diesel fuels blended with CARB certified diesel fuel. This study is part of CARB efforts to identify the need for additional regulations to facilitate the introduction of larger volumes of renewable fuels into use. The larger program included engine dynamometer testing, chassis dynamometer testing, and testing of off-road engines on several biodiesel and renewable diesel fuels [18]. The importance of this study is that it provides a very robust set of data using CARB certified and CARB-like diesel fuels, which are produced to more stringent standards than other diesel fuels throughout the United States, and for which there is more limited data in the literature. This paper summarizes the results of the PM, THC, CO, and CO₂ emissions from the heavy-duty engine dynamometer part of this larger study. This is a companion paper to another article that focused on the nitrogen oxides (NO_x) emissions results for the heavy-duty engine dynamometer testing [19].

Experimental Methods

Five primary fuels were blended at various levels from B5 to straight B100. These fuels include, a commercially available CARB-certified diesel fuel, soy-based and animal-based biodiesel fuels, a renewable diesel fuel produced from

renewable biomass sources, such as fatty acids from vegetable oils and animal fats, via a hydro-treating process [20,21,22], and a gas to liquid (GTL) diesel fuel produced via Fisher-Tropsch procedure. The biodiesel feedstocks were selected to provide a range of properties of the typical biodiesel feedstocks such as cetane number and degree of saturation (iodine number). The renewable diesel fuel was the Neste Oil biomass-to-liquid (NExBTL) diesel fuel. Six tests were nominally performed for every fuel/cycle combination. A summary of selected properties for the neat fuels is provided in Table 2.

Table 2. Selected Fuel Properties

	CARB	Renewable	GTL	Soy	Animal
API gravity (@ 60°F)	39.3	51.3	48.4	28.5	28.5
Aromatics, vol. %	18.7	0.4	0.5	NA	NA
PNAs, wt. %	1.5	0.1	<0.27	NA	NA
Cetane number, D613	55.8	72.3	>74.8	47.7	57.9
Cetane number, IQT		74.7			
Sulfur, ppm	4.7	0.3	0.9	0.7	2
Carbon, % Wt.	86.1	84.83	84.6	76.72	75.89
Hydrogen, %Wt.	13.67	15.14		11.97	12.22
Oxygen, % Wt.	0.23	0.03		11.31	11.89
C/H Ratio	6.3	5.6		6.4	6.2
Cloud Point, °C	-6.6	-27.1	-1	0	12.5
Pour Point, °C	-12	-47	-6	NA	NA
Distillation, °F					
ibp	337	326	419	NA	NA
10%	408	426	482	NA	NA
50%	519	521	568	NA	NA
90%	612	547	648	NA	NA
ep	659	568	673	NA	NA
Distillation, T90 AET, °C	NA	NA	NA	350	347.5
Acid Number	NA	NA	NA	0.20	0.26
Free Glycerin%	NA	NA	NA	0.001	0.008
Total glycerin%	NA	NA	NA	0.080	0.069
Oxidation Stability				6.7	3.9

NA = either Not Available or Applicable, IQT = ignition quality test derived cetane number

Two engines selected from 2 model year categories: 2002-2006 and 2007-2009 were tested on a 600 hp General Electric DC electric heavy-duty engine dynamometer located at the University of California at Riverside's College of Engineering-Center for Environmental Research and

Technology's (CE-CERT). The 2002-2006 engines are estimated to represent an important contribution to the emissions inventory from the present through 2017. The 2007-2009 model year engine represents the latest technology that was available at the time of testing. The 2002-2006 engine was a 2006 model year, 10.8 L, Cummins ISM engine, and the 2007-2009 engine was a 2007, 12.8 L, Detroit Diesel MBE 4000. The Detroit Diesel MBE 4000 was equipped with an original equipment manufacturer (OEM) diesel particulate filter (DPF). Both engines were equipped with exhaust gas recirculation (EGR). More specifications of the engines are provided in Table 3.

