Final Report

CARB Assessment of the Emissions from the Use of Biodiesel as a Motor Vehicle Fuel in California
"Biodiesel Characterization and NO_x Mitigation Study"

October 2011

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Disclaimer

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Acknowledgments

The authors thank the following organizations and individuals for their valuable contributions to this project.

The authors acknowledge Bob Okamoto, Floyd Vergara, Alexander Mitchell, Stephen d'Esterhazy, Dean Bloudoff, Hector Maldonado, Jim Guthrie, Aubrey Sideco, Keshev Sahay, Dr. Bill Robertson, Dr, Kwangsam Na, Dr. Subhasis Biswas, Thomas Ladzinski, Christian Hall, Ralph Rodas, George Gatt, Eric White, Paul Rieger, Dr. M-C Oliver Chang, Yanbo Pang, Mark Fuentes, Dr. Christopher Brandow, Richard Ong, Michael Okafor, Dr.Yong Yu, Lyman Dinkins, Christine Maddox, Dr. Richard Ling, Julia Sandoval, Luzviminda Salazar, Don Chernich, Mark Burnitzki, Tullie Flower, Robert Ianni, Harlan Quan, Roelof Riemersma, Wayne Sobieralski, Michael Veridiano, Christopher Milton, Ramon Cabrera, Dr. Pablo Cicero-Fernandez, Dr. Tin D. Truong, Tai Sea Yen, Travis Wong, John P. Nguyen, Ron Walter, Dr. Leo Zafonte, Dr.Darey Huo, Inna Dzhema, Dr. Shoahua Hu, Jeff Austin, and Dr. Alberto Ayala of the California Air Resources Board (CARB) for their assistance in developing the test plan procedures, blending the test fuels, conducting emissions tests, and data analysis. We also thank Uka Enkhbayar, Connie Chao, Christina La, Brian Do from the Dept. of Environmental Toxicology, UC Davis for their help throughout this study, and Dr. Michael Madden from U.S Environmental Protection Agency (EPA) for his helpful discussions regarding inflammatory markers as well as information on the Comet Assay.

We acknowledge funding from the California Air Resources Board (CARB) under contract No. 05-410 and grant No. G06-AF38, from the South Coast Air Quality Management District under contract Nos. 00-188 and 08-263, from the National Biodiesel Board, and from Neste Oil Inc.

We acknowledge Neste Oil Inc. and the National Biodiesel Board for providing fuel for this program. We acknowledge Interstate Oil Company for assisting with and providing facilities for the mixing of the test fuels.

We acknowledge Donald Pacocha and Joe Valdez, University of California, Riverside for their contributions in conducting the emissions testing for this program.

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Abstract

California currently has several legislative initiatives that promote increased alternative fuels use to reduce oil dependency, greenhouse gases, and air pollution. To develop these regulations, a technical evaluation of the emissions impacts was needed to be conducted, and therefore a comprehensive emissions study comparing biodiesel, and to a lesser extent renewable diesel fuels, to California Air Resources Board (CARB) diesel fuel was conducted. This program was coordinated by CARB in conjunction with researchers from the University of California Riverside (UCR), the University of California Davis (UCD), and others including Arizona State University (ASU). The study was divided into two main areas, NO_x impacts and filling of knowledge gaps. Two heavy-duty on-road engines were tested at the College of Engineering - Center for Environmental Research and Technology (CE-CERT) and two non-road engines were tested at CARB emissions test facilities in Stockton and El Monte. The second main area was to fill knowledge gaps in the area of health impacts and unregulated emissions. The study was conducted on four vehicles at the CARB's heavy-duty emissions test facility in Los Angeles.

NO_x Impact and Mitigation Studies

A 2006 Cummins ISM and 2007 MBE4000 engine equipped with a diesel particle filter (DPF) were tested at CE-CERT. For both the 2006 Cummins engine and 2007 MBE4000 engine, the average NO_x emissions show increasing trends with increasing biodiesel blend level. The magnitude of the effects did differ between the different biodiesel feedstocks. The soy-based biodiesel blends showed a higher increase in NO_x emissions for essentially all blend levels and test cycles in comparison with the animal-based biodiesel blends. For the 2006 Cummins engine, the trends for other emissions components were similar to those from previous studies, with biodiesel providing reductions in THC and PM. The CO emissions results on this engine showed consistent reductions for the animal-based biodiesel, but not for the soy-based biodiesel. For the 2007 MBE4000, the PM, THC, and CO emissions were all well below certification limits and the emissions levels for the 2006 engine due to the DPF, and generally did not show strong fuel impacts. CO_2 emissions showed a slight increase of 1-5% for B100 and some B50 combinations. Fuel consumption increased with increasing levels of biodiesel, with increases of 5-10% for the B100 blends.

For the renewable and GTL diesel fuels in the 2006 Cummins, the results showed a steady decrease in NO_x emissions with increasing levels of renewable/GTL diesel fuel. For the renewable diesel fuel, these reductions ranged from 2.9% to 4.9% for R20, 5.4% to 10.2% for R50, and 9.9% to 18.1% for R100 through all the cycles. For the GTL fuel the reductions were 5.2% and 8.7%, respectively, for GTL50 and GTL100 for the FTP cycle. In comparison with the biodiesel feedstocks, the levels of NO_x reduction for the renewable and GTL fuels are less than the corresponding increases in NO_x seen for the soy-based biodiesel, but are more comparable to the increases seen for the animal-based biodiesel blends. This suggests that the renewable and GTL diesel fuel levels need to be blended at higher levels than the corresponding biodiesel in order to mitigate the associated NO_x increase, especially for the soy-based biodiesel blends. The renewable and GTL fuels also provided reductions in PM and CO emissions, with the GTL fuel also providing reductions in THC. The renewable and GTL fuels provided a slight reduction in CO_2 emissions at the higher blends, with a slight, but measureable, increase in fuel consumption.

Several NO_x mitigation formulations were evaluated on 2006 Cummins engine, including those utilizing renewable and GTL diesel fuels, and additives. Successful formulations included those with higher levels of renewable diesel (R80 or R55) with a B20-soy biodiesel. Blends of 15% renewable or GTL diesel were also proved successful in mitigating NO_x for a B5 soy blend, giving a formulation more comparable to what might be implemented with the low carbon fuel standard. A 1% di tertiary butyl peroxide (DTBP) additive blend was found to fully mitigate the NO_x impacts for a B20 and B10 soy biodiesel, while 2-ethylhexyl nitrate (2-EHN) blends had little impact on improving NO_x emissions. It was found that the level of renewable or GTL diesel fuels needed for blending can be reduced if a biodiesel fuel with more favorable NO_x characteristics, such as animal-based biodiesel, is used, or if an additive with more favorable NO_x characteristics, such as DTBP, an additive evaluated in this study, is used. For the MBE4000, only two blends were tested, CARB80/R15/B5-S and B-5 soy with a 0.25% DTBP additive. Of these two, only the B-5 soy with a 0.25% DTBP additive provided NO_x neutrality. Overall, it appears that different strategies will provide mitigation for different engines, but that the specific response varies from engine to engine.

Non-Road NO_x Impact Study Results and Conclusions

Testing was conducted on a John Deere non-road, industrial engine and a Transportation Refrigeration Unit (TRU) engine at CARB facilities in El Monte, CA and Stockton, CA, respectively. The NO_x emissions show general increases with increasing biodiesel blend level for both the John Deere and TRU engines. The NO_x increases were statistically significant for the B100 blends for all testing combinations, for B50 blends for the soy-based biodiesel for the John Deere engine and for the first series of tests on the TRU engine, and for the soy-based B20 for the John Deere engine. The NO_x increases for the TRU engine were comparable with the ones obtained for the 2006 Cummins engine, but were lower than the ones obtained for the 2007 MBE4000. The magnitudes of the increases in NO_x emissions for the John Deere engine were less than those for either the TRU or the on-road heavy-duty engines. The animal-based biodiesel also did not show as great a tendency to increase NO_x emissions compared to the soy-based biodiesel for the John Deere engine, with only the B100 animal-based biodiesel showing statistically significant increases in NO_x emissions.

PM, THC, and CO emissions showed consistent reductions with increasing biodiesel blend level for both the John Deere and the TRU engines. The magnitude of the reductions in the PM emissions for the John Deere engine were comparable to those of the 2006 Cummins ISM engine dynamometer tests, while the reductions seen for the TRU engine were less than those seen for the 2006 Cummins. The THC reductions for the off-road engines were generally either comparable to slightly less than those seen for the 2006 Cummins ISM engine dynamometer testing. The CO reductions for the John Deere engine were comparable to those seen for the 2006 Cummins ISM engine for the engine dynamometer testing, while the CO reductions for the TRU engine were generally greater than those found for the 2006 Cummins. CO_2 emissions showed some slight increases for the biodiesel blends for both the John Deere and TRU engines.

Knowledge Gaps Study Results and Conclusions

Testing was conducted on heavy-duty vehicles on a chassis dynamometer at CARB's facility in Los Angeles, CA, including two vehicles with pre-2007 engines, one vehicle with a 2007 engine with a DPF, and one vehicle with a 2010 engine equipped with a DPF and a selective catalytic reduction (SCR) system, which is not included in this report. For the heavy-duty chassis results, the NO_x emissions showed a consistent trend of increasing emissions with increasing biodiesel blend level. These differences were statistically significant or marginally statistically significant for nearly all test sequences for the B50 and B100 fuels, and for some B20 blends, but not others. These increases ranged from 7% to 16% for B50, and 15% to 27% for B100 for 2000 Caterpillar C-15, 4% to 8% for B20, 2% to 16% for B50, and 9% to 34% for B100 for 2006 Cummins ISM, and 11% to 13% for B50, and 28% to 36% for B100 for 2007 MBE4000. The percentage increases for the NO_x emissions with biodiesel were generally greater for soy-based biodiesel compared with the animal-based biodiesel. The magnitude of the increases in NO_x emissions for the biodiesel blends for the 2006 Cummins ISM engine were either greater than or comparable to those found for the engine testing on this engine. For the 2007 MBE4000, the overall NO_x increases are in the same range for the chassis and engine dynamometer testing, with some differences seen for cycle/fuel/blend level combinations. For the 2000 Caterpillar C-15, the renewable diesel fuel showed NO_x reductions for the UDDS cycle, but not statistically significant reductions over the 50-mph cruise cycle. The magnitude of the reductions found for the renewable diesel was similar to those found in the engine testing. The reductions for the renewable diesel blends ranged from 4% to 12% for the UDDS cycle.

PM, THC, and CO emissions showed consistent reductions for most biodiesel blend level and cycle combinations for the two non-DPF equipped vehicles (2000 Caterpillar C-15 and the 2006 Cummins ISM), with the magnitude of the reductions generally increasing with blend level. The PM emissions reductions for the chassis dynamometer testing are similar to or greater than the reductions seen in the engine testing for the Cummins ISM engine for most testing combinations. The THC reductions for the highest blend levels were slightly less consistent and were slightly less than those seen in the corresponding engine tests for the Cummins ISM. The CO reductions were statistically significant for most of the B50 and B100 blends, and some of the B20 blends. PM, THC, and CO also showed some reductions for the renewable diesel, although these reductions were sometimes only seen for the higher blend levels. PM, THC, and CO emissions did not show any consistent trends for the DPF-equipped 2007 MBE4000 as a function of biodiesel level, since most of the combustion-related PM is eliminated in the DPF, although statistically significant CO reductions were found for the B100 soy-based and animal-based blends for the UDDS cycle. CO_2 emissions showed some reductions for the R100 and R50 fuels for the 2000 Caterpillar C-15 and some increases for the animal-based and soy-based biodiesel blends for the 2007 MBE4000, although these trends were not consistent across the range of vehicles/engines testing on the chassis dynamometer. The CO_2 increases fall within the 1-5% range that was seen in the heavy-duty engine dynamometer testing for the various biodiesel blends.

The VOC emissions measured for the chassis testing included benzene, toluene, ethylebenzene,1,3-butadiene, *m-/p*-xylene and *o*-xylene. The VOC emissions typically showed only trends for the higher biodiesel blend levels, with the emissions for biodiesel being lower

than those for CARB. Generally, the reductions in aromatic VOCs were consistent with the reduction in aromatics in the fuel. For the lower biodiesel blend levels, the differences with the CARB diesel were typically not significant. Carbonyl emissions did not show consistent trends as a function of biodiesel or renewable diesel blend level. In some cases, trends were seen for particular vehicle/fuel combinations, but these trends were not seen for other fuel/cycle combinations. Reactive carbonyl measurements did show showed that certain reactive carbonyls were higher for the higher biodiesel blends, including acrolein, while others, such as aromatic aldehyde species, were lower for the pure biodiesel fuels. PAH and Nitro-PAH emissions both decreased as a function of increasing blend level for soy biodiesel, animal-based biodiesel and renewable diesel. The emission trends for Oxy-PAH emissions showed different trends for different compounds, with some compounds showing generally higher emissions in soy and animal-based biodiesels compared to CARB diesel, whereas others decreased in animal biodiesel and renewable diesel. For all toxic species, emission levels were significantly reduced in the DPF-equipped vehicle, and there were few fuel related trends.

The PM mass was composed predominantly of carbonaceous material for all fuel combinations. The total carbon and the elemental carbon components of the PM both showed reductions increasing in magnitude at progressively higher biodiesel blends. Both of these trends are consistent with the overall reduction in PM mass with higher biodiesel levels. The organic carbon levels did not show significant differences between the different fuel blends, and in fact were relatively flat as a function of blend level. The renewable diesel blends showed trends of decreasing elemental and total carbon emissions as a function of blend level, but this was only statistically significant for the R100 fuel. The ion and trace element emissions were generally very low, comprising less than 1% and 2%, respectively, of the total PM mass, and did not show consistent trends between the different fuels.

Mutagen emissions generally decreased as a function of increasing biodiesel blend level for the 2000 Caterpillar C-15 vehicle. CARB diesel, biodiesel, and renewable diesel all induced inflammatory markers, such as COX-2 and IL-8 in human macrophages and the mucin related MUC5AC markers in Clara type cells, with the inflammatory markers higher in the 2000 Caterpillar C-15 engine vehicle than the 2007 MBE4000 engine vehicle. For the comet assay, at the limited dose levels tested, there was little increase of chromosomal damage (gross DNA damage) from the various fuels tested, including the CARB diesel.

Acronyms and Abbreviations

ARB	Air Resources Board
CARB	California Air Resources Board
CEC	California Energy Commission
CE-CERT	College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CFR	Code of Federal Regulations
CO	carbon monoxide
COV	coefficient of variation
CO2	carbon dioxide
CVS	constant volume sampling
DNA	deoxyribonucleic acid
DNPH	2,4-dinitrophenylhydrazine
DPF	diesel particle filter
DR	dilution ratio
ECM	engine control module
FTP	Federal Test Procedure
g/mi	grams per mile
g/bhp-hr	grams per brake horsepower hour
GC	gas chromatography
GC/FID	gas chromatography/flame ionisation detector
GTL	gas-to-liquid
GVWR	gross vehicle weight rating
HDDT	Heavy-Duty Diesel Truck
HDETL	CARB's Heavy-Duty Emissions Testing Laboratory
HDV	heavy-duty vehicle
HPLC	High Performance Liquid Chromatography
LDV	light-duty vehicle
lpm	liters per minute
MDL	minimum detection limit
MEL	CE-CERT's Mobile Emissions Laboratory
nm	nanometers
NMHC	non-methane hydrocarbons
NO_x	nitrogen oxides
NO_2	nitrogen dioxide
OEM	original equipment manufacturer
PAH	poly-aromatic hydrocarbons
PM	particulate matter
PUF	polyurethane foam
QA	quality assurance
QC	quality control
scfm	standard cubic feet per minute
THC	total hydrocarbons
UDDS	Urban Dynamometer Driving Schedule
ULSD	ultralow sulfur diesel

Executive Summary

California, as well as the United States as a whole, is making a concerted effort to increase the use of alternative fuels in transportation and other areas. In California, a number of legislative measures and regulations are targeted at increase the use of renewable fuels. This includes AB1007, which requires the California Air Resources Board (CARB) and California Energy Commission (CEC) to develop a plan to increase alternative fuels use in California, and the Global Warming Solutions Act, AB32, which requires California to develop regulations that will reduce greenhouse gas emissions to 1990 levels by 2020. In response to these policy drivers, CARB has implemented the Low Carbon Fuel Standard (LCFS) that will reduce the carbon intensity of fuels, measured on a full lifecycle basis, by 10% by 2020. CARB has identified biodiesel as a potential strategy in meeting these regulatory goals for diesel fuel. Biodiesel is an alternative diesel fuel that has the potential to reduce greenhouse gas emissions, other pollutants, and can partially offset our use of petroleum-based fuels.

Although biodiesel has been studied extensively over the past 20 years, knowledge gaps still exist and further research is needed to fully characterize the impact biodiesel has on oxides of nitrogen (NO_x) emissions and the effects various feedstocks have on various emissions. A comprehensive assessment of the impact of biodiesel on pre-2002 engines was conducted by the US Environmental Protection Agency in 2002 (US EPA, 2002), which estimated that a soy-based biodiesel at a B20 level would increase NO_x emissions about 2% compared to an average Federal base fuel. Additional analyses in this same study did indicate that the impacts of biodiesel on NO_x emissions using a "cleaner" base fuel, more comparable to that utilized in California, could be greater than that found for the average Federal fuel, but data was more limited in this area. More recent reviews have been conducted by McCormick et al. (2006) and Hoekman et al. (2009). These more recent reviews have emphasized the considerable variations in the results from study to study and engine to engine, and have suggested that on average there is either no net effect for B20 on NO_x emissions or there is at most a very small effect. Many of these studies are limited in their direct application to California, however, because exhaust emissions from diesel engines fueled with biodiesel were not compared to these engines fueled with CARB diesel, or because they use only soy-based biodiesel that may not be the major feedstock used in California. Additionally, most of these studies are not as extensive as the testing requirements used in the certification of CARB alternative diesel formulations, which require fuels to be shown to be equivalent to a 10% aromatic reference diesel fuel over a test sequence of 20 or more iterations (CARB, 2004).

In order to better characterize the emissions impacts of renewable fuels under a variety of conditions, CARB has conducted a comprehensive study of biodiesel and other alternative diesel fuels with CARB diesel. This program was coordinated by CARB in conjunction with researchers from the University of California Riverside (UCR), the University of California Davis (UCD), and others including Arizona State University (ASU). The goal of this study was to understand and, to the extent possible, mitigate any impact that biodiesel has on NO_x emissions from diesel engines. The study also looked at the impact of biodiesel on toxic emissions. This study provides an important assessment of the potential impact of renewable fuel use in California and a basis for the development of NO_x mitigation strategies for meeting CARB

regulations. This study also makes an important contribution to the scientific knowledge of the impacts of biodiesel with "clean" or CARB-like diesel in heavy-duty engines.

The testing included engine dynamometer testing of heavy-duty, on-highway engines and off-road engines, and chassis dynamometer testing of heavy-duty, on-highway vehicles. The full test matrix included testing on 2 heavy-duty engines, 4 heavy-duty vehicles, and 2 off-road engines. The testing included a baseline CARB ultralow sulfur diesel (ULSD) fuel, two biodiesel feedstocks (one soy-based and one animal-based) tested on blend levels of B5, B20, B50, and B100, a biomass-to-liquid (BTL) or renewable diesel, and a gas-to-liquid (GTL) diesel fuel tested at 20%, 50%, and 100% blend levels. For the on-highway engine and chassis dynamometer testing, several test cycles were also utilized to evaluate the impact of biodiesel on emissions under different operating conditions and loads. This report discusses the results and conclusions for all elements of this study.

Test Fuels

The test fuels for this program included 5 primary fuels that were subsequently blended at various levels to comprise the full test matrix. A CARB-certified ultralow sulfur diesel (ULSD) fuel was the baseline for testing. Two biodiesel feedstocks were utilized for testing, including one soy-based and animal-based biodiesel fuel. These fuels were selected to provide a range of properties that are representative of typical feedstocks, but also to have feedstocks representing different characteristics of biodiesel in terms of cetane number and degree of saturation. A BTL diesel and a GTL diesel were also used for testing. The renewable diesel was provided by Neste Oil, and it is known as NExBTL. This fuel is denoted as the renewable diesel in the following results sections. This fuel is produced from renewable biomass sources, such as fatty acids from vegetable oils and animal fats, via a hydrotreating process (Rantanen et al. 2005; Kuronen et al. 2007).

The two biodiesel feedstocks (one soy-based and one animal-based) were blended at levels of B5, B20, B50, and B100, and the renewable and the GTL diesel fuel were blended at 20%, 50%, and 100% levels. For the engine testing, the biodiesel, renewable and GTL diesels were tested at all of the blend levels. For the chassis testing, the blends were tested at only the 20%, 50%, and 100% blend levels because the typically greater variability for the chassis dynamometer testing would make it difficult to identify trends for lower blend levels, such as 5-10%. The fuels for all testing utilized the same batches of primary fuels, and the blending for all testing was also done at the same time.

Test Matrix

Testing for this program was conducted on a wide range of engines from heavy-duty on-highway engines, off-road engines, and heavy-duty vehicles. A breakdown of the engines/vehicles used for this testing is provided in Table ES-1. The 2007 MBE4000 engine and the 2010 Cummins ISX15 were both equipped with original equipment manufacturer (OEM) aftertreatment systems. The 2007 MBE4000 engine was equipped with a diesel particle filter (DPF) and the 2010 Cummins ISX15 was equipped with a DPF and a selective catalytic reduction (SCR) system. The 2010 Cummins ISX15 engine is certified to EPA 2010 model year standards, with a NO_x

certification level of 0.22 g/bhp-hr and a PM certification level of 0.08 g/bhp-hr. The 2006 Cummins ISM and the 2007 MBE4000 engine were both tested in their original chassis were removed from the chassis for the engine dynamometer testing.

Table ES-1. A Breakdown of the Test Engines for the Different Categories of Testing

Engine	Category	Test type	Other
2006 Cummins ISM	Heavy-duty on-highway	Engine dynamometer	
2007 MBE4000	Heavy-duty on-highway	Engine dynamometer	
1998, 2.2 liter, Kubota V2203-DIB	Off-road	Engine dynamometer	
2009 John Deere 4.5 L	Off-Road	Engine dynamometer	
2000 Caterpillar C-15	Heavy-duty on-highway	Chassis dynamometer	Freightliner chassis
2006 Cummins ISM	Heavy-duty on-highway	Chassis dynamometer	International chassis
2007 MBE4000	Heavy-duty on-highway	Chassis dynamometer	Freightliner chassis
2010 Cummins ISX15	Heavy-duty on-highway	Chassis dynamometer	Kenworth chassis

Test Procedures

Testing of the heavy-duty on-road engines was conducted using up to 4 different engine test cycles including a light loaded Urban Dynamometer Driving Schedule (UDDS) cycle, the Federal Test Procedure (FTP), and 40 mph and 50 mph CARB heavy heavy-duty diesel truck (HHDDT) cruise cycles. These cycles were selected to represent different operating conditions, and low, medium, and high loads. The engine dynamometer test cycles for the UDDS, and 40 and 50 mph cruise cycles were developed from torque and engine rpm data collected as these cycles were run on a chassis dynamometer. For the 2006 Cummins ISM, the UDDS and 40 mph cruise cycles were developed from data collected specifically from the actual test engine. The 50 mph cruise cycle for the 2006 Cummins ISM utilized cycle information that was developed from data collected through the E55/59 chassis dynamometer study of heavy-duty trucks (Clark et al., 2007) and subsequently utilized for cycles for the ACES program. For the 2007 MBE4000, the UDDS and the 50 mph cycles was developed from engine data directly from that engine.

The off-road engines were tested using the ISO 8178, Part 4 “Test Cycle Type C1 off-road vehicles, industrial and Medium/High load.” This test cycle is composed of 8 steady-state modes. The cycle includes 4 modes conducted at the rated speed at 4 different loads, 3 modes conducted at the intermediate speed at 3 different loads, and 1 mode at idle.

Two test cycles were utilized for the chassis dynamometer testing, UDDS and CARB HHDDT 50 mph Cruise cycle. These test cycles were designed to provide a range of loads, with the UDDS representing a medium load and the 50 mph cruise cycle representing a high load. The test cycles were performed at different test weights to provide a broader range of load over which the impacts of biodiesel could be investigated, with the UDDS loaded with a medium weight and the 50 mph cruise cycle being loaded near the high end of the vehicle gross vehicle weight rating (GVWR).

The test matrix for the different portions of the study was designed to provide randomization along with long range replication. This sequence included replication of the CARB fuel at

regular intervals within the sequence of testing the biodiesel/renewable/GTL diesel blends, and testing the cycles in a random order for each fuel sequence. For the DPF equipped 2007 MBE4000, a regeneration was incorporated with each fuel change. This eliminated the possibility of regeneration occurring randomly during the emissions test sequence, but at the same time this represents a limitation in that the fuel impacts during regeneration could not be evaluated.

Emissions Measurements

Emissions measurements for the heavy-duty on-highway engine dynamometer test and the off-road engine tests focused primarily on standard emissions, including total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2). More extensive testing was conducted for the heavy-duty chassis dynamometer testing, which included regulated emissions, real-time PM analysis, and sampling for exhaust composition, toxicity, and health effects. For PM composition, analyses were done for organic and elemental carbon, ions, and elements. Toxic analyses included polyaromatic hydrocarbons (PAHs), nitro-PAHs, and oxy-PAHs, volatile organic compounds (VOC), and carbonyls. The health effects analyses include mutagenicity, oxidative stress, inflammation, and DNA damage.

Biodiesel Characterization Results – Heavy-Duty Engine Testing

Tables ES-2 to ES-5 show the percentage differences for the soy-based and animal-based biodiesel feedstocks, respectively, compared with the CARB ULSD for different test engines, blend levels, and test cycles, along with the associated p-values for statistical comparisons using a 2-tailed, 2 sample equal variance t-test. For the discussion of the on-road engine dynamometer testing results in this report, results are considered to be statistically significant for the for p-values ≤ 0.05, which represents a 95% confidence level. The statistically significant results are shaded in the tables.

The NO_x emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock on two different mentioned engines are presented in Figures ES-1 to ES-4, respectively, on a gram per brake horsepower hour (g/bhp-hr) basis. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination. The error bars represent one standard deviation on the average value.

Table ES-2. Percentages changes for Soy-Biodiesel blends relative to CARB and associated statistical p-values 2006 Cummins

		THC		CO		NO_x		PM		CO_2		BSFC	
		% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
UDDS	B20	-12%	0.000	5%	0.115	4.1%	0.002	-24%	0.002	0.8%	0.448	1.8%	0.093
	B50	-28%	0.000	26%	0.000	9.8%	0.000	-30%	0.000	2.5%	0.055	5.1%	0.001
	B100	-55%	0.000	62%	0.000	17.4%	0.000	-33%	0.000	4.2%	0.003	9.8%	0.000
FTP	B5-mit	-1%	0.087	-1%	0.471	2.2%	0.000	-6%	0.000	0.1%	0.816	0.3%	0.228
	B10-mit	-6%	0.000	-2%	0.171	2.6%	0.000	-17%	0.000	-0.1%	0.569	0.3%	0.167
	B20	-11%	0.000	-3%	0.078	6.6%	0.000	-25%	0.000	0.4%	0.309	1.4%	0.001
	B50	-29%	0.000	-4%	0.038	13.2%	0.000	-46%	0.000	0.5%	0.159	3.1%	0.000
	B100	-63%	0.000	3%	0.163	26.6%	0.000	-58%	0.000	1.5%	0.007	6.8%	0.000
40 mph Cruise	B5	-1%	0.573	2%	0.427	1.7%	0.135	-6%	0.101	1.7%	0.085	1.9%	0.065
	B20	-16%	0.000	-3%	0.160	3.9%	0.000	-26%	0.000	0.8%	0.056	1.8%	0.001
	B50	-36%	0.000	0%	0.986	9.1%	0.000	-48%	0.000	1.3%	0.053	3.8%	0.000
	B100	-70%	0.000	0%	0.868	20.9%	0.000	-69%	0.000	3.0%	0.000	8.4%	0.000
50 mph Cruise	B5	-2%	0.222	1%	0.649	-1.1%	0.588	-5%	0.036	0.0%	0.959	0.3%	0.690
	B20	-12%	0.000	-2%	0.330	0.5%	0.800	-18%	0.000	0.6%	0.227	1.6%	0.002
	B50	-31%	0.000	-6%	0.002	6.3%	0.001	-43%	0.000	1.2%	0.008	3.8%	0.000
	B100	-68%	0.000	-14%	0.000	18.3%	0.000	-50%	0.000	2.6%	0.000	8.0%	0.000

Table ES-3. Percentages changes for Animal-Biodiesel blends relative to CARB and associated statistical p-values 2006 Cummins ISM

		THC		CO		NO_x		PM		CO_2		BSFC	
		% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
UDDS	B20	-16%	0.000	-10%	0.000	-1.5%	0.376	-10%	0.009	-0.6%	0.640	1.2%	0.404
	B50	-38%	0.000	-12%	0.000	0.1%	0.935	-24%	0.001	1.2%	0.201	3.1%	0.005
	B100	-73%	0.000	-20%	0.000	1.9%	0.243	-31%	0.000	2.5%	0.016	6.7%	0.000
FTP	B5	-3%	0.011	-4%	0.008	0.3%	0.298	-9%	0.000	-0.3%	0.191	2.9%	0.031
	B20	-13%	0.000	-7%	0.000	1.5%	0.000	-19%	0.000	0.1%	0.733	1.4%	0.145
	B50	-36%	0.000	-14%	0.000	6.4%	0.000	-42%	0.000	0.4%	0.117	1.8%	0.038
	B100	-71%	0.000	-27%	0.000	14.1%	0.000	-64%	0.000	0.7%	0.018	4.4%	0.001
50 mph Cruise	B20	-14%	0.000	-7%	0.003	-2.3%	0.151	-16%	0.000	0.7%	0.170	2.6%	0.010
	B50	-37%	0.000	-9%	0.066	0.8%	0.588	-35%	0.000	1.5%	0.014	3.5%	0.000
	B100	-73%	0.000	-25%	0.000	5.3%	0.000	-59%	0.000	1.6%	0.008	5.9%	0.000

Table ES-4. Percentages changes for Soy-Biodiesel blends relative to CARB and associated statistical p values 2007 MBE4000

		THC		CO		NO_x		PM		CO_2		BSFC	
		% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
UDDS	B20	-11%	0.770	-62%	0.453	4.4%	0.005	-94%	0.187	0.0%	0.971	1.0%	0.121
	B50	27%	0.400	-111%	0.154	15.3%	0.000	9%	0.874	0.9%	0.334	2.5%	0.083
	B100	-18%	0.683	-67%	0.491	36.6%	0.000	-37%	0.470	5.0%	0.000	8.3%	0.000
FTP	B5	38%	0.005	-20%	0.135	0.9%	0.007	-61%	0.096	0.0%	0.398	0.3%	0.113
	B20	33%	0.005	13%	0.534	5.9%	0.000	-4%	0.944	0.0%	0.909	1.0%	0.016
	B50	25%	0.018	-50%	0.031	15.3%	0.000	58%	0.216	0.2%	0.722	1.7%	0.034
	B100	20%	0.081	-74%	0.002	38.1%	0.000	64%	0.403	2.4%	0.000	5.6%	0.000
50 mph Cruise	B20	-5%	0.801	-6%	0.809	6.9%	0.000	-19%	0.746	0.4%	0.249	1.5%	0.002
	B50	-20%	0.430	-33%	0.302	18.2%	0.000	2%	0.970	0.4%	0.548	1.9%	0.081
	B100	-13%	0.594	-21%	0.508	47.1%	0.000	-100%	0.704	2.6%	0.000	5.9%	0.000

Table ES-5. Percentages changes for Animal-Biodiesel blends relative to CARB and associated statistical p values 2007 MBE4000

		THC		CO		NO_x		PM		CO_2		BSFC	
		% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
UDDS	B20	33%	0.000	18%	0.003	1.6%	0.000	224%	0.779	0.0%	0.000	0.2%	0.000
	B50	8%	0.695	-16%	0.875	7.3%	0.000	285%	0.219	1.0%	0.024	1.2%	0.008
	B100	6%	0.755	109%	0.238	16.0%	0.000	1043%	0.000	1.5%	0.009	8.1%	0.000
FTP	B5	13%	0.612	-11%	0.202	1.3%	0.000	-32%	0.553	0.3%	0.007	0.5%	0.001
	B20	13%	0.376	-3%	0.841	5%	0.000	-40%	0.341	0.1%	0.743	0.3%	0.182
	B50	-13%	0.568	-39%	0.040	12.1%	0.000	15%	0.757	0.2%	0.391	0.4%	0.069
	B100	5%	0.756	-73%	0.000	29%	0.000	-24%	0.611	1.6%	0.000	8%	0.000
50 mph Cruise	B20	17%	0.425	-7%	0.733	5.9%	0.000	-49%	0.143	0.0%	0.837	0.2%	0.301
	B50	-13%	0.448	-36%	0.144	16.3%	0.000	-58%	0.103	0.4%	0.150	0.6%	0.036
	B100	3%	0.905	-55%	0.027	39.4%	0.000	-39%	0.237	1.3%	0.002	7.8%	0.000

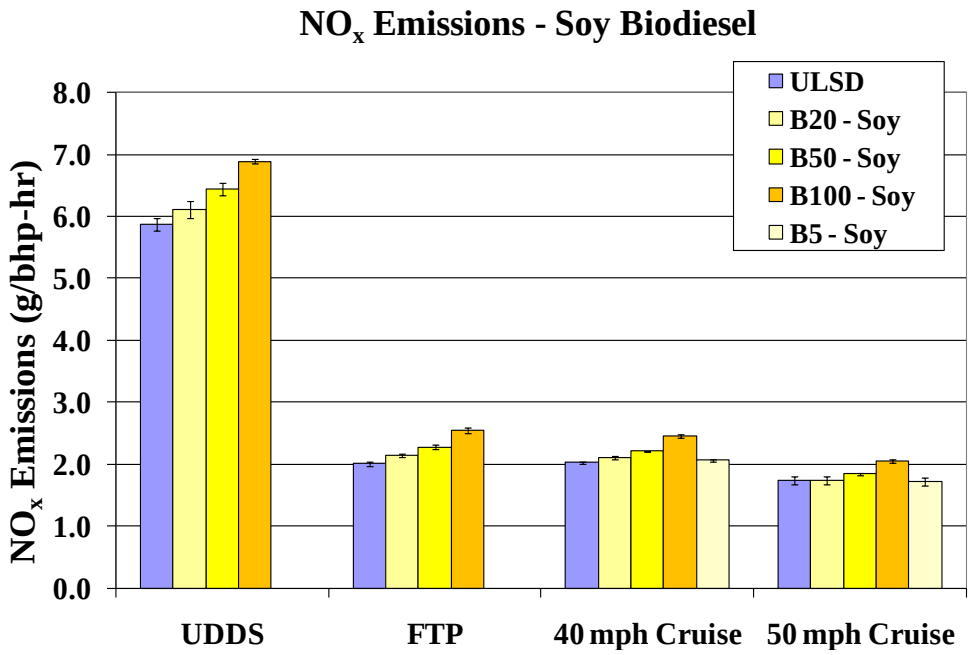


Figure ES-1. Average NO_x Emission: Soy-Based Biodiesel Feedstock 2006 Cummins ISM

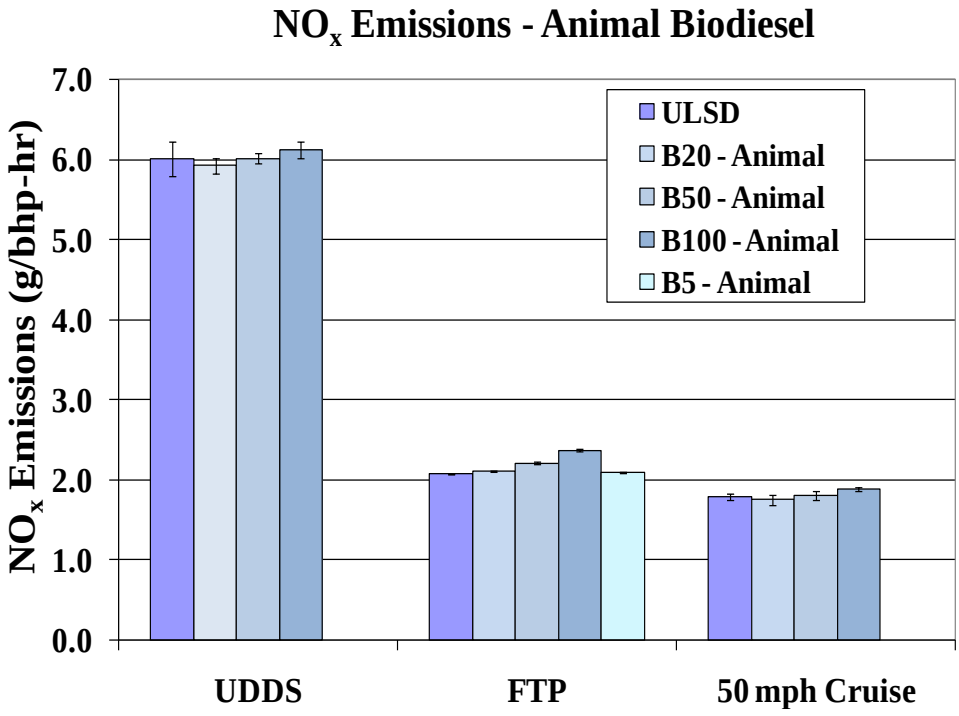


Figure ES-2. Average NO_x Emission: Animal-Based Biodiesel Feedstock 2006 Cummins ISM