For every fuel/engine combination, different cycles representing different load and driving conditions were used. These cycles include: lightly loaded Urban Dynamometer Driving Schedule (UDDS), standard Federal Testing Procedure (FTP) for heavy-duty engines, 40 mile per hour (mph) CARB heavy heavy-duty diesel truck (HHDDT) Cruise, and a 50 mph CARB HHDDT Cruise. From a load perspective, the UDDS represents lowest load, the FTP and 40 mph Cruise represent the medium loads, and the 50 mph Cruise represents the highest load. A randomized test matrix, including interspersed testing of the base fuel after a specific number of tests on other fuel blends and performing different cycles during each test day, was used for this study. After the initial round of testing on the soy-based biodiesel for the 2006 Cummins ISM, it was determined that the loads for the FTP and the 40 mph CARB Cruise cycle were very similar, and hence did not provide a sufficient load range to meet the study goals. Therefore, it was decided that an additional higher load cycle was needed to provide a larger range of load conditions. The cycle that was selected was the 50 mph CARB HHDDT Cruise cycle, with an average speed of 50 mph instead of 40 mph. This cycle was used for some further testing on the Cummins engine, but it did not provide stable enough operation to provide valid fuel comparisons for this engine. It was then also used in place of the 40 mph Cruise cycle for the MBE4000, where it provided more stable operation. The GTL diesel fuel was tested primarily for inclusion in another separate, but related, study on NO_x mitigation, which was performed over the FTP cycle and mainly for the 2006 Cummins ISM engine. Therefore, the GTL blends emissions were only characterized over the FTP cycle.

For all tests, standard emissions measurements of THC, CO, PM, and CO₂ were performed from a dilution tunnel using the standard analyzers in CE-CERT's heavy-duty Mobile Emissions Laboratory (MEL) trailer [23,24]. PM mass in the diluted exhaust were collected over a 47 mm Teflon filters and measured gravimetrically with a Mettler Toledo, UMX 2 microbalance.

RESULTS AND DISCUSSION

The results of the average PM, THC, CO, CO₂ emissions and brake specific fuel consumption (BSFC) from soy-based

and animal-based biodiesel blends, renewable and GTL diesel fuel for the 2006 Cummins ISM are shown in [Figure 1](#), [Figure 2](#), [Figure 3](#), [Figure 4](#), [Figure 5](#), respectively, on a gram per brake horse power hour (g/bhp-hr) and gallons per brake horse power hour (gals/bhp-hr) basis for the three different cycles. Since B5 was tested outside of the test matrix sequence, the average emissions for B5 were only compared to the average of CARB emissions for tests immediately before and immediately after the B5 was tested (CARB diesel-B5 in the figures). [Table 4](#) and [Table 5](#) in the [appendix](#) show the emissions averages and the percentage differences for different feedstocks and blend levels for different cycles and for the 2006 Cummins and 2007 MBE4000, respectively, along with the associated p-values for statistical comparisons between the CARB diesel and different biodiesel/renewable/GTL diesel blends using a 2-tailed, 2-sample, equal variance t-test. These statistical analyses provide information on the statistical significance of the different findings. For this study, the results were considered to be statistically significant for p-values below 0.05, which represents a 95% confidence level.

Table 3. Test Engines Specification

Engine Manufacturer	Cummins, Inc.	Detroit Diesel Corp.
Engine Model	ISM 370	MBE4000
Model Year	2006	2007
Engine Family Name	6CEXH0661MAT	7DDXH12.8DJA
Displacement (liter)	10.8	12.8
Power Rating (hp)	385 @ 1800 rpm	Varies, 350-450 hp @ 1900 rpm
After-treatment	EGR	EGR & DPF

PM Emissions

PM emissions, for 2006 Cummins ISM engine, showed consistent and significant reductions for biodiesel blends and renewable/GTL diesel fuels, with greater reductions with increasing blend level. For this engine, the PM percentage reductions for the biodiesel blends compared to CARB diesel over all cycles were 10 to 26% for B20 and 31 to 69% for B100, and 9% for B5 for the FTP on the animal-based biodiesel. There also appears to be a trend of greater reduction in PM with increasing cycle load for both biodiesel fuels.