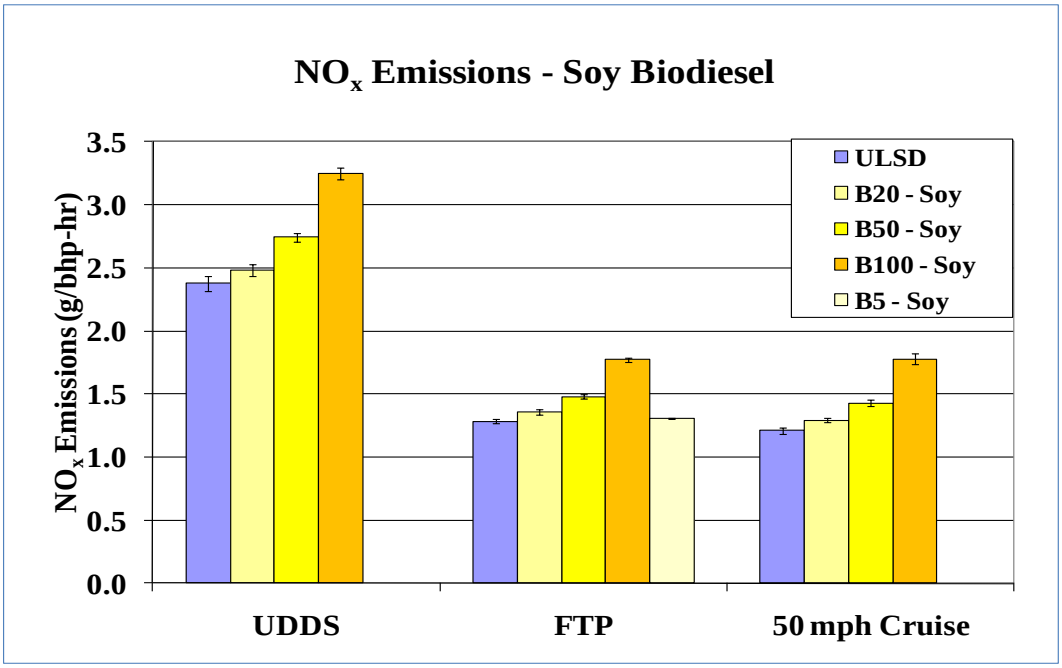


Figure ES-3. Average NO_x Emission: Soy-Based Biodiesel Feedstock 2007 MBE4000

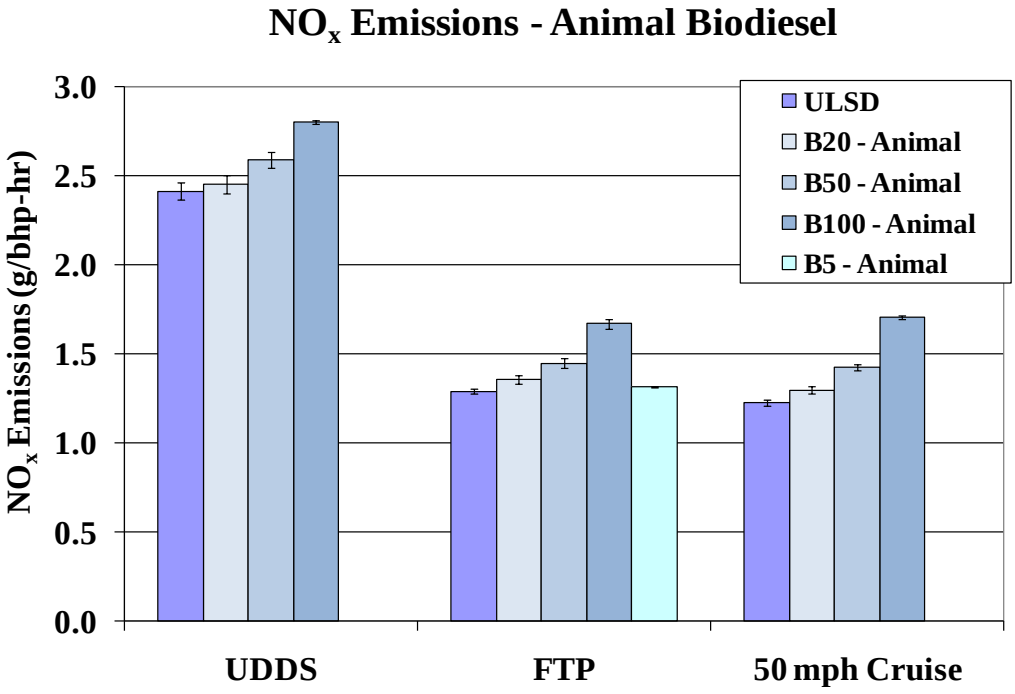


Figure ES-4. Average NO_x Emission: Animal-Based Biodiesel Feedstock 2007 MBE4000

For both the 2006 Cummins and 2007 MBE4000 engines, the average NO_x emissions show trends of increasing NO_x emissions with increasing biodiesel blend level, but the magnitude of the effects differ between the different feedstocks. The soy-based biodiesel blends showed a

higher increase in NO_x emissions for essentially all blend levels and test cycles in comparison with the animal-based biodiesel blends.

For the 2006 Cummins engine, for the soy-based biodiesel over the FTP, the NO_x impact ranged from an increase of 2.2% at the B5 level, to 6.6% at the B20 level, to 27% at the B100 level. The biodiesel emissions impacts for the other cycles were comparable to but less than those found for the FTP for the different blend levels, although the impacts for the 50 mph cruise cycle were obscured by changes in the engine operation and control strategy that occurred during the cycle, as discussed further below. These increases were higher than the EPA base case estimates for all of the test cycles. The NO_x impacts found for the soy-based biodiesel were consistent, however, with the EPA estimates for the "clean base fuel" case, which would be more representative of a CARB diesel fuel.

For the 2006 Cummins engine, for the animal-based biodiesel feedstock, the NO_x emission increases with biodiesel for the FTP cycle were consistent with the EPA base case estimates. The NO_x impact for the animal-based biodiesel over the FTP ranged from an increase of 1.5% at the B20 level to 14% at the B100 level. For the lower load UDDS cycle for the animal-based biodiesel feedstock, the emissions differences were not statistically significant for any of the blend levels. For the 50 mph cruise cycle, a statistically significant increase in NO_x emissions was only found for the B100 animal-based biodiesel. The 50 mph cruise results were obscured, however, by changes in the engine operation and control strategy that occurred over a segment of this cycle.

For the 2007 MBE4000 engine, the magnitude of the NO_x emissions increases, on percentage basis, were greater than those for the 2006 Cummins engine for nearly all biodiesel blends and test cycles. The absolute differences in the emission levels for the CARB and biodiesel fuels, however, were less for the 2007 MBE4000, due to its lower overall NO_x emission levels. The emissions increases for the both the soy-based and the animal-based biodiesel were higher than those for the EPA base case estimates. The NO_x increases for the soy-based biodiesel were also higher than those for the EPA estimates for a clean base fuel for most test combinations. The animal-based biodiesel showed estimates comparable to the EPA clean base fuel estimates for the FTP, but showed a lower NO_x impact for the lighter load UDDS cycle and a higher NO_x impact for the 50 mph cruise cycle.

NO_x emissions were found to increase as a function of engine load for both engines, as expected. Comparing different cycles for 2006 Cummins engine, the FTP showed the strongest NO_x increases for biodiesel for both soy-based and animal-based blends. The impact of biodiesel on NO_x emissions was not found to be a strong function of engine load, as was observed in previous studies by EPA (Sze et al., 2007). This trend was obscured, however, by the differences in engine operation that were observed for the 50 mph cruise cycle. For the 2007 MBE4000 engine, the animal-based biodiesel testing showed increases in the NO_x differential with increasing cycle power. There were also some trends of a higher NO_x differential for the B50 and B100 soy-based biodiesels on the highest load 50 mph cruise cycle, as well as a slight trend with these fuels for the other cycles.

PM emissions, for 2006 Cummins engine, showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. This is consistent with a majority of the previous studies of emissions from biodiesel blends. The PM reductions for both the soy-based and animal-based biodiesel blends were generally larger than those found in the EPA study, and are closer to the estimates for a base case fuel than a clean base fuel. Over the FTP, the PM reductions for the soy-based biodiesel ranged from 6% for a B5 blend, to 25% for a B20 blend, to 58% for B100. For the animal-based biodiesel over the FTP, the PM reductions ranged from 19% for the B20 blend to 64% for B100. The smallest reductions were seen for the UDDS, or the lightest loaded cycle. The PM reductions for biodiesel for the FTP and the cruise cycles were comparable for both fuels. Although there were some differences in the percent reductions seen for the soy-based and animal-based biodiesel fuels, there were no consistent differences in the PM reductions for these two feedstocks over the range of blend levels and cycles tested here.

THC emissions for the 2006 Cummins engine showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. The THC reductions over the FTP for the soy-based biodiesel ranged from 6% for a B10 blend, to 11% for a B20 blend, to 63% for B100. For the animal-based biodiesel over the FTP, the THC reductions ranged from 13% for the B20 blend to 71% for B100. Overall, the THC reductions for the 2006 Cummins engine seen in this study are consistent with and similar to those found by EPA. The THC reductions for both the soy-based and animal-based biodiesel blends for B100 were closer to those found in the EPA study for the B100 level for the base case fuels, while the lower blend levels (i.e., B20 and B50), were in between those estimated by EPA for the clean and base case fuels. For the soy-based biodiesel, the reductions are slightly less for the lower load UDDS, but for the animal-based biodiesel the THC reductions for all the test cycles were similar. There was not a strong trend in the THC reductions with biodiesel as a function of either power or fuel consumption.

CO emissions, for 2006 Cummins Engine, showed consistent and significant reductions for the animal-based biodiesel blends, consistent with previous studies. Over the FTP, the CO reductions for the animal-based biodiesel ranged from 7% for a B5 blend, to 14% for a B20 blend, to 27% for B100. The CO reductions seen for the animal-based biodiesel are comparable to those seen for the EPA clean base fuel estimates, but are lower than those for the EPA base case. The CO trends for the soy-based biodiesel were less consistent. The CO emissions for the soy-based biodiesel did show consistent reductions with increasing biodiesel blend levels for the highest load, the 50 mph cruise cycle. For the FTP and 40 mph cruise cycles, the soy-based biodiesel blends did not show any strong trends relative to the CARB ULSD and a number of differences were not statistically significant. Interestingly, the CO emissions for the lowest load UDDS cycle showed higher emissions for the biodiesel blends, with the largest increase (62%) seen for the highest blend level. Additional testing would likely be needed to better understand the nature of these results, which are opposite the trends seen in most previous studies.

For the 2007 MBE4000 engine, the PM, THC, and CO emissions were all well below certification limits and the emission levels for the 2006 Cummins due to the DPF. For the most part, PM, THC, and CO differences between fuels were not statistically significant. For THC, one exception to this was for the soy-based biodiesel, which actually showed statistically

significant increases ranging from 20 to 33% compared to the CARB diesel over the FTP. CO emissions did show lower emissions for the B50 and B100 fuels over the FTP as well. It should be noted that in the cases where statistically significant differences were found, the differences were small on an absolute basis and additional tests would be needed to verify these trends on a larger set of fuels/engines.

Throughout the course of testing on the 2006 Cummins engine some outliers were observed in the testing that appeared to be related to conditions set within the engine control module (ECM). Changes in engine operation were observed within the 50 mph CARB HHDDT cycle. For this test cycle, for a period of the test cycle from approximately 300 to 400 seconds, two distinct modes of operation were observed. These tests were not removed from the analysis, as it was surmised that these conditions could potentially occur in real-world operation. During initial testing, significant changes were also found when the temperature of the coolant water to the charge air cooler dropped below 68°F. This situation was remedied and these tests were removed from the subsequent analyses.

CO_2 emissions showed a slight increase for the higher biodiesel blends. For the 2006 Cummins engine, this increase ranged from about 1-4%, with the increases being statistically significant for the B100 fuels for all of the tests, for the B50 fuel for the cruise cycles, and for some other testing combinations. For the 2007 MBE4000 engine, only the B100 blends showed consistent, statistically significant increases in CO_2 emissions for the different cycles, with the increases ranging from 1-5%.

The biodiesel blends showed an increase in fuel consumption with increasing levels of biodiesel. This is consistent with expectations based on the lower energy density of the biodiesel. The fuel consumption differences were generally greater for the soy-based biodiesel in comparison with the animal-based biodiesel for the 2006 Cummins engine, but not for the 2007 MBE4000 engine. The changes in fuel consumption for the soy-based biodiesel blends for the 2006 Cummins engine range from 1.4 to 1.8% for B20 to 6.8 to 9.8% for B100. The changes in fuel consumption for the animal-based biodiesel blends for the 2006 Cummins engine range from no statistical difference to 2.6% for B20 to 4.4 to 6.7% for B100. For the 2007 MBE4000 engine, the differences in fuel consumption ranged from no change to 2.5% for B50 and lower blends, while the increases for the B100 blends ranged from 5.6 to 8.3%.

Renewable & GTL Diesel Results – Heavy-Duty Engine Testing

Table ES-6 shows the percentage differences for the renewable and the GTL fuels compared with the CARB ULSD for different blend levels and test cycles, along with the associated p-values for statistical comparisons using a 2-tailed, 2 sample equal variance t-test.

For the renewable and GTL diesel fuels, the results show a steady decrease in NO_x emissions with increasingly higher levels of renewable/GTL diesel fuel. The NO_x emission results for the testing with the renewable diesel and the GTL diesel are presented in Figures ES-5 and ES-6, respectively, on a gram per brake horsepower hour (g/bhp-hr) basis. Over the FTP cycle, the NO_x reductions for the renewable and GTL diesel were comparable for each of the blend levels. For the FTP, the NO_x reductions for the renewable diesel ranged from 2.9% for the 20% blend to

9.9% for the 100% blend, while the NO_x reductions for the GTL ranged from ~1% for the 20% blend to 8.7% for the 100% blend. Larger emissions reductions were found over the UDDS and Cruise cycles, where only the renewable diesel fuel was tested. The reductions in NO_x for the renewable diesel fuel are comparable to those found in previous studies of heavy-duty engines. In comparison with the biodiesel feedstocks, the levels of NO_x reduction for the renewable and GTL fuels are generally less than the corresponding increases in NO_x seen for the biodiesel blends. With respect to NO_x mitigation, this suggests that the renewable and GTL diesel fuel levels need to be blended at higher levels than the corresponding biodiesel in order to mitigate the associated NO_x increase, as discussed in further detail below.

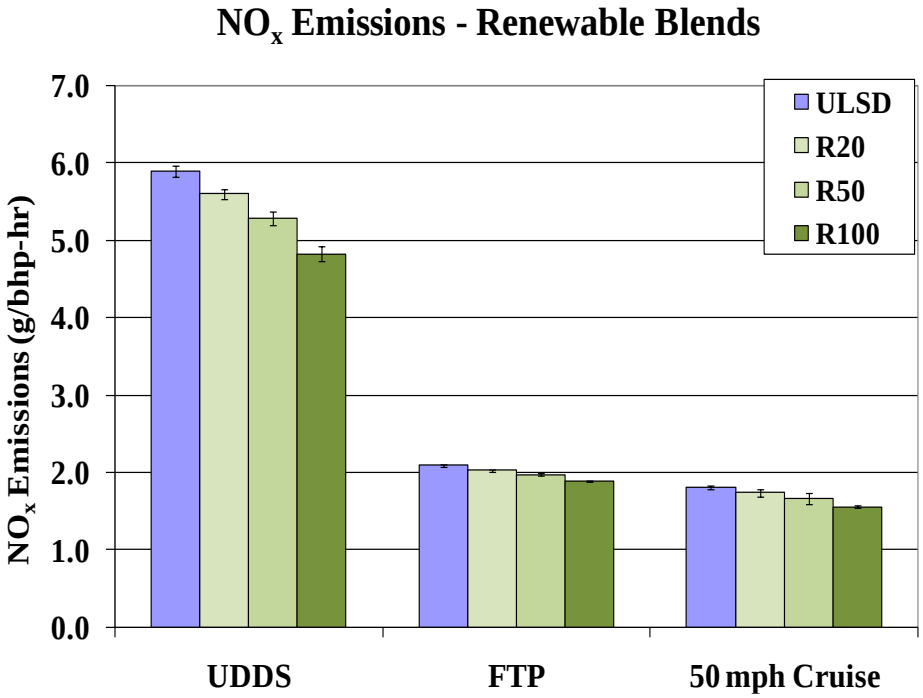


Figure ES-5. Average NO_x Emission Results for the Renewable Blends

Table ES-6. Percentages changes and associated statistical p values for Renewable and GTL blends relative to CARB for the 2006 Cummins

		THC		CO		NO_x		PM		CO_2		BSFC	
		% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
UDDS	R20	-3%	0.018	-16%	0.000	-4.9%	0.000	-5%	0.401	-0.4%	0.595	1.0%	0.255
	R50	-6%	0.002	-23%	0.000	-10.2%	0.000	-12%	0.044	-0.7%	0.448	3.1%	0.007
	R100	-12%	0.000	-33%	0.000	-18.1%	0.000	-28%	0.000	-3.3%	0.002	5.1%	0.000
FTP	R20	0%	0.719	-4%	0.022	-2.9%	0.000	-4%	0.023	-0.3%	0.652	1.1%	0.117
	R50	0%	0.777	-8%	0.000	-5.4%	0.000	-15%	0.000	-1.0%	0.124	2.9%	0.001
	R100	-4%	0.057	-12%	0.000	-9.9%	0.000	-34%	0.000	-3.4%	0.000	5.2%	0.000
	GTL20	-5%	0.000	-6%	0.000	-0.9%	0.053	-8%	0.000	0.0%	0.933	1.3%	0.001
	GTL50	-16%	0.000	-10%	0.000	-5.2%	0.000	-12%	0.000	-1.9%	0.001	1.4%	0.008
	GTL100	-28%	0.000	-14%	0.000	-8.7%	0.000	-29%	0.000	-3.5%	0.000	3.3%	0.000
50 mph Cruise	R20	2%	0.207	0%	0.831	-3.8%	0.007	-3%	0.220	0.0%	0.972	1.4%	0.107
	R50	2%	0.230	1%	0.234	-7.8%	0.000	-14%	0.000	0.0%	0.996	4.0%	0.000
	R100	-1%	0.510	3%	0.022	-14.2%	0.000	-24%	0.000	-2.1%	0.011	6.6%	0.000

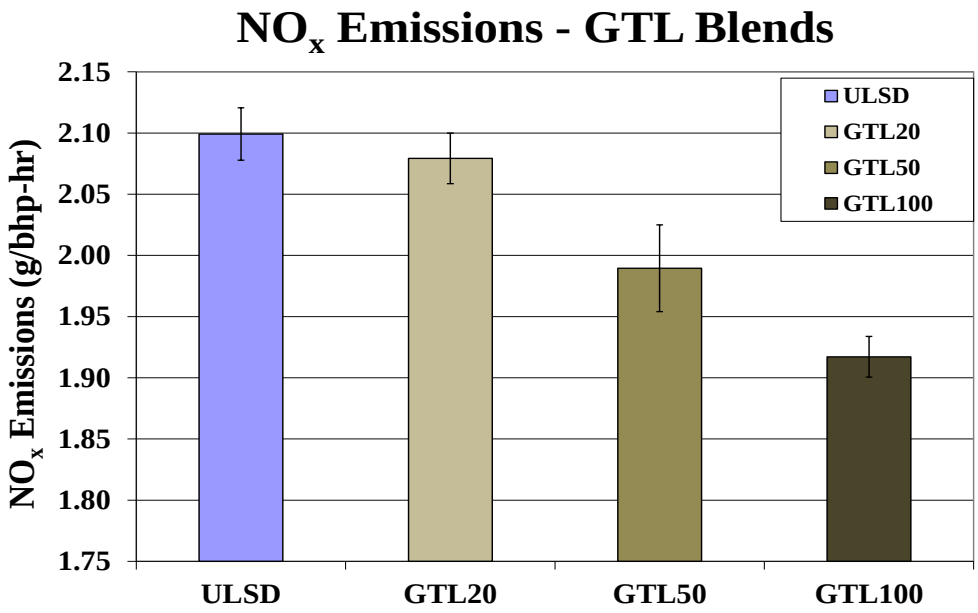


Figure ES-6. Average NO_x Emission Results for the GTL Blends

PM emissions showed consistent and significant reductions for the renewable and GTL blends, with the magnitude of the reductions increasing with blend level. The reductions for the renewable diesel were statistically significant for the higher blends and ranged from 12-15% for the R50 and from 24-34% for the R100. A statistically significant 4% reduction was also found for the R20 over the FTP. The GTL fuel showed a statistically significant reduction over the FTP, with reductions ranging from 8% for the 20% blend to 29% for the 100% blend. Similar reductions are found for the UDDS, FTP, and Cruise cycles indicating that cycle load does not have a significant impact on the PM reductions.

For the THC emissions, the GTL fuel showed statistically significant reductions over the FTP that increased with increasing blend level. These reductions ranged from 5% for the 20% blend to 28% for the 100% blend. The renewable diesel did not show consistent trends for THC emissions over the different test cycles. This finding was consistent with predictions based on the EPA's Unified Model and the associated distillation temperatures and other parameters of the fuels that showed there should not be any significant differences between the THC emissions for the CARB fuel in comparison with the renewable winter blend used in the study (Hodge, 2009). Statistically significant THC reductions were found for the renewable diesel fuel for the lowest load UDDS cycle, with the THC reductions increasing with increasing levels of the renewable diesel fuel.

Reductions in CO emissions with the renewable diesel fuel were found for the UDDS and FTP cycles, but not for the cruise cycle. Over these cycles, the percentage reductions increased with increasing renewable diesel fuel blend. Over the FTP, these reductions ranged from 4% for the R20 to 12% for the R100. The comparisons of CO emissions over the 50 mph cruise were complicated by the changes in engine operation that were seen for that cycle, as discussed above.

The GTL fuel also showed similar reductions over the FTP, with reductions ranging from 6% for the GTL20 blend to 14% for the GTL100 blend.

The CO_2 emissions for the neat or 100% blend renewable and GTL fuels were lower than those for the CARB ULSD for each of the test cycles. The reduction was on the order of 2-4% for the 100% blends. This slight reduction in CO_2 emissions is consistent and comparable to previous studies of the renewable diesel fuel.

The brake specific fuel consumption increased with increasing levels of renewable and GTL fuels. The increases in fuel consumption range from 1.0-1.4% for the R20 and 5.1 to 6.6% for the R100. The increases in fuel consumption with blend level are slightly higher for the cruise cycle compared to the lower load UDDS and FTP. The fuel consumption increases for the GTL ranged from 1.3% for the 20% blend to 3.3% for the 100% blend. The fuel consumption differences are consistent with the results from previous studies, and can be attributed to the lower density or energy density of the renewable and GTL fuels compared to the CARB baseline fuel.

Off-Road Engine Testing Results

Tables ES-7 to ES-8 show the percentage differences and statistical analysis results for the John Deere and TRU engines, respectively.

Table ES-7. Percentages changes and statistical analysis for the John Deere Engine.

		THC		CO		NO_x		PM		CO_2	
		% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
Soy-based	B20	-5.22%	0.498	-3.80%	0.142	2.82%	0.021	-23.25%	0.028	1.16%	0.154
	B50	-15.12%	0.104	-12.43%	0.001	7.63%	0.000	-31.75%	0.013	0.87%	0.082
	B100	-27.54%	0.001	-25.14%	0.000	13.76%	0.000	-55.93%	0.000	2.09%	0.001
Animal-based	B5	-7.54%	0.442	1.32%	0.603	-1.00%	0.314	-5.63%	0.151	0.48%	0.499
	B20	-12.22%	0.189	-6.98%	0.009	0.66%	0.528	-21.77%	0.000	1.12%	0.081
	B100	-47.13%	0.001	-29.54%	0.000	7.63%	0.000	-55.42%	0.000	1.23%	0.069

Table ES-8. Percentages changes and statistical analysis for the TRU Engine.

		THC		CO		NO_x		PM		CO_2	
		% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
Soy-based Series 1	B50	-22.77%	0.000	-22.42%	0.000	9.85%	0.000	-16.86%	0.000	1.38%	0.000
	B100	-57.12%	0.000	-49.01%	0.000	21.20%	0.000	-37.31%	0.000	2.96%	0.000
Soy-based Series 2	B5	3.01%	0.436	-1.46%	0.567	0.97%	0.412	-0.13%	0.594	-0.10%	0.753
	B20	-5.68%	0.153	-8.04%	0.005	2.25%	0.086	-6.91%	0.011	0.45%	0.114
	B100	-58.53%	0.000	-50.25%	0.000	18.89%	0.000	-40.30%	0.000	2.06%	0.000

The NO_x emission results for the John Deere and TRU engine testing are presented in Figures ES-7 to ES-8, respectively, on a gram per brake horsepower hour (g/bhp-hr) basis. The NO_x emissions show general increases with increasing biodiesel blend level for both off-road engines. The NO_x increases were statistically significant for the B100 blends and the soy-based B50 blends for both engines. The soy-based B20 blends also showed increases that were statistically significant for the John Deere engine and statistically significant at the less than 90% confidence level for the TRU engine. The NO_x increases for the TRU engine were comparable with the ones

obtained for the 2006 Cummins engine (9.8-13.2% for B50 & 17.4-26.6% for B100), but were lower than the ones obtained for the 2007 MBE4000 (15.3-18.2% for B50 & 36.6-47.1% for B100). The magnitude of the increases in NO_x emissions for the John Deere engine were less than those for either the TRU or the on-road heavy-duty engines. The animal-based biodiesel also did not show as great a tendency to increase NO_x emissions compared to the soy-based biodiesel for the John Deere engine, with only the B100 animal-based biodiesel showing statistically significant increases in NO_x emissions of 7.6%.

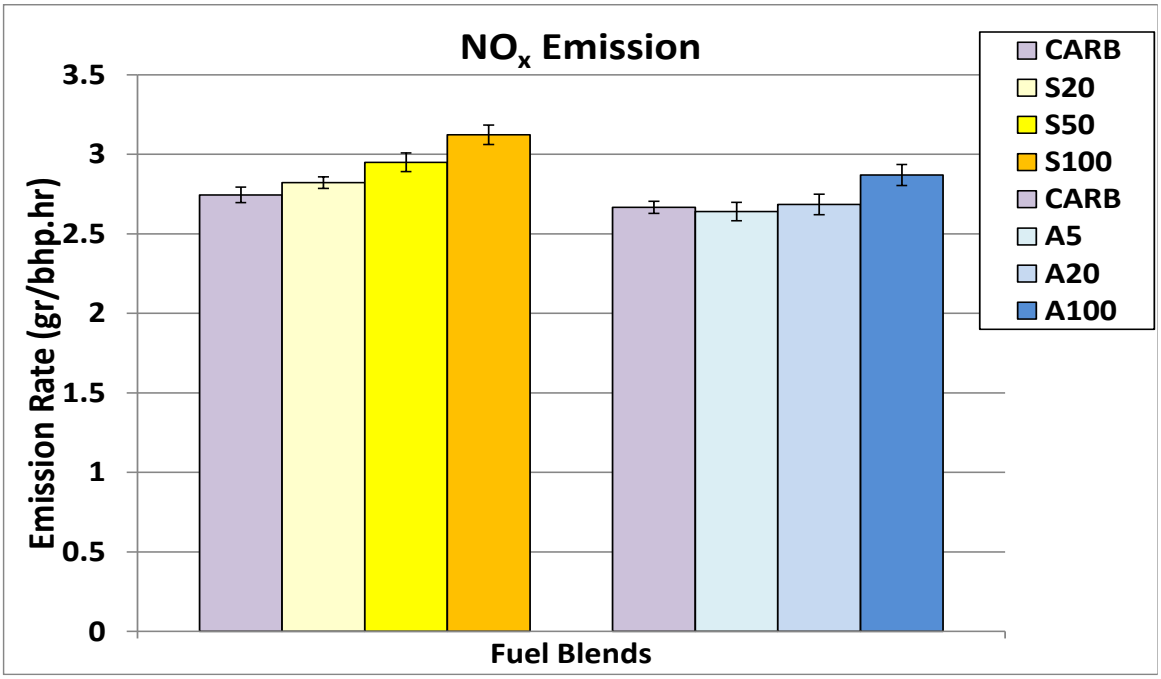


Figure ES-7. Average NO_x Emission Results for the John Deere Engine

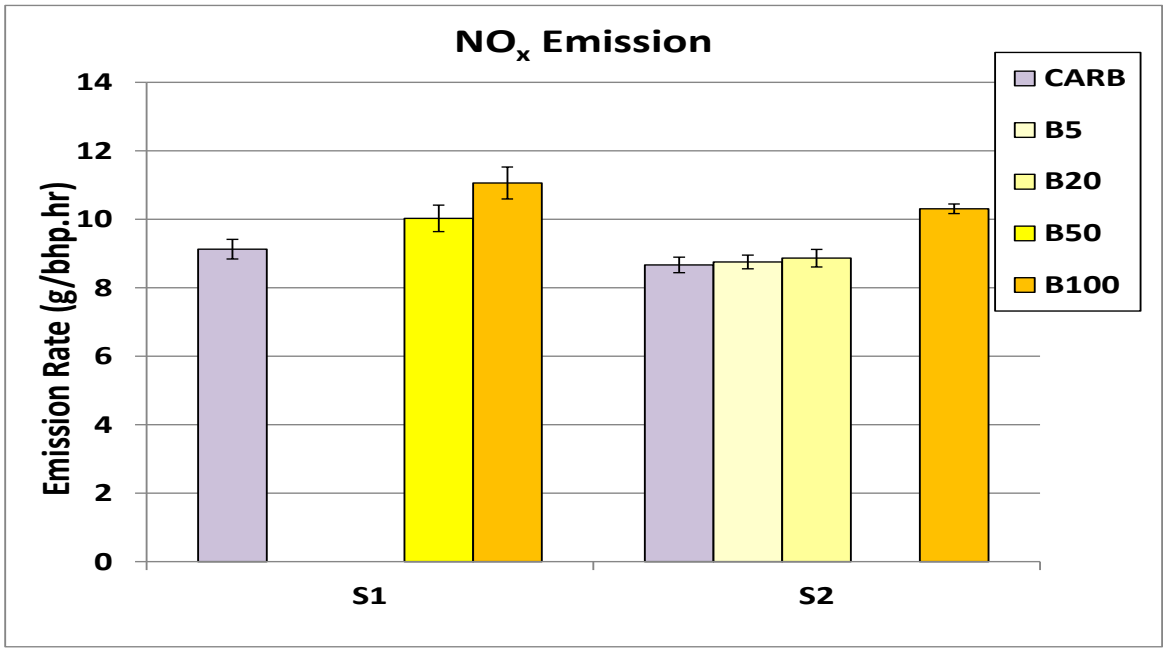


Figure ES-8. Average NO_x Emission Results for the TRU engine.

PM emissions showed consistent reductions with increasing biodiesel blend level for both the John Deere and the TRU engines. The magnitude of the reductions in the PM emissions for the John Deere engine were comparable to those of the 2006 Cummins ISM engine dynamometer tests, while the reductions seen for the TRU engine were less than those seen for the 2006 Cummins.

THC emissions showed consistent reductions with increasing biodiesel blend level for both the John Deere and the TRU engines. The magnitude of the reductions in the PM emissions depended on the specific engine/fuel/blend level combination. The THC reductions for the off-road engines were generally either comparable to slightly less than those seen for the 2006 Cummins ISM engine dynamometer testing.

CO emissions showed consistent reductions with increasing biodiesel blend level for both the John Deere and TRU engines. The CO reductions for the John Deere engine were comparable to those seen for the animal-based biodiesel for the 2006 Cummins ISM engine for the engine dynamometer testing, while the CO reductions for the TRU engine were generally greater than those found for the 2006 Cummins.

CO_2 emissions showed some slight increases (i.e., 1-3%) for the biodiesel blends for both the John Deere and TRU engines. These increases were statistically significant for the TRU engine for both the B50 and B100 blends on the first series of tests and for the B100 blend on the second series of tests. Increases of 1-5% in CO_2 emissions were also seen for the 2006 Cummins and 2007 MBE4000 in the on-road engine dynamometer testing. For the TRU engine, N_2O and CH_4 emissions were characterized along with CO_2 to provide total tailpipe greenhouse gases. These results showed that the B50 and B100 blends produced some increases in tailpipe greenhouse gas equivalent emissions relative to the CARB diesel. It must be emphasized that these increases represent only the tailpipe contribution to the greenhouse gas emissions. The actual contribution of each fuel towards total greenhouse gas emissions would need to be assessed through a full lifecycle analysis, which would account for the emissions attributed to harvesting, extracting, and producing the various fuels.

Heavy-Duty Chassis Dynamometer Testing Results – Regulated and Unregulated Emissions

Tables ES-9 through ES-11 show the percentage differences and the statistical analysis results for the vehicles equipped with 2000 Caterpillar C-15, 2006 Cummins ISM, and the 2007 MBE4000 engines, respectively. The shaded results represent p-values that were statistically significant or marginally statistically significant (i.e., a p-value between 0.05 and 0.1).

The NO_x emission results for the chassis dynamometer testing of the vehicles with the three engines discussed above are presented in Figures ES-9 to ES-11, respectively, on a gram per mile (g/mile) basis. For the heavy-duty chassis results, the NO_x emissions showed a consistent trend of increasing emissions with increasing biodiesel blend level. These differences were statistically significant or marginally statistically significant for nearly all of the test sequences for the B50 and B100 fuels, and for some B20 blends, but not others. The percentage increases for the NO_x emissions with biodiesel were generally greater for soy-based biodiesel compared

with the animal-based biodiesel. The magnitude of the increases in NO_x emissions for the biodiesel blends for the 2006 Cummins ISM engine were either greater than or comparable to those found for the engine testing on this engine. For the 2007 MBE4000, the overall NO_x increases are in the same range for the chassis and engine dynamometer testing, with some differences seen for cycle/fuel/blend level combinations. The results for the renewable diesel fuel showed NO_x reductions for the UDDS cycle, but not statistically significant reductions over the 50-mph cruise cycle, except at the 100% blend level. The magnitude of the reductions found for the renewable diesel was similar to those found in the engine testing.

PM emissions showed consistent reductions for the all biodiesel blends and both cycles, with the magnitude of the reductions increasing with blend level for the 2000 Caterpillar C-15 and the 2006 Cummins ISM. These reductions were statistically significant for nearly all of the B50 and B100 cases, but for only a subset of the B20 results. The PM emissions reductions for the chassis dynamometer testing are comparable to the reductions seen in the engine testing for the 2006 Cummins ISM engine for most testing combinations. The renewable blend also showed some statistically significant PM reductions for the R100 on the 2000 Caterpillar C-15, but no consistent trends for the other blend levels. PM emissions did not show any consistent trends for the DPF equipped 2007 MBE4000, since most of the combustion-related PM is eliminated by the DPF.

THC emissions showed reductions for the B100 for nearly all cycles for the non-DPF equipped engines and for the B50 for the 2006 Cummins ISM and the B50 animal-based biodiesel for the 2000 Caterpillar C-15. The reductions for the highest blend levels are less than those seen in the corresponding engine tests for the Cummins ISM and for the EPA estimates. The renewable diesel also showed lower THC emissions, but these were only statistically significant or marginally statistically significant for the R100 for the 2000 Caterpillar C-15 over the UDDS cycle.

CO emission results showed consistent and generally significant reductions for all biodiesel blends for the non-DPF-equipped engines, with higher reductions with increasing blend levels. The CO reductions were statistically significant for most of the B50 and B100 blends, and some of the B20 blends. For the renewable diesel, both the R50 and R100 showed reductions in CO that were either statistically significant or marginally statistically significant. CO emissions did not show consistent trends for the DPF equipped 2007 MBE4000, although statistically significant CO reductions were found for the B100 soy-based and animal-based blends for the UDDS cycle.

CO_2 emissions showed some reductions for the R100 and R50 fuels for the 2000 Caterpillar C-15 and some increases for the animal-based and soy-based biodiesel blends for the 2007 MBE4000, although these trends are not consistent across the range of vehicles/engines testing on the chassis dynamometer. The CO_2 increases fall within the 1-5% range that was seen in the heavy-duty engine dynamometer testing for the various biodiesel blends.