The PM emission results for biodiesel blends are consistent with the majority of previous studies, reporting PM emissions reductions from biodiesel blends. The 2006 Cummins ISM results showed reductions comparable to, but generally higher than those found in the broader biodiesel emissions analyses discussed above. The 2006 Cummins engine is newer than the engines used in most previous studies up to this time. McCormick et al. did find PM emissions reductions for 2003 vintage heavy-duty engines were larger than those found for older engines [25]. In a review over a wider range of studies, however, Yanowitz and

McCormick did not find a correlation between emissions trends for engines with different model years [12].

The reduction of PM with biodiesel is due to its ability to lower soot formation during combustion, which can be attributed to a number of different factors. The presence of oxygen in the biodiesel can reduce local fuel-rich regions during combustion, limiting the formation of soot [8,9,11,26]. In a study focusing primarily on NO_x emissions, Mueller et al. emphasized that charge-gas mixtures that are closer to stoichiometric for biodiesel blends at ignition and in the standing premixed autoignition zone near the flame lift-off length would lead to a higher local and average in-cylinder temperatures, lower radiative heat losses, and a shorter, more advanced combustion event, all of which could contribute to lower PM [27]. Cheung et al. suggested that greater heat release in premixed combustion and higher heat radiation are other factors that promote more complete combustion and favor lower soot formation for biodiesel [28]. There are other factors that have been reported to reduce PM emissions with biodiesel blends. These include the absence in biodiesel of aromatics that are soot precursors, advanced injection timing in older engine technologies with in-line/mechanical pump systems with biodiesel blends that increases the residence time of soot particles in higher temperature conditions, a different structure for biodiesel and diesel soot that affects the oxidation of soot, and finally, a lower boiling point for biodiesel, in general, despite its higher average distillation temperature, which reduces the probability of soot formation from heavier hydrocarbons [4,29,30,31,32,33,34].

It should be noted some previous studies have also shown conditions where the PM emissions benefits for biodiesel are not as prevalent, but many of these studies were conducted under different conditions, such as at light loads or chassis dynamometer tests of light- or medium-duty vehicles [13,14,15,16,17].

For the 2007 MBE4000 engine, the PM emissions values were well below the 0.01 g/bhp-hr emissions standard, and were essentially at the measurement detection limit. For this engine, the differences in PM emissions between various biodiesel blends and CARB diesel were not statistically significant. This is not unexpected due to the efficiency of the DPF in removing particles from the exhaust, which minimizes any fuel differences. Williams et al. similarly found that the traditional emissions benefits of biodiesel become immeasurable for engines equipped with DPFs [35].

The PM percentage reductions of renewable/GTL diesel compared to CARB diesel for all the cycles were 4% for R20 and 28 to 34% for R100, and 8% for GTL20 and 29% for GTL100. The PM emissions reductions for the renewable diesel fuel were also consistent with the results of previous studies that found reductions in PM or smoke of 28-35% for heavy-duty engine dynamometer tests with neat NExBTL [20,22]. Some studies of light-duty vehicles showed some tendency of PM reductions for different NExBTL blends, but also greater testing variability [21]. The PM emissions

reductions for the renewable fuels can be attributed to their lower density and aromatic content compared to diesel fuel. The more paraffinic nature of renewable diesel fuel also increases the fuel cetane number and boiling point, which are reported to reduce PM emissions [36].

THC Emissions

THC emissions for the 2006 Cummins ISM engine showed consistent and significant reductions for the biodiesel blends, renewable, and GTL diesel fuel, with greater reductions increasing with increasing blend level. The THC percentage reductions for the biodiesel blends compared to CARB diesel over all cycles were 11 to 16% for B20 and 55 to 73% for B100 for biodiesel blends, and 3% for B5 for the FTP on the animal-based biodiesel. There also appears to be a trend of greater reductions in THC with increasing cycle load for soy-based biodiesels.