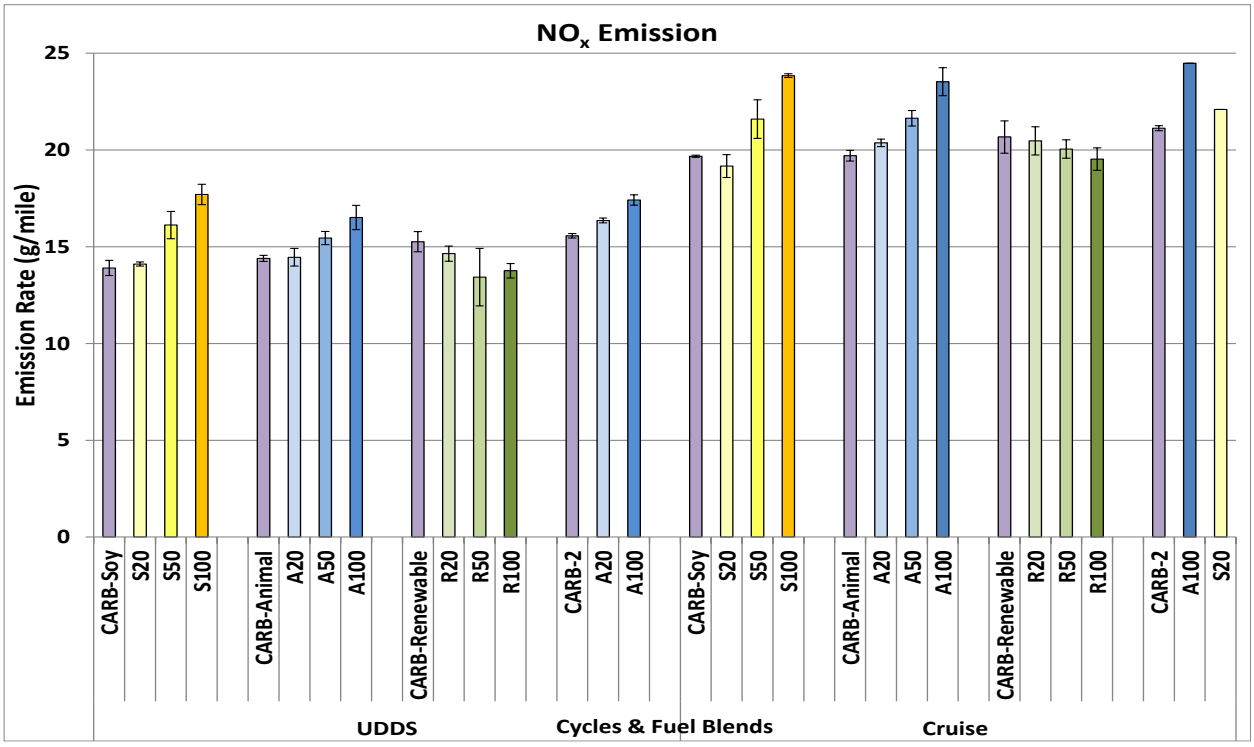


Figure ES-9. Average NO_x Emission Results for the Soy- and Animal-Biodiesel and Renewable Diesel Blends for 2000 Caterpillar C-15

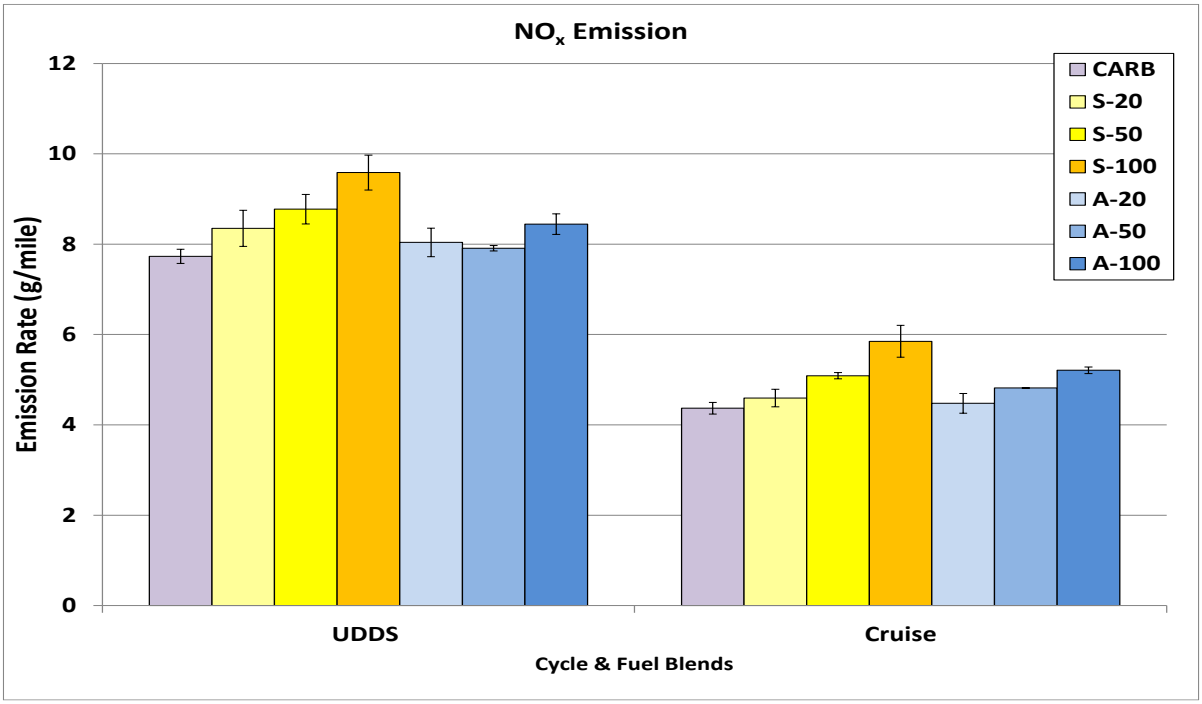


Figure ES-10. Average NO_x Emission Results for the Soy- and Animal-Biodiesel and Renewable Diesel Blends for 2006 Cummins

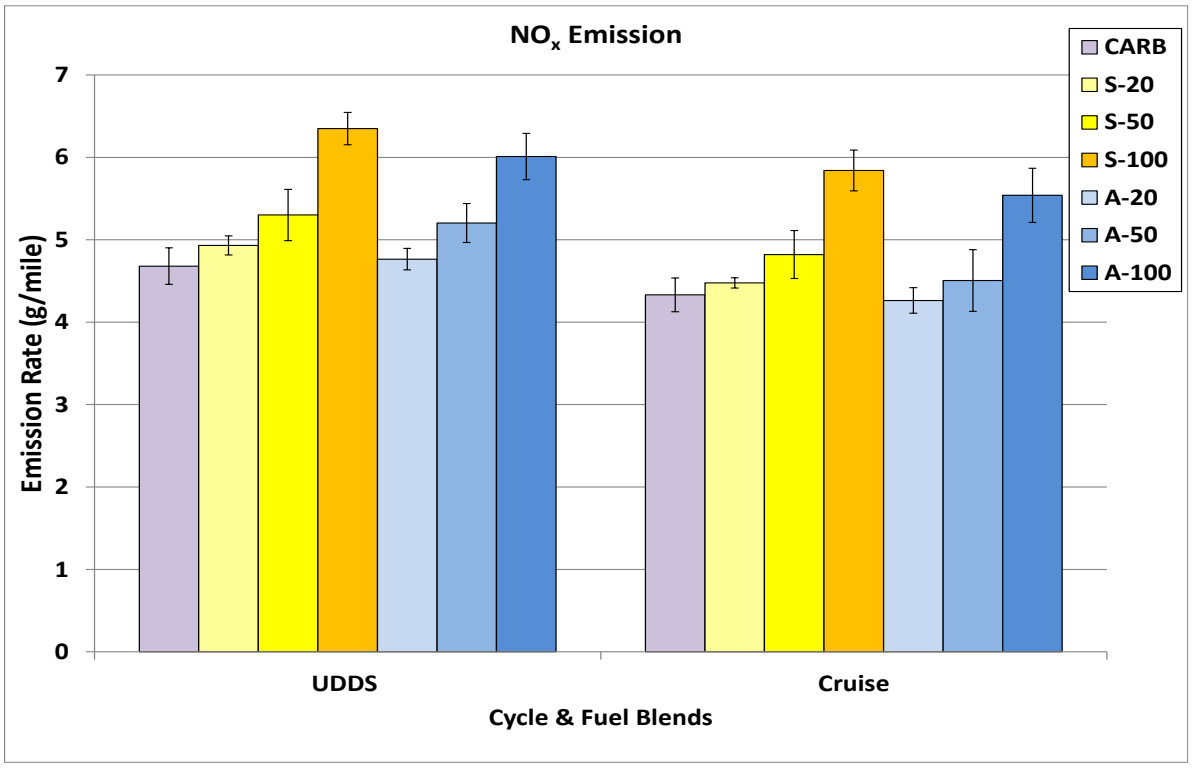


Figure ES-11. Average NO_x Emission Results for the Soy- and Animal-Biodiesel and Renewable Diesel Blends for 2007 MBE 4000

The VOC emissions measured for the chassis testing included benzene, toluene, ethylebenzene, 1,3-butadiene, *m-/p*-xylene and *o*-xylene. The VOC emissions typically only showed trends for the higher biodiesel blend levels, with the emissions for biodiesel being lower than those for CARB. Generally, the reductions in aromatic VOCs were consistent with the reduction in aromatics in the fuel. For the lower biodiesel blend levels, the differences with the CARB diesel were typically not significant. VOC emissions were typically higher on a g/mi basis for the UDDS cycle compared with the 50 mph Cruise cycle. Benzene emissions were the highest of the VOCs for both test cycles and each of the fuels for the Caterpillar C-15, while benzene and 1,3-butadiene were the highest VOCs for the Cummins ISM.

The PM mass was composed predominantly of carbonaceous material for all fuel combinations. The total carbon and the elemental carbon components of the PM both showed reductions increasing in magnitude at progressively higher biodiesel blends. Both of these trends are consistent with the overall reduction in PM mass with higher biodiesel levels. The organic carbon levels did not show significant differences between the different fuel blends, and in fact were relatively flat as a function of blend level. The renewable diesel blends showed trends of decreasing elemental and total carbon emissions as a function of blend level, but this was only statistically significant for the R100 fuel.

The ion and trace element emissions were generally very low, comprising less than 1% and 2%, respectively, of the total PM mass and did not show any consistent trends between the different

fuels. Overall, it does not appear that biodiesel or renewable blends will have a significant impact on ion or trace element emissions, based on the results of this study.

Particle number (PN) showed some differences between fuels, but in general, the differences in PN were not as consistent as those found for PM mass, and they did not follow the same trends that were observed for the PM mass. Particle size distributions showed an increase in nucleation and a decrease in accumulation mode particles for the biodiesels for the non-DPF equipped vehicles, and an opposite increase in accumulation modes particles and a decrease in nucleation for the biodiesel for the DPF-equipped vehicle. Particle length measurements were relatively similar over the whole spectrum of fuel types and driving conditions for the 2006 Cummins vehicle, and for the 2007 MBE4000 vehicle showed some increase for the B100 blends for the UDDS and some decreases for the intermediate blends for the 2006 Cummins vehicle. Particle-bound PAHs showed a consistent trend of decreasing pPAHs with increasing biodiesel level for the 2006 Cummins ISM vehicle, but showed some increases in pPAHs for the 2007 MBE4000, corresponding to an increase in accumulation mode particles.

Table ES-9. Percentages changes and associated statistical p values for Soy-based, Animal-based and Renewable blends relative to CARB for the 2000 Caterpillar C-15.

Cycle	Fuel	Blend level	THC		CO		NO_x		PM		CO_2		BSFC	
			% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
UDDS	Soy-based	B20	-2%	0.893	-9%	0.018	1%	0.252	-30%	0.118	-1%	0.529	1%	0.547
		B50	-9%	0.470	-25%	0.000	16%	0.000	-59%	0.009	-2%	0.425	2%	0.430
		B100	-40%	0.002	-32%	0.000	27%	0.000	-78%	0.003	-1%	0.705	1%	0.621
50 mph Cruise		B20	0%	0.982	-9%	0.305	-3%	0.334	-23%	0.053	-1%	0.813	1%	0.822
		B50	-14%	0.173	-20%	0.025	10%	0.082	-51%	0.004	0%	0.970	0%	0.969
		B100	-41%	0.011	-37%	0.006	21%	0.000	-67%	0.002	1%	0.794	-1%	0.792
		B20-2	0%		-20%		5%		-32%		-1%		1%	
UDDS	Animal-Based	B20	-3%	0.763	-13%	0.007	0%	0.779	-31%	0.076	1%	0.534	-2%	0.333
		B50	-28%	0.004	-27%	0.000	7%	0.000	-49%	0.003	-1%	0.669	0%	0.726
		B100	-52%	0.000	-41%	0.000	15%	0.000	-79%	0.002	1%	0.542	0%	0.726
		B20-2	-14%	0.137	-12%	0.001	5%	0.000	-46%	0.039	-1%	0.141	1%	0.147
		B100-2	-53%	0.003	-46%	0.000	12%	0.000	-82%		-2%	0.128	3%	0.081
50 mph Cruise		B20	-9%	0.054	-12%	0.125	3%	0.028	-14%	0.346	0%	0.713	0%	0.916
		B50	-22%	0.005	-27%	0.006	10%	0.002	-37%	0.050	1%	0.326	-1%	0.488
		B100	-55%	0.000	-45%	0.000	19%	0.001	-59%	0.023	2%	0.163	-1%	0.366
		B100-2	-53%		-45%		16%		-71%		1%		-1%	
UDDS	Renewable	B20	-9%	0.169	-1%	0.810	-4%	0.027	-4%	0.510	-1%	0.279	1%	0.401
		B50	-11%	0.119	-9%	0.011	-12%	0.003	-26%	0.022	-4%	0.003	4%	0.002
		B100	-22%	0.003	-15%	0.000	-10%	0.000	-33%	0.002	-4%	0.004	4%	0.001
50 mph Cruise		B20	3%	0.627	-6%	0.252	-1%	0.753	-7%	0.576	-1%	0.454	1%	0.385
		B50	-6%	0.402	-12%	0.081	-3%	0.306	1%	0.962	-2%	0.047	2%	0.034
		B100	-12%	0.103	-21%	0.007	-6%	0.101	-22%	0.086	-3%	0.005	3%	0.003

Table ES-10. Percentages changes and associated statistical p values for Soy-based, Animal-based and Renewable blends relative to CARB for the 2006 Cummins ISM.

Cycle	Fuel	Blend level	THC		CO		NO_x		PM		CO_2		BSFC	
			% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
UDDS	Soy-based	B20	-7%	0.084	-13%	0.044	8%	0.001	-25%	0.144	-3%	0.024	3%	0.027
		B50	-18%	0.001	-16%	0.016	14%	0.000	-40%	0.033	-1%	0.407	1%	0.418
		B100	-35%	0.000	-8%	0.275	24%	0.000	-55%	0.011	1%	0.580	-1%	0.594
50 mph Cruise		B20	-3%	0.285	-7%	0.118	5%	0.059	-2%	0.890	-2%	0.133	2%	0.137
		B50	-10%	0.003	-17%	0.002	16%	0.000	-32%	0.033	-1%	0.327	1%	0.333
		B100	-23%	0.000	-24%	0.000	34%	0.000	-39%	0.005	2%	0.098	-2%	0.110
UDDS	Animal-Based	B20	-5%	0.229	-3%	0.680	4%	0.019	-12%	0.470	0%	0.809	0%	0.864
		B50	-18%	0.000	-25%	0.001	2%	0.018	-39%	0.036	-1%	0.521	1%	0.499
		B100	-42%	0.000	-32%	0.000	9%	0.000	-62%	0.006	2%	0.195	-2%	0.204
50 mph Cruise		B20	-4%	0.133	-5%	0.289	2%	0.348	-6%	0.614	0%	0.762	0%	0.776
		B50	-12%	0.001	-17%	0.002	10%	0.000	-33%	0.065	-1%	0.294	1%	0.328
		B100	-27%	0.000	-27%	0.000	19%	0.000	-42%	0.008	1%	0.484	-1%	0.503

Table ES-11. Percentages changes and associated statistical p values for Soy-based, Animal-based and Renewable blends relative to CARB for the 2007 MBE4000.

Cycle	Fuel	Blend level	THC		CO		NO_x		PM		CO_2		BSFC	
			% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
UDDS	Soy-based	B20	-15%	0.613	-14%	0.579	5%	0.000	-6%	0.732	0%	0.714	0%	0.260
		B50	-53%	0.046	-32%	0.160	13%	0.000	76%	0.003	0%	0.330	0%	0.346
		B100	-76%	0.004	-48%	0.027	36%	0.000	1%	0.959	2%	0.000	-2%	0.000
50 mph Cruise		B20	-14%	0.606	7%	0.753	3%	0.286	17%	0.419	1%	0.165	-1%	0.290
		B50	14%	0.806	-6%	0.763	11%	0.021	19%	0.442	1%	0.087	-1%	0.297
		B100	0%	0.808	-1%	0.793	35%	0.000	114%	0.000	3%	0.001	-2%	0.032
UDDS	Animal-Based	B20	-26%	0.494	-18%	0.561	2%	0.318	17%	0.478	3%	0.000	-2%	0.059
		B50	-48%	0.195	-26%	0.384	11%	0.000	-11%	0.613	4%	0.000	-6%	0.000
		B100	-83%	0.031	-61%	0.048	28%	0.000	33%	0.227	5%	0.000	-4%	0.000
50 mph Cruise		B20	-6%	0.750	-4%	0.770	-2%	0.556	-10%	0.502	1%	0.011		
		B50	-14%	0.750	-4%	0.800	4%	0.354	-16%	0.294	4%	0.080		
		B100	-14%	0.778	-5%	0.782	28%	0.000	188%	0.012	2%	0.001		

NO_x Mitigation Results – Engine Testing

Tables ES-12 and ES-13 show the percentage differences for the NO_x mitigation formulations compared with the CARB ULSD for different blend levels and test cycles for the 2006 Cummins ISM and the 2007 MBE4000, respectively, along with the associated p-values for statistical comparisons using a 2-tailed, 2 sample equal variance t-test. The shaded regions represent the formulations that provided NO_x neutrality relative to the CARB ULSD. The NO_x emission results for the various mitigation strategies are presented in Figures ES-12 and ES-13 on a gram per brake horsepower hour basis for the 2006 Cummins ISM and the 2007 MBE4000, respectively. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination within a particular test period. For the 2006 Cummins ISM, the NO_x mitigation testing was conducted over three separate test periods, the results of which are separated by the vertical lines in the figure. All comparisons with the CARB diesel are based on the CARB diesel results from that specific test period, so that the impacts of drift between different test periods were minimized.

The impact of biodiesel on NO_x emissions depends on the feedstock or fundamental properties of the biodiesel being blended. Blends of two biodiesels with different emissions impacts for NO_x provides a blend that shows a NO_x impact that is intermediate between the two primary biodiesel feedstocks. This can be seen for the results of the CARB80/B10-S/B10-A, which showed a NO_x increase intermediate to that of the B20-S and the B20-A. This indicates that the NO_x impact for a particular biodiesel feedstock can be mitigated in part by blending with another biodiesel feedstock with a lower tendency for increasing NO_x.

Two additives were tested for NO_x mitigation for 2006 Cummins engine, 2-EHN and DTBP. Of these two additives, the DTBP was effective in this testing configuration. A 1% DTBP additive blend was found to fully mitigate the NO_x impacts for a B20 and B10 soy biodiesel. The 2-EHN was tested at 1% level in both a B20-soy and B5-soy blend and did not show any significant NO_x reductions from the pure blends.

The testing showed that renewable diesel fuels can be blended with biodiesel to mitigate the NO_x impact. This included higher levels of renewable diesel (R80 or R55) with a B20-soy biodiesel. Several lower level blends, designed to be more comparable to those that could potentially be used to meet the low carbon fuel standard, also showed NO_x neutrality, including a CARB75/R20/B5-soy blend, a CARB80/R13/B3-soy/B4-animal blend, a CARB80/R15/B5-soy blend, and a CARB80/GTL15/B5-soy blend. Overall, the renewable and GTL diesels provide comparable levels of reductions for NO_x neutrality at the 15% blend level with a B5-soy.

The level of renewable or GTL diesel fuels can be reduced if a biodiesel fuel with more favorable NO_x characteristics is used. This is demonstrated by the success of the CARB80/R13/B3-S/B4-A blend that combined both the soy and animal-based biodiesel. The use of an additive in conjunction with lower levels of renewable diesel and GTL can also be used to provide NO_x neutrality, as shown by the success of the CARB80/R10/B10-S 0.25% DTBP blend.

For the 2007 MBE4000 engine only two blends were tested. The blends included a CARB80/R15/B5-soy and, a B-5 soy with a 0.25% DTBP additive. Of these two blends, only the CARB95/B5-S 0.25% DTBP blend was found to provide NO_x neutrality. Overall, it appears that different strategies will provide mitigation for different engines, but that the specific response will vary somewhat from engine to engine.

The NO_x mitigation formulations for the 2006 Cummins showed reductions in PM, THC, and CO that were consistent with those for the biodiesel and renewable diesel fuels by themselves, with some slightly larger reductions seen when higher levels of biodiesel and renewable diesel were combined or when additives were used. For the 2007 MBE4000, the differences in PM, THC, and CO were generally not statistically significant due to the low emissions levels from the DPF. For CO_2, between the two engines, about half of the formulations showed statistically significant differences. This included reductions for some of the higher blends that were on the order of 2% or less, consistent with the main test results, as well as some mixed results of increases in CO_2 emissions that would need to be verified with further testing. Fuel consumption was also higher for all the NO_x formulations, consistent with expectations, with increases ranging up to ~6% for the higher blend levels.

Table ES-12. Percentages changes for GTL blends relative to CARB and associated statistical p values 2006 Cummins ISM

	THC		CO		NO_x		PM		CO_2		BSFC	
	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
B5 - S	-1%	0.087	-1%	0.471	2.2%	0.000	-6%	0.000	0.1%	0.816	0.3%	0.228
B10 - S	-6%	0.000	-2%	0.171	2.6%	0.000	-17%	0.000	-0.1%	0.569	0.3%	0.167
B20 – S*	-11%	0.000	-3%	0.078	6.6%	0.000	-25%	0.000	0.4%	0.309	1.4%	0.001
B20-S 1% DTBP	-16%	0.000	-19%	0.000	0.0%	0.959	-16%	0.000	-0.9%	0.000	0.1%	0.748
B10-S 1% DTBP	-9%	0.000	-14%	0.000	-1.1%	0.002	-6%	0.000	-0.2%	0.258	0.2%	0.445
B20-S 1% 2-EHN	-16%	0.000	-15%	0.000	6.3%	0.000	-17%	0.000	0.2%	0.362	1.2%	0.000
B5-S 1% 2-EHN	-6%	0.000	-12%	0.000	3.1%	0.000	-4%	0.007	-0.1%	0.782	0.1%	0.564
R80/B20-soy	-13%	0.000	-16%	0.000	-3.0%	0.000	-47%	0.000	-2.0%	0.000	5.7%	0.000
C25/R55/B20-S	-12%	0.000	-13%	0.000	-0.8%	0.029	-40%	0.000	-1.5%	0.000	4.1%	0.000
C70/R20/B10-S	-8%	0.000	-3%	0.013	0.9%	0.014	-17%	0.000	-0.4%	0.059	1.7%	0.000
C75/R20/B5-S	-3%	0.014	-3%	0.048	0.2%	0.674	-11%	0.000	0.3%	0.309	2.2%	0.000
C80/B10-S/B10-A	-12%	0.000	-6%	0.000	3.9%	0.000	-26%	0.000	1.2%	0.003	2.2%	0.000
C80/R15/B5-S	-3%	0.024	-4%	0.000	0.7%	0.117	-11%	0.000	0.2%	0.686	1.6%	0.000
C80/R13/B3-S/B4-A	-2%	0.039	-4%	0.005	-0.3%	0.501	-9%	0.000	0.4%	0.251	1.9%	0.000
C53/G27/B20-S	-21%	0.000	-10%	0.000	2.1%	0.000	-32%	0.000	-1.4%	0.001	1.3%	0.002
C80/G10/B10-S	-7%	0.000	-5%	0.000	2.4%	0.000	-18%	0.000	0.6%	0.150	1.7%	0.000
C80/G15/B5-S	-7%	0.000	-5%	0.000	-0.7%	0.068	-9%	0.000	-0.6%	0.018	0.6%	0.010
C80/R10/B10-S 0.25% DTBP	-9%	0.000	-11%	0.000	-1.3%	0.002	-11%	0.000	-0.8%	0.006	0.5%	0.081

Notes: C = CARB ULSD; R = renewable, G = GTL; Bxx = biodiesel blend level; S = soy biodiesel; A = animal biodiesel; * from testing with the soy-biodiesel feedstock

Table ES-13. Percentages changes for GTL blends relative to CARB and associated statistical p values 2007 MBE4000

	THC		CO		NO_x		PM		CO_2		BSFC	
	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
CARB80/R15/B5-S	25%	0.240	-27%	0.000	1.1%	0.029	-126.0%	0.551	0.2%	0.061	1.2%	0.000
B5-S 0.25% DTBP	50%	0.040	-9%	0.127	0.4%	0.175	88%	0.694	0.5%	0.003	0.7%	0.000

Notes: C = CARB ULSD; R = renewable, G = GTL; Bxx = biodiesel blend level; S = soy biodiesel; A = animal biodiesel

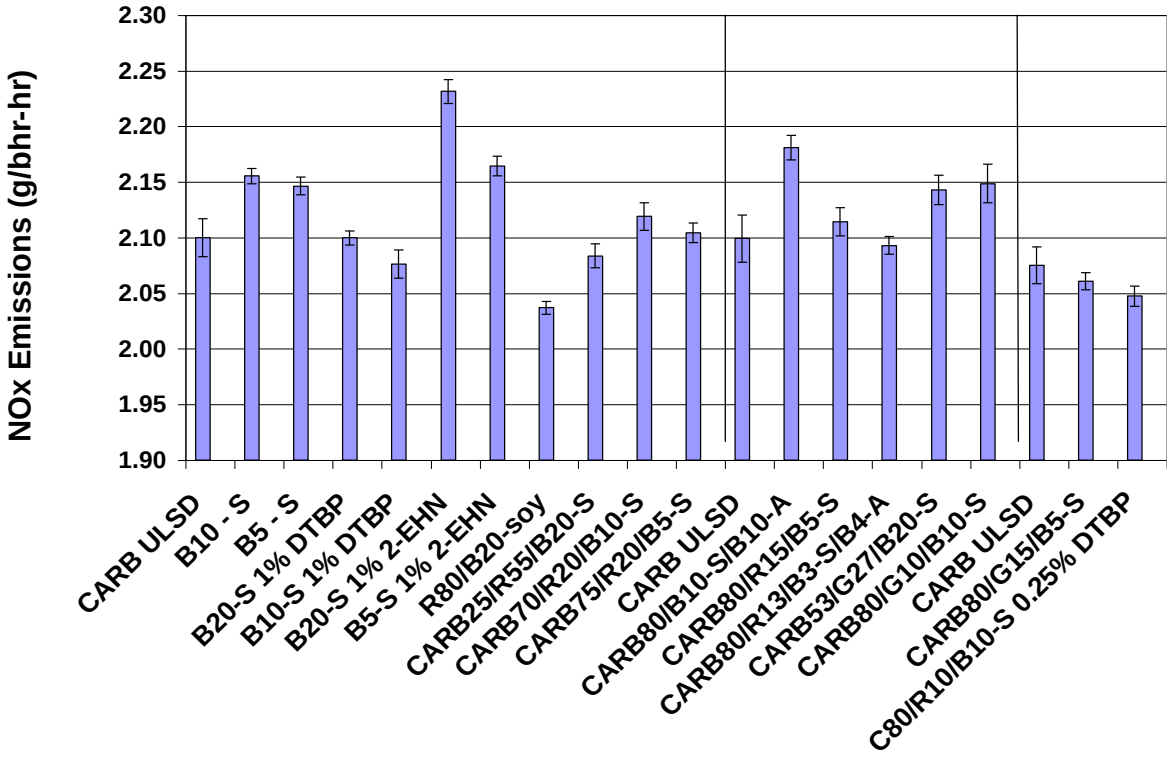


Figure ES-12. Average NO_x Emissions: NO_x Mitigation Formulations - 2006 Cummins ISM

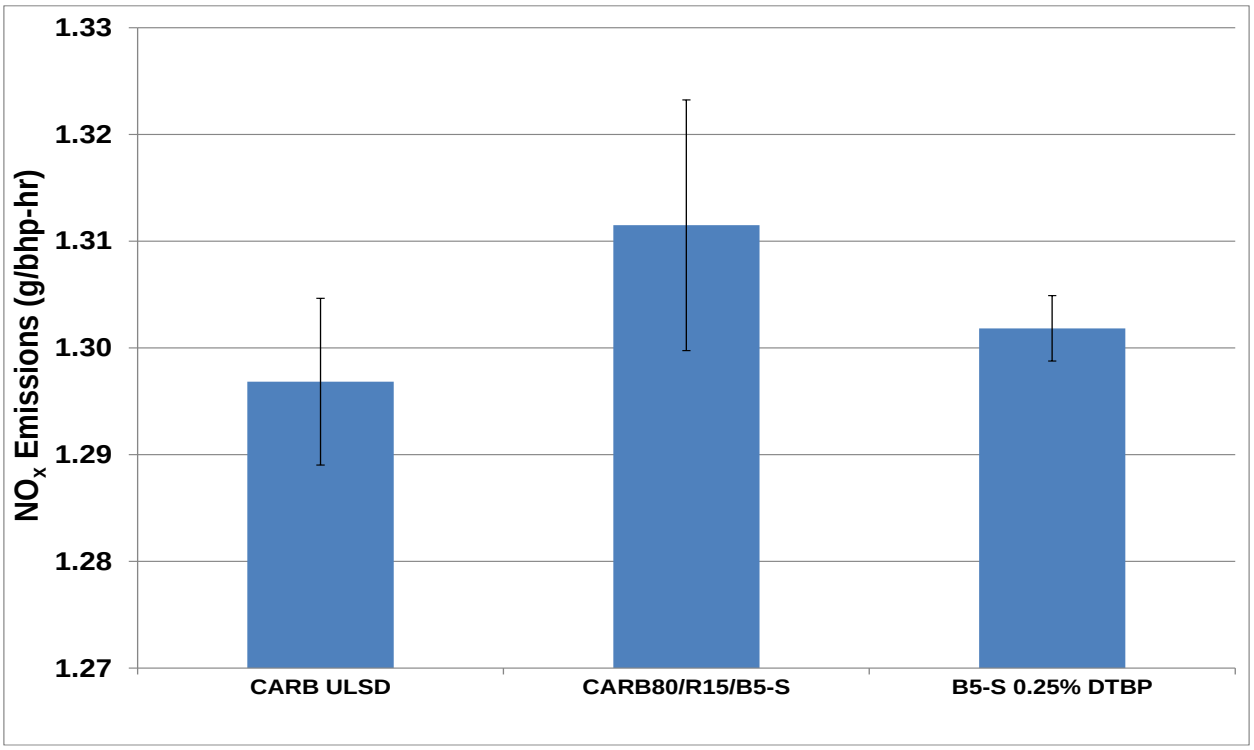


Figure ES-13. Average NO_x Emissions: NO_x Mitigation Formulations - 2007 MBE4000

Toxicological Characterization – Chassis Testing Results:

The toxicity testing phase of the study, as described in the Methods section, was conducted on the CARB MTA Heavy Duty Chassis Dynamometer testing facility. The vehicles equipped with a 2000 Caterpillar C-15 engine and a 2007 MBE4000 engine were tested for this part of the program. The testing included the baseline CARB diesel, two biodiesel feedstocks (one soy-based and one animal-based) tested on blend levels of B20, B50, and B100% and the renewable diesel fuel at a R20, R50 and R100 blend levels. The data were mostly collected for a UDDS test cycle, with carbonyls also being collected for the 50 mph Cruise test cycle. For the carbonyls, the 2006 ISM Cummins vehicle was also tested.

Carbonyl emissions - The results show that formaldehyde and acetaldehyde were the most prominent carbonyls, consistent with previous studies. Acetone emissions were also prominent for the 2000 Caterpillar C-15. The carbonyl emissions for the 2000 Caterpillar C-15 and the Cummins ISM were considerably higher than those for the DPF-equipped 2007 MBE4000. There was also a trend of higher emissions for the UDDS than the 50-mph cruise for the 2000 Caterpillar C-15 and for formaldehyde and acetaldehyde for the 2007 MBE4000. This trend was not seen for the 2006 Cummins ISM. Overall, carbonyl emissions did not show any consistent trends between different fuels.

Reactive carbonyl emissions - The results showed that certain reactive carbonyls were higher for the 2000 Caterpillar C-15 for the soy-based B50 and B100 and the animal-based B50 and B100 fuels, including acrolein. There were also trends of lower aromatic aldehyde emissions for the pure biodiesel fuels compared to CARB diesel. The reactive carbonyls did not show any

differences for the renewable diesel relative to the CARB diesel for the 2000 Caterpillar C-15. Overall, the reactive carbonyl emissions were much lower for the 2007 MBE4000 in comparison with the 2000 Caterpillar C-15.

PAH emissions for the 2000 Caterpillar C-15 vehicle were investigated for the CARB diesel, the soy- and animal- based biodiesel, renewable diesel, and their respective blends with the CARB diesel (20% and 50%) over the UDDS cycle, both in the particle and vapor-phases. They also were investigated for the 2007 MBE4000 vehicle for the CARB, soy biodiesel and their blends (20% and 50%). PAH emissions for the 2000 Caterpillar C-15 vehicle decreased as a function of increasing blend level of soy biodiesel, animal-based biodiesel and renewable diesel. Emission reductions for different feedstocks were generally similar, except that the reduction in renewable diesel for particle associated PAHs was slightly lower than the reductions observed for the soy- and animal-based biodiesels. This may be explained by relatively higher PM emissions from renewable diesel compared to the soy or animal biodiesel. For the 2007 MBE4000 vehicle, the concentrations were orders of magnitude lower than for the 2000 Caterpillar C-15 vehicle, essentially masking any significant differences between CARB diesel, soy biodiesel, and the blends. The results indicate that the DPF for the 2007 MBE4000 was effective in reducing PAH emissions both in the particle and in the vapor-phase.

Nitro-PAH emissions were measured in the same particle and vapor phase samples as for PAHs for the 2000 Caterpillar C-15 and 2007 MBE4000 vehicles. The concentrations of nitro-PAHs were orders of magnitude lower than the corresponding PAHs. A trend was clearly observed for the 2000 Caterpillar C-15 vehicle, however. Nitro-PAH emissions for the 2000 Caterpillar C-15 vehicle decreased as a function of increasing blend levels of soy biodiesel, animal-based biodiesel, and renewable diesel. Emission reductions for different feedstocks were similar. However, for semivolatile nitro-PAHs, the renewable diesel may be slightly more effective in reducing emissions than soy- or animal-based biodiesels. For the 2007 MBE4000 vehicle, nitro-PAHs were detected in low concentrations, essentially masking any significant differences between CARB diesel, soy biodiesel, and the blends. The DPF for the 2007 MBE4000 was effective in reducing nitro-PAH emissions.

Oxy-PAH emissions over the UDDS cycle were investigated in the particle samples for the 2000 Caterpillar C-15 vehicle only. The results were obtained for the CARB diesel, the soy and animal- based biodiesel, renewable diesel, and their respective blends with the CARB diesel (20% and 50%), except the soy 100% biodiesel was not analyzed due to the sample availability. Emissions of some oxy-PAHs were as high as the volatile PAHs, and much higher than nitro-PAHs. The emission trends observed for biodiesel and renewable diesel were different for different compounds. For example, the results for 1,2-naphthoquinone (2-ring oxy-PAH) showed generally higher emissions in soy and animal-based biodiesels compared to CARB diesel, whereas perinaphthenone, 9-fluorenone, and 1,8-naphthalic anhydride (3-ring oxy-PAHs) emissions decreased in animal biodiesel and renewable diesel.

Genotoxicity - Mutagen emissions – Mutagen emissions generally decreased as a function of increasing biodiesel blend level for the 2000 Caterpillar C-15 vehicle. For the 2000 Caterpillar C-15 PM samples, the TA98 strains (+ or – S9) were more sensitive than the TA100 strains for all fuels. The vapor phase samples showed lower mutagen emissions than the PM samples, and

the TA100 strain measurements were slightly more sensitive for vapor phase samples. For the 2007 MBE4000 vehicle, the mutagen emissions, in general, were considerably lower for both particle and vapor-phase than emissions from the 2000 Caterpillar C-15 vehicle. The levels were orders of magnitude lower for the PM and many fold lower for the vapor-phase than the emissions from the 2000 Caterpillar C-15 vehicle.

Inflammatory and oxidative response – CARB diesel, biodiesel, and renewable diesel all induced inflammatory markers, such as COX-2 and IL-8 in human macrophages and the mucin related MUC5AC markers in Clara type cells. In general, the emissions of the inflammatory markers were higher in the 2000 Caterpillar C-15 engine vehicle than the 2007 MBE4000 engine vehicle.

Comet assay result – At the limited dose levels tested, there was little increase of chromosomal damage (gross DNA damage) from the various fuels tested, including the CARB diesel.

1.0 Introduction

There is currently a growing interest in increasing the use of alternative fuels in transportation applications to reduce oil dependency, greenhouse gases, and air pollution. In California, AB1007 requires the California Air Resources Board (CARB) and California Energy Commission (CEC) to develop a plan to increase alternative fuels use in California (Pavley, 2005). Other initiatives include the Global Warming Solutions Act, AB32 (Nunez/Pavley 2006), which requires California to develop regulations that will reduce greenhouse gas emissions to 1990 levels by 2020, and CARB's Low Carbon Fuel Standard (LCFS) that will reduce the carbon intensity of fuels, measured on a full lifecycle basis, by 10% by 2020 (CARB, 2010). At the Federal level, the Energy Policy Act of 2005 (US Congress, 2005). and its associated amendments and Renewable Fuels Standards (RFS1, 2007; RFS2, 2010), also contain provisions to increase the use of renewable transportation fuels over the next decade.

CARB has identified biodiesel as a potential strategy in meeting these regulatory goals for diesel fuel. Biodiesel and renewable diesel are alternative diesel fuels that have the potential to reduce greenhouse gas emissions, other pollutants, and can partially offset our use of petroleum-based fuels. However, knowledge gaps exist and further research is needed in characterizing the impact biodiesel and renewable diesel have on oxides of nitrogen (NO_x) emissions, the effects various feedstocks have on air emissions, and the effect biodiesel has on emissions from non-road and newer on-road diesel engines. This research is needed to conduct lifecycle analyses and to determine the potential health and environmental benefits and disbenefits of biodiesel. Additionally, for the conditions under which NO_x is found to increase, it is important to identify methods which can mitigate the NO_x increases.

The impact of biodiesel on emissions has been the subject of numerous studies over the past 20 years. Looking at the available literature as a whole, studies have generally shown hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) are reduced using biodiesel, while trends for NO_x emissions have been less clear. The US EPA conducted a comprehensive assessment of the impact of biodiesel on pre-2002 engines (US EPA, 2002). Most of the studies cited in this report were on soy-based biodiesel in comparison with an average federal diesel base fuel. Based on this analysis, it was estimated that a soy-based biodiesel at a B20 level would increase NO_x emissions about 2% compared to an average Federal base fuel. Additional analyses in this same study did indicate that the impacts of biodiesel on NO_x emissions using a cleaner base fuel, more comparable to that utilized in California, could be greater than that found for the average Federal fuel, but data was more limited in this area. Clean diesel fuels were defined by EPA as diesel fuels meeting the CARB requirements for sale in California, or diesel fuels with cetane numbers greater than 52, aromatic contents less than 25 vol.%, and specific gravities less than 0.84.