The results of the 2006 Cummins engine were consistent with those of previous studies. Overall, the reductions obtained for both biodiesel fuels for the 2006 Cummins ISM for THC show reasonably good comparisons with the results for various heavy-duty engine biodiesel studies in the literature. The reductions of unburned hydrocarbons with biodiesel can be attributed to the presence of oxygen in the biodiesel fuel and its impact on more complete combustion of the unburned fuel, similar to the discussion provided above for PM emissions. Other parameters that are reported to decrease THC emissions when using biodiesel include advanced injection timing in older engine technologies and combustion timing [29].

For the 2007 MBE4000, the THC emissions did not show consistent trends, which can be attributed to the efficiency of the DPF. Interestingly, this engine showed some statistically significant increases of THC emissions for the soy-based biodiesel, but these were small on an absolute level. Additional testing would be needed to further clarify this trend for the 2007 MBE4000 engine.

The renewable diesel fuel showed statistically significant percentage reductions of 3% for R20 and 12% for R100 for only the UDDS cycle. The GTL diesel fuel also showed reductions in THC emissions of 5% for GTL20 and 28% for GTL 100 over the FTP. The renewable diesel fuel did not show any consistent THC trends over the FTP, however. Previous studies have reported reductions in THC with neat NExBTL in the range of 30-50% [20,22]. The differences between these studies and the present study might be related to different distillation properties of the fuels used in the studies. In the European studies, a summer grade NExBTL was used, while here a winter grade was used. The summer grade NExBTL had higher T_{10} and T_{50} distillation temperatures, which are important parameters with respect to hydrocarbon emissions in the EPA's Unified Model, [37] and tend to produce lower THC emissions.

CO Emissions

CO emissions for the 2006 Cummins ISM engine showed consistent and significant reductions for the animal-based biodiesel blends and renewable/GTL diesel fuels. The percentage reductions for all cycles ranged from 4% for B5, 7 to 10% for B20, and 20 to 27% for B100 for the animal-based biodiesel, 4 to 16% for R20 and 12 to 33% for R100 for the renewable diesel fuel, and 6% for GTL20 and 14% for GTL100. The soy-based biodiesel blends did not show any strong fuel trends relative to the CARB diesel over the FTP and 40-mph Cruise cycle, with only the B50 over FTP showing a statistically significant 4% CO emissions reduction. For the UDDS cycle, on the other hand, the B50 and B100 soy-based biodiesel blends, respectively, showed statistically significant 26% and 62% CO emissions increases. Interestingly, statistically significant reductions in CO for the 2007 MBE4000 were found for both the B50 and B100 blend levels in comparison with the CARB diesel, but these were small on an absolute level due to the DPF.

The results for CO emissions for the animal-based biodiesel and renewable diesel for the 2006 Cummins ISM were also in good agreement with the previous studies. The reductions of CO emissions with biodiesel can be attributed to the oxygen in the biodiesel fuel and more complete combustion, as discussed above in relation to PM emissions. For the renewable blends, the observation of reduced CO emissions is consistent with the results seen in previous studies, although previous heavy-duty engine studies showed reductions closer to 30% for a neat NExBTL fuel [20,22].

The reason for the lack of CO reductions for the soy-based biodiesel for the 2006 Cummins is not readily apparent, especially given that consistent reductions are seen for both THC and PM on this engine, and for CO for the animal-based biodiesel. Some other studies have shown a lack of strong trends for CO emissions for biodiesel for different types of tests/vehicles/engines ranging from steady state tests to chassis dynamometer tests [13,17,38]. Overall, the CO emissions results for the soy-based biodiesel blends could be impacted by a number of different factors, including the engine load or cycle, differences in the base fuels, or differences between different engines or engines certified to different emissions standards. Additional testing would likely be needed to better understand the nature of these results.

CO₂ Emissions

CO₂ emissions showed a slight increase for the higher biodiesel blends and a slight decrease for the renewable/GTL diesel fuel. The increases were statistically significant largely only for B100, and showed a range at that level from 0.7% to 4.2% for the 2006 Cummins engine and from 1.6 to 5.0% for the 2007 MBE4000 engine. The renewable diesel fuel showed a statistically significant reduction of 3.3 to 3.4% in CO₂ for the R100. GTL diesel fuel showed a statistically significant reduction of 1.9% for GTL50 and 3.5% for GTL100.