Researchers at the National Renewable Energy Laboratory (NREL) conducted further analysis of more recent engine and chassis dynamometer test results (McCormick et al., 2006). These researchers noted that nearly half of the data observations used for the EPA's analysis were 1991-1997 DDC engines, with a majority of these being the Series 60 model, so the analysis might not be representative of a wider range of technologies. They also noted that the engine testing results were highly variable for NO_x, with percentage changes for NO_x ranging from -7%

to +7%. Reviewing more recent studies of newer engines, these researchers found an average change in NO_x emissions for the more recent engine studies of -0.6%±2.0%. Similar results were found for recent chassis dynamometer tests, which when the results were combined yielded an average change of 0.9%±1.5%. Hoekman et al. (2009) also conducted an extensive analysis of the literature on emissions impacts of biodiesel. They evaluated results for heavy-duty engines, light-duty engines, and single cylinder engines, and suggested a best estimate for the NO_x impact for biodiesel was a 2-3% increase at a B100 level, with NO_x emissions unchanged for conventional diesel fuel for B20 blends. Many of these studies are limited in their direct application to California, however, because exhaust emissions from diesel engines fueled with biodiesel were not compared to these engines fueled with CARB diesel, or because they use only soy-based biodiesel that may not be the major feedstock used in California. Additionally, most of these studies are not as extensive as the testing requirements used in the certification of CARB alternative diesel formulations, which require fuels to be shown to be equivalent to a 10% aromatic reference diesel fuel over a test sequence of 20 or more iterations (CARB, 2004).

Research has also suggested that the impact of biodiesel on NO_x emissions can depend on operating conditions, load, or engine configuration (McCormick et al. 2006; Sze et al. 2007). Studies have also shown that operating condition and load can impact the effects of biodiesel on emissions and NO_x. The US EPA conducted some analysis of the impact of test cycle on biodiesel emissions impacts (Sze et al. 2007). They found that biodiesel increased NO_x emissions over different test cycles from 0.9 to 6.6% for a B20 blend, with the change in NO_x emissions increasing linearly with the average cycle load. Some studies have also examined mechanisms via which biodiesel might impact NO_x emissions. Researchers have suggested a number of explanations including chemical structure (McCormick et al., 2001; Ban Weiss et al., 2005), such as fatty chain length and number of double bonds, an advancement in timing related to bulk modulus (Szybist et al., 2003 a,b), and/or increases in combustion temperature (Cheng et al. 2007). Researchers at Cummins Inc. have also shown that both the combustion process and the engine control system must be taken into account when determining the net NO_x effect of biodiesel compared to conventional diesel fuel (Eckerle et al. 2008).

Given the range of results in the literature, and the limited extent of studies with CARB-like diesel, further research is needed to understand the impacts biodiesel would have in California with widespread use. If biodiesel blends are determined to increase NO_x emissions, then it is important to find mitigation strategies that make biodiesel NO_x neutral or better when compared to CARB diesel use. It is known that the properties of diesel fuel can affect the emissions of NO_x as well as other emission components (Miller, 2003). It is possible that the fuel specifications of diesel fuel can be altered such that any negative impacts of biodiesel in a blend could be overcome or such that the properties of biodiesel blends could be made such that the blend would have the same properties as a typical diesel fuel. Biodiesel could potentially even be incorporated into more traditional petroleum refinery processes as a feedstock. The use of additives and cetane improvers has also shown some potential for reducing NO_x emissions from biodiesel blends (McCormick et al., 2002, 2005; Sharp, 1994).

To facilitate the introduction of a larger percent of renewable fuels into use and better characterize the emissions impacts of renewable fuels under a variety of conditions, CARB implemented one of the most comprehensive studies of renewable and CARB certified diesel

fuels to date. This program was coordinated by CARB in conjunction with researchers from the University of California Riverside (UCR), the University of California Davis (UCD), and others including Arizona State University (ASU). The focus of this research study is on understanding and, to the extent possible, mitigating any impact that biodiesel has on NO_x emissions from diesel engines. This program incorporates heavy-duty engine dynamometer testing, heavy-duty chassis dynamometer vehicle testing, and testing of non-road engines on a range of biodiesel and renewable diesel fuels. This includes heavy-duty diesel engines from different vintages, including a 2007 with a diesel particle filter (DPF) engine, a 2000 engine, a 2006 engine, a 2010 engine with a DPF and selective catalytic reduction (SCR), and two non-road engines. The testing included soy-based and animal-based biodiesels tested at blend levels of B5, B20, B50, and B100, a renewable or biomass-to-liquid (BTL) diesel fuel and a gas-to-liquid (GTL) diesel fuel at 20%, 50% and 100% blend levels, and other fuel formulations/additive combinations designed to mitigate any potential increases in NO_x emissions with biodiesel. Testing was conducted on several cycles designed to represent low, medium, and high power engine operation, such that the effects of biodiesel on NO_x emissions can be understood over a range of different operating conditions. This report discusses the results and conclusions for all elements of this study. This study provides an important assessment of the potential impact of renewable fuel use in California and a basis for the development of NO_x mitigation strategies for meeting CARB regulations. This study also makes an important contribution to the scientific knowledge of the impacts of biodiesel with “clean” or CARB-like diesel in heavy-duty engines.

2.0 Experimental Procedures – On-Road, Heavy-Duty Engine Dynamometer Testing

2.1 Test Fuels

The test fuels for this program included 5 primary fuels that were subsequently blended at various levels to comprise the full test matrix.

A CARB-certified ultralow sulfur diesel (ULSD) fuel was the baseline for testing. The CARB fuel was obtained from a California refinery. The properties of the fuel were reviewed by CARB staff prior to selection to ensure they were consistent with those of a typical ULSD in California. The key target parameters evaluated included aromatics, sulfur, and cetane number.

Two biodiesel feedstocks were utilized for testing, including one soy-based and animal-based biodiesel fuel. These fuels were selected to provide a range of properties that are representative of typical feedstocks, but also to have feedstocks representing different characteristics of biodiesel in terms of cetane number and degree of saturation.

A renewable feedstock and a gas-to-liquid (GTL) diesel were also used for testing. The renewable feedstock was provided by Neste Oil, and it is known as Neste Oil biomass to liquid (NExBTL). This fuel is denoted as the renewable diesel in the following results sections. This fuel is produced from renewable biomass sources such as fatty acids from vegetable oils and animal fats via a hydrotreating process (Rantanen et al. 2005; Kuronen et al. 2007; Aatola et al. 2008; Erkkila and Nylund; Kleinschek 2005; Rothe et al. 2005). The GTL diesel fuel was provided by a petroleum company.

A summary of selected for properties for the neat fuels is provided in Table 2-1, with the full fuel characterization provided in Appendix A.

The biodiesel and renewable diesel feedstocks were blended with the ULSD base in different blending ratios. The soy-based and animal-based biodiesels were blended at levels of B5, B20, B50, as well as using the straight B100. The renewable and GTL diesel fuels were blended at 20% and 50% levels with the CARB base fuel.

The ULSD and the renewable diesel were tested in triplicate upon arrival to the fuel storage facility for all properties under ASTM D975 and density. The GTL fuel was also tested for the ASTM D975 properties, density, and other properties by the fuel supplier. For the renewable diesel, the cetane number was also determined using the ignition quality test, since the accuracy of the D613 cetane number tests has limitations at cetane values above 60. The analyses for the ULSD, the renewable diesel, and the GTL diesel were all conducted at the Southwest Research Institute (SwRI) in San Antonio, TX. The pure biodiesel feedstocks were tested in triplicate upon arrival to the fuel storage facility for all properties under ASTM D6751 and for density. The biodiesel analyses were primarily conducted by Magellan Midstream Partners, L.P., with some testing also conducted by SwRI.

Blending of the biodiesel fuels was performed at the Interstate Oil Inc. fueling facility in Woodland, CA. The fuels were blended on a gravimetric basis using the fuel densities to achieve the appropriate volumetric blend levels. The neat biodiesel fuels were additized with the stability additive tertiary butylhydroquinone (TBHQ) to help provide sufficient stability against oxidation throughout the program. Oxidation stability tests conducted towards the end of the testing program showed that the additized neat blends had oxidation stability values in excess of 20 hours. After blending, the biodiesel blends were tested via ASTM-D7371 to ensure the blending was uniform and consistent with the targeted blend values. Blending for the renewable diesel blends was conducted at the facilities at CE-CERT using a gravimetric method. The finished blends were tested in triplicate for the properties under ASTM D975. The GTL blends were also blended at CE-CERT, but on a volumetric basis and on a drum by drum basis since smaller quantities of this fuel were needed. Samples of the GTL blends were collected but not analyzed, except for one sample to characterize cetane number. The results of the fuel analyses for the blended fuels are provided in Appendix A.

Table 2-1. Selected Fuel Properties

	CARB ULSD	NExBTL Renewable Diesel	GTL	Soy-biodiesel	Animal-biodiesel
API gravity (@ 60ºF)	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			
Distillation, IBP	337	326	419		
T10, ºF	408	426	482		
T50,ºF	519	521	568		
T90, ºF	612	547	648	350ºC	347.5ºC
FBP	659	568	673		
Free glycerin, mass %	NA	NA	NA	0.001	0.008
Total glycerin, mass %	NA	NA	NA	0.080	0.069
Sulfur, ppm	4.7	0.3	0.9	0.7	2

Notes: NA = either Not Available or Applicable; IQT = ignition quality test derived cetane number
Distillation temperature for biodiesel samples provided in degrees C for comparison with D675

2.2 Engine Selection

The engines were selected from 2 model year categories; 2002-2006 and 2007-2009. The 2002-2006 engines are estimated to represent an important contribution to the emissions inventory from the present through 2017. The 2007-2009 engine model year represents the latest technology that was available at the time of testing.

The specifications of the test engines are provided in Table 2-2. The engines were typical 6 cylinder, in-line, direct injection, turbocharged, heavy-duty diesel engines. The 2002-2006 engine was a 2006 model year Cummins ISM engine. This engine was pulled from a truck that was purchased specifically for this project, and run at CARB's chassis dynamometer laboratory in Los Angeles, CA to obtain the engine operating parameters (as discussed below). The truck had accumulated approximately 92,000 miles at the time the engine was pulled. The engine selected from the 2007-2009 model year category was a 2007 Detroit Diesel Corporation (DDC) MBE 4000. This engine was also pulled from a truck purchased specifically for the heavy-duty chassis dynamometer testing portion of this program. The 2007 MBE 4000 is a 12.8 liter diesel engine that also employs cooled EGR and a passive/active diesel oxidation catalyst (DOC)/DPF combination. The truck had accumulated approximately 8,000 miles at the time the engine was pulled.

Table 2-2. Test Engines Specifications

Engine Manufacturer	Cummins, Inc.	Detroit Diesel Corp.
Engine Model	ISM 370	MBE4000
Model Year	2006	2007
Engine Family Name	6CEXH0661MAT	7DDXH12.8DJA
Engine Type	In-line 6 cylinder, 4 stroke	In-line 6 cylinder, 4 stroke
Displacement (liter)	10.8	12.8
Power Rating (hp)	385 @ 1800 rpm	410 hp @ 1900 rpm
Fuel Type	Diesel	Diesel
Induction	Turbocharger with charge air cooler	Turbocharger with after cooler

2.3 Test Cycles

The test cycles included the standard Federal Testing Procedure (FTP) for heavy-duty engines and three other cycles based on engine parameters collected over standard cycles on a chassis dynamometer. Initially, two additional cycles were selected for testing that included a lightly loaded Urban Dynamometer Driving Schedule (UDDS) cycle and a 40 mile per hour (mph) CARB heavy heavy-duty diesel truck (HHDDT) cruise cycle. Later, a 50 mph CARB heavy heavy-duty diesel truck (HHDDT) cruise cycle was added to provide a greater range in the load between the different test cycles. The different cycles were initially selected to provide a range of operating conditions and operational loads, and some connection to the chassis dynamometer testing being conducted in CARB's Los Angeles laboratory.

The engine dynamometer cycles for the light UDDS and the 40 mph CARB cruise cycle for the 2006 Cummins engine and the light UDDS and the 50 mph CARB cruise cycle for the 2007 MBE4000 engine were developed utilizing engine parameters downloaded when the chassis versions of these were run with the test vehicle on the chassis dynamometer at CARB's heavy-duty engine emissions testing laboratory (HDEETL) in Los Angeles, CA. The light UDDS cycle was run over the standard UDDS cycle, with the test vehicle loaded at the weight of the truck cab itself with no trailer. This represents the most lightly loaded test cycle. The 40 and 50 mph

CARB cruise cycles represented a heavier load cycle, and were based on the vehicle being run at near its fully loaded weight.

The torque and engine rpm were directly obtained from the J1939 signal for the test vehicle while it was driven on the chassis dynamometer. These cycles were then programmed into the CE-CERT engine dynamometer software prior to engine testing. In the process of translating the cycles from the chassis to the engine dynamometer, the cycles were optimized by setting the torque and engine RPM values equal to zero during periods of idle operation and the regression validation criteria were modified to account for the differences between the test cycles developed using chassis dynamometer data and the standard FTP. The procedures for the development of these cycles are described in greater detail in Appendix B.

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 program goals. 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 an additional round of supplementary tests on the soy-based biodiesel, and then it was substituted for the 40 mph cruise cycle on the subsequent testing for the animal and renewable feedstocks. Since logistics of replacing the engine back into the vehicle to generate the J1939 data for this specific engine were too impractical, an engine dynamometer test cycle version of this cycle that was developed for the Advanced Collaborative Emissions Study (ACES) program was utilized (Clark et al., 2007). This cycle was developed from data collected through the E55/59 chassis dynamometer study of multiple heavy-duty trucks.

2.4 Test Matrix

The test matrix was developed in conjunction with statisticians at CARB and the US EPA, based on estimates of the magnitude of the impact biodiesel can have on NO_x emissions at a B20 level and estimates of test-to-test repeatability.

2.4.1 2006 Cummins ISM

The test matrix is based on providing a randomized test matrix with long range replication. The initial test matrix provided replication of all test blends with replication of the base ULSD every 2 days. The initial test matrix also included randomization within the test day with different fuels being tested in the morning vs. the afternoon and with the cycles being conducted in a random order for each fuel sequence. After the completion of the first round of testing on the soy-based biodiesel, it was decided to accelerate the rate of testing. The accelerated test matrix used for the remainder of the testing on the soy-based biodiesel utilized a test sequence similar to that used in the initial testing, but with essentially two days of the initial test matrix, or 12 tests, run in a single day.

Since the expected NO_x impact for the B5 level was less than that of B20, and hence more difficult to statistically differentiate from the testing variability, the B5 blend was run outside the

sequence. Initially, for the soy-based biodiesel, the B5 level was run only for the higher load cruise cycles, since it was expected that larger impacts would be seen at higher loads. For the animal-based biodiesel, it was decided to test the B5 fuel on the FTP instead, since the testing repeatability was better for the FTP tests. The test matrices for the main portion of the engine testing are provided below.

Some additional tests were also run on the soy-based biodiesel since a number of tests were identified to be outliers, and because a new higher load cruise cycle was substituted into the test matrix. The nature of the outlier tests is discussed below. The number of additional test replicates conducted on a particular soy-based blend depended on the number of outliers in the initial round of testing. A full complement of tests on the 50 mph CARB HHDDT cycle was also conducted to allow for full comparability between the soy-based, animal-based, and renewable fuels.

2.4.2 2007 MBE4000

The test matrix for the 2007 MBE4000 was based on a similar randomization as that used for the 2006 Cummins ISM. For the 2007 MBE4000, the characterization testing was only performed on the soy-based and animal-based biodiesel feedstocks. The DPF that the MBE4000 was equipped with and its regeneration cycle represented an additional element that had to be incorporated into the test matrix. Preliminary testing showed that the DPF would enter a regeneration enabled conditioned after 10,000 seconds of accumulated run time. This was approximately the run time needed to complete the appropriate conditioning, engine mapping, and emissions testing on each fuel. In order to eliminate the possibility of a regeneration occurring during one of the emission test, it was decided that the DPF would be regenerated with each fuel change. To accommodate the additional time for regeneration, the test matrix for the B50 and B100 blends was reduced from 6 iteration to 4 iterations since earlier testing had indicated this would provide a sufficient number of replicates for the statistical analysis. This prevented a random regeneration event from occurring that would have masked the fuel effects being examined in this study. At the same time, this represents a limitation in that the fuel effects under regeneration conditions were not evaluated.

Table 2-3.Engine 1-2006 Cummins ISM test matrix

A = Lght. UDDS B = FTP C1 = ARB 40 mph Cruise C = ARB 50 mph Cruise

Engine 1-2006 cummins ISM

Soy based biodiesel

Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7		Day 8		Day 9	
Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
CARB	A	B20	B	B50	A	CARB	C1	B100	B	B20	C1	CARB	B	B50	A	B100	A
	C1		A		B		A		C1		B		A		B		C1
	B		C1		C1		B		A		A		C1		C1		B
B20	C1	B50	B	CARB	C1	B100	A	B20	B	CARB	A	B50	B	B100	C1	CARB	B
	B		C1		A		B		A		C1		A		A		C1
	A		A		B		C1		C1		B		C1		B		A

Day 10		Day 11		Day 12		Day 13		Day 14	
Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
CARB	A	B20	B	B50	A	B100	C1	CARB	C1
	C1		A		B		A		C1
	B		C1		C1		B		C1
B20	A	B50	C1	B100	B	CARB	C1	B5	C1
	B		B		C1		A		C1
	C1		A		A		B		C1

Day 16		Day 17		Day 18		Day 19		Day 20		Day 21	
Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
CARB	C	CARB	A	CARB	A	CARB	C	CARB	C	B50	A
	A		C		B		C		C		B
	B		B		C		C		C		A
B20	A	B50	C	B100	B	B5	C		C		B
	C		A		A		C	B20	C	B100	C
	B		B		C		C		C		C
B20	B	B50	C	B100	A	B5	C		C		C
	A		B		C		C		C		C
	C		A		B		C	B50	C	CARB	C
CARB	C	CARB	A	CARB	B	CARB	C		C		C
	B		C		C		C		C		C
	A		B		A		C		C		C

A = Lght. UDDS B = FTP C1 = ARB 40 mph Cruise C = ARB 50 mph Cruise

Engine 1-2006 cummins ISM

Animal based BDSL

Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7		Day 8	
Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
CARB	A	B50	A	B100	C	CARB	B	B100	A	B20	C	B100	B	B5	B
	C		B		B		C		C		A		C		B
	B		C		A		A		B		B		A		B
B20	B	CARB	C	B20	B	B50	B	CARB	C	B50	A	CARB	B	CARB	B
	A		B		C		A		A		B		A		B
	C		A		A		C		B		C		C		B
B20	C	CARB	B	B20	A	B50	B	CARB	A	B50	A	CARB	B		
	A		C		B		A		C		B		B		
	B		A		C		C		B		C		B		
B50	A	B100	A	CARB	A	B100	C	B20	C	B100	B	B5	B		
	B		C		C		B		B		C		B		
	C		B		B		A		A		A		B		

Renewable Diesel

Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7	
Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
CARB	A	R50	C	R100	C	CARB	B	R100	A	R20	C	R100	B
	B		A		B		C		C		A		A
	C		B		A		A		B		B		C
R20	C	CARB	B	R20	A	R50	C	CARB	B	R50	B	CARB	A
	A		A		B		A		A		C		C
	B		C		C		B		C		A		B
R20	A	CARB	B	R20	A	R50	B	CARB	A	R50	C		
	C		C		B		A		B		B		
	B		A		C		C		C		A		
R50	B	R100	C	CARB	A	R100	C	R20	A	R100	B		
	C		A		C		B		C		C		
	A		B		B		A		B		A		

GTL Diesel

Day 1		Day 2		Day 3	
Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
CARB	B	G50	B	G100	B
	B		B		B
	B		B		B
G20	B	CARB	B	CARB	B
	B		B		B
	B		B		B
G20	B	CARB	B		
	B		B		
	B		B		
G50	B	G100	B		
	B		B		
	B		B		

Table 2-4 Engine 2-2007 MBE4000 test matrix

Engine 2 – 2007 MBE4000

Day 1	Cycle	Day 2		Day 3		Day 4		Day 5		Day 6		Day 7		Day 8		Day 9	
Fuel	A	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
CARB	C	B50	A	CARB	C	B20	B	CARB	C	B100	B	CARB	B	CARB	B	CARB	B
	B		B		A		A		A		A		C		B		B
	C		C		B		C		B		C		A		B		B
B20	A		C	B100	B		A	B50	B		B	B20	C	B5	B		
	B		B		A		B		C		C		B		B		
	C		A		C		C		A		A		A		B		
	A	CARB	B	B100	C	CARB	A		C	CARB	A		C		B		
	B		C		A		C		B		C		A		B		
			A		B		B		A		B		B		B		

Day 1	Cycle	Day 2		Day 3		Day 4		Day 5		Day 6		Day 7		Day 8		Day 9	
Fuel	B	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
CARB	C	B50	C	CARB	C	B20	C	CARB	A	B100	A	CARB	B	CARB	B	CARB	B
	A		B		A		A		C		B		C		B		B
	C		A		B		B		B		C		A		B		B
B20	A		A	B100	B		C	B50	C		B	B20	A	B5	B		
	B		C		C		B		A		C		B		B		
	B		B		A		A		B		A		C		B		
	A	CARB	A		A	CARB	C		C	CARB	B		B	B5	B		
	C		C		C		B		A		A		A		B		
			B		B		A		B		C		C		B		

Day 1	Cycle	Day 2	
Fuel	B	Fuel	Cycle
	B		B
	B	Blend 2	B
CARB	B		B
	B		B
Blend 1	B		B
	B		B
	B		B
	B		B

A = light UDDS B = FTP C = 50 mph Cruise

2.5 Preliminary Testing

Prior to initiating the full testing on the test matrix, several preliminary tests were conducted on the Cummins engine. These preliminary tests included tests on both the CARB baseline and a B20 animal blend. The objective of these preliminary tests was to verify that the experimental parameters, such as test repeatability and the biodiesel NO_x differential, were consistent with the estimates used in developing the test matrix. The results of this preliminary testing are provided below. The results show that the NO_x differential for this feedstock was similar to that expected based on EPA current estimates. Additionally, the coefficient of variation (COV) was on the order of 1%, similar to what was expected. The preliminary results showed that with these constraints, statistically significant differences in NO_x could be measured between the different test fuels at the 95%+ percent confidence level.

Table 2-5. Results of Preliminary Biodiesel Testing

	THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2 g/bhp-hr
CARB ULSD*					
ave.	0.289	0.757	2.108	0.078	632.492
st dev.	0.003	0.026	0.022	0.002	4.343
COV	1.1%	3.4%	1.0%	2.8%	0.7%
B20-Animal *					
ave.	0.250	0.692	2.146	0.061	637.065
st dev.	0.004	0.013	0.016	0.000	4.056
COV	1.8%	1.9%	0.7%	0.7%	0.6%
% difference (B20 – CARB)	-13.8%	-8.6%	1.8%	-21.2%	0.7%
T-Test	0.000	0.000	0.006	0.000	0.089

* Results based on 6 replicate FTP tests on each fuel

2.6 Emissions Testing

The engine emissions testing was performed at the University of California at Riverside's College of Engineering-Center for Environmental Research and Technology (CE-CERT) in CE-CERT's heavy-duty engine dynamometer laboratory. This engine dynamometer test laboratory is equipped with a 600 hp General Electric DC electric engine dynamometer and is a Code of Federal Regulations (CFR) compliant laboratory.

An engine map was conducted on the test fuel in the engine for the first test of the day. Given the random order of testing, this fuel was usually the fuel from the fuel change from the day before. A second engine map was also obtained for the second fuel tested each day. In order to provide a consistent basis for comparison of the emissions, all cycles were developed and run based on the initial engine map from operating the engine on the baseline CARB ULSD. This is consistent with the procedures used in the CARB procedures for certifying alternative diesel formulations.

Testing was conducted on an FTP, a light-UDDS, and combinations of the CARB HHDDT 40 mph and 50 mph cruise cycles. For all tests, standard emissions measurements of total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) were measured. The emissions measurements were made using the standard analyzers in CE-CERT's heavy-duty Mobile Emissions Laboratory (MEL) trailer. A brief description of the MEL is provided in Appendix C, with more details on the MEL provided in Cocker et al. (2004 a,b). No toxic testing was conducted in conjunction with this portion of the testing.

2.7 Outlier Tests

Throughout the course of testing on the 2006 engine some outliers were observed in the testing that appeared to be related to conditions set within the engine control module (ECM).

One outlier condition was identified for the 50 mph CARB HHDDT cycle, where changes in engine operation were observed between different tests. For this test cycle, for a period of the test cycle from approximately 300 to 400 seconds, two distinct modes of operation were observed. This is shown in Figure 2-1, which shows all of the real-time NO_x traces for 50 mph CARB HHDDT cycle run on the animal-based biodiesel feedstock, as well as the associated CARB tests. The conditions associated with this engine operating condition and the statistics relating with this phenomena are described in greater detail in Appendix E. Of the ninety two 50 mph cruise cycles that were conducted on the first engine, approximately 2/3rds of the tests showed emissions at the lower NO_x level and $1/3^{rd}$ of the tests showed emissions at the higher NO_x level during this 300-400 second period. For the different fuels, CARB diesel showed a greater propensity for operating in the higher emission mode, while the higher biodiesel blends showed a greater propensity for operating in the low NO_x emissions mode during the 300-400 second time period. The primary impact in the regulated emissions was an increase in NO_x emissions, which ranged from 4.0 to 7.4% over the different test periods between the high and low mode operations. The operational conditions had the opposite impact on the other emissions, with emissions reductions ranging from 1-4.2% for THC, from 2.4 to 6.8% for CO, from 1.5 to 6.2% for PM, and from 0.7 to 1.9% for CO_2. As this operating conditioning could represent typical operation under these conditions, no tests were removed from the data sets and the associated analyses below. This complicated the statistical comparisons, especially at the 20% and lower blend levels.

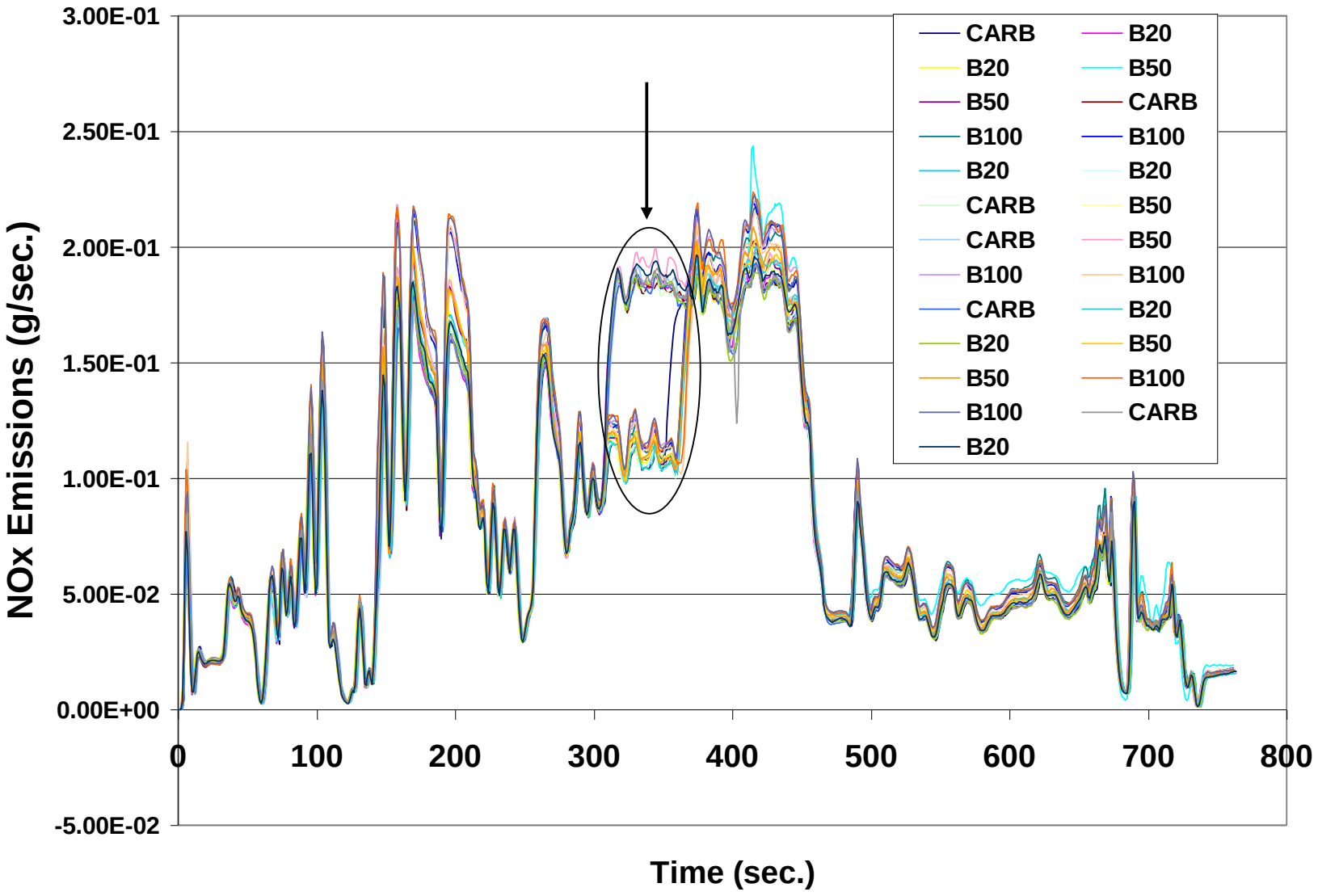


Figure 2-1. Real-Time NO_x Emission Traces for the 50 MPH CARB Cruise Cycle for the Animal-Based Biodiesel Feedstock.

A second outlier condition was also identified that was related to the temperature of the water controlling the turbocharged inlet air temperature. Prior to initiating the testing program, CE-CERT switched from an air-cooled to a water-cooled temperature control system for the turbocharged inlet air. This system operated well during the preliminary testing, but had some issues when the ambient temperature declined and the cooling water temperature dropped to levels below 68°F. Figure 2-2 shows real-time NO_x traces for four tests conducted over the UDDS cycle using the CARB ULSD. These traces clearly show significant differences in the emissions profiles between the tests. Figure 2-3 shows the corresponding intake air temperature (IAT) profiles for the same tests as recorded from the J1939 signal. As shown, tests with the cooler intake air temperature profiles, where the minimum temperature drops below 60°F, had considerably higher NO_x emissions compared to those with the higher intake air temperatures.

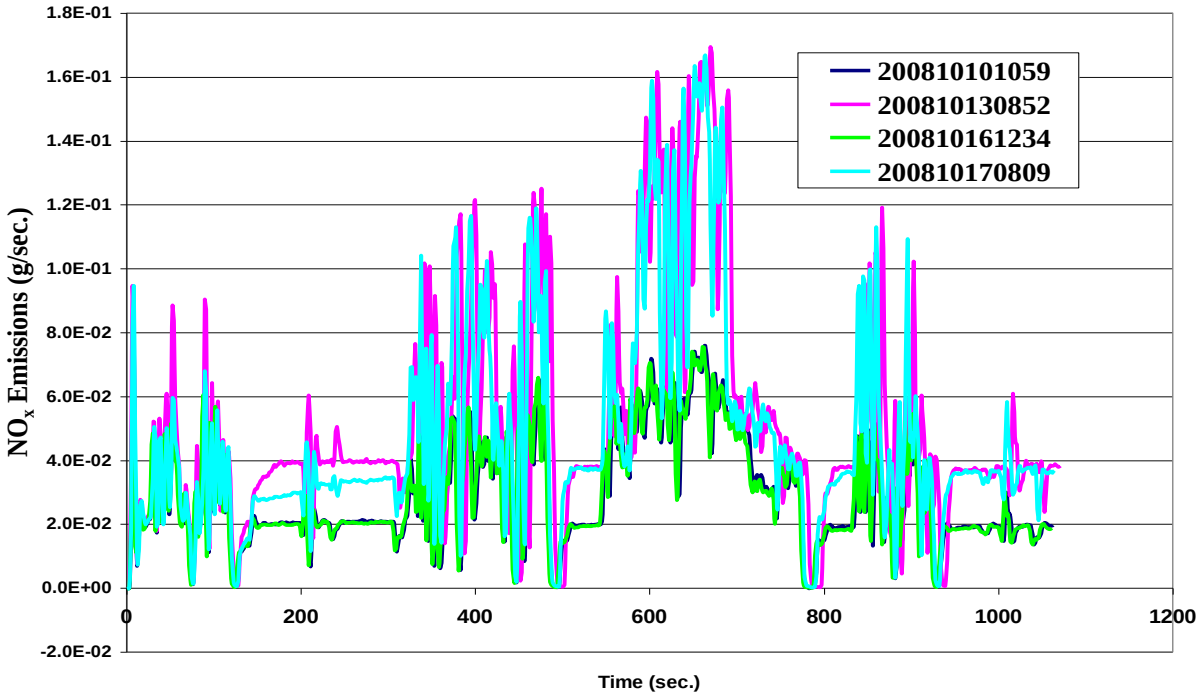


Figure 2-2. Real-Time NO_x traces for four tests using CARB ULSD over the UDDS Cycle.

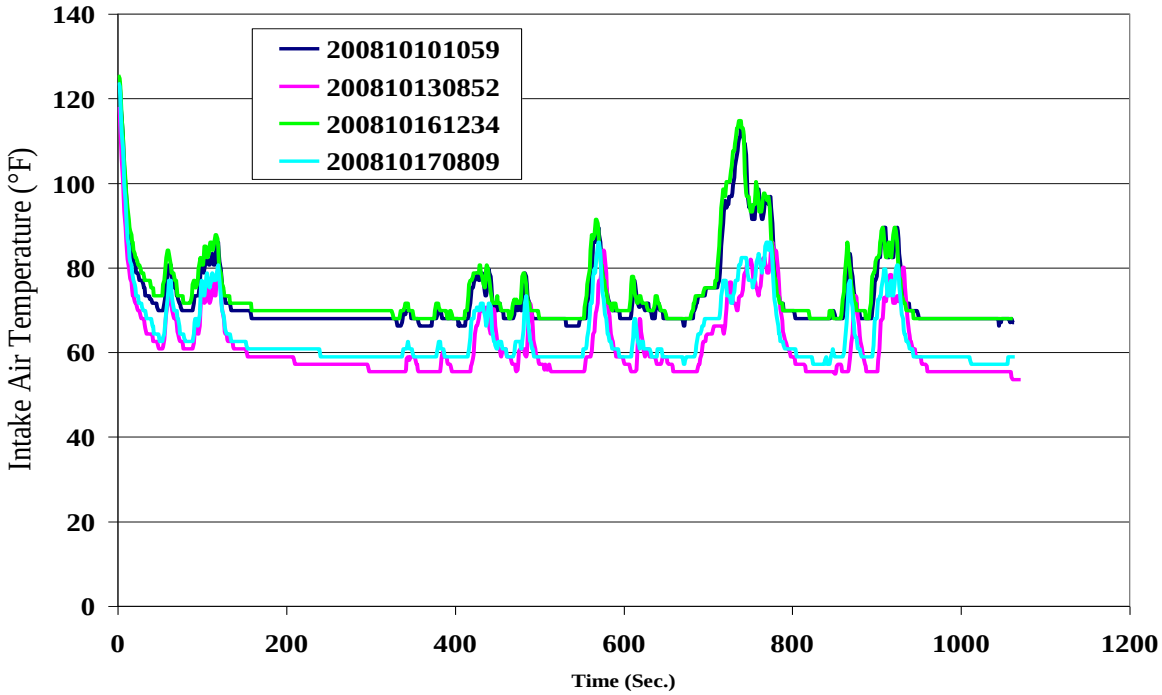


Figure 2-3. Real-Time Intake Air Temperature traces for four tests using CARB ULSD over the UDDS Cycle.

These differences were seen both within the transient portion of the test and during the idle periods as well. These trends were also observed on the FTP and cruise cycles, but to a lesser extent since these cycles have higher loads and generally warmer operating conditions. In analyzing the first batch of testing rests, the real-time NO_x and IAT results were plotted for all tests to identify tests where this phenomena was observed. For the subsequent analyses and subsequent plots in this report, all tests where the cooling water temperature to the intercooler was found to drop below 68°F were removed. A total of 45 of 159 tests were removed based on this criteria for the testing on the soy-based biodiesel feedstock. The water-based temperature control system was redesigned to provide full temperature control for the remainder of the tests and the temperature was set to slightly higher than 70 ^{0}F. This phenomena was not observed with the new system. Some additional tests were also performed to ensure there were sufficient replicates for subsequent statistical analysis for each of the different fuel blend/test cycle combinations for the soy-based biodiesel.

3.0 Experimental Procedures – Off-Road Engine Dynamometer Testing

The off-road engine testing was conducted on two engines at two separate CARB facilities. A transportation refrigeration unit (TRU) was tested at CARB's facilities in El Monte, CA, and a John Deere engine was tested at CARB's facilities in Stockton, CA. The experimental methods used for both of these engine tests are discussed in this section.

3.1 Test Fuels

The primary fuels for the off-road engine testing were the same as those used for the engine dynamometer testing. This includes CARB-certified ultralow sulfur diesel (ULSD) as the base fuel, and the soy-based and animal-based biodiesels as blend stocks. These fuels were obtained from the same batches of primary fuels as used for the engine dynamometer testing and the fuels were blended at the same time as well. The details relating to the fuel properties and blending for the different fuels are provided in Section 2.1 and Appendix A. The testing of the TRU engine included the CARB baseline diesel and the soy-based biodiesel at the B5, B20, B50, and B100 levels. For the John Deere engine testing, the test fuels were CARB ULSD, and the soy-based B20, B50, and B100 blends, and the animal-based B5, B20, and B100 blends.

3.2 Engine Selection

Two off-road engines were tested as part of this program. One engine was a Transportation Refrigeration Unit (TRU) engine and the other was a new John Deere non-road, industrial engine. The TRU engine was a Pre Tier 1-1998, 2.2 liter, Kubota V2203-DIB engine. The specifications for this engine are provided in Table 3-1. The other engine was a 2009 John Deere 4045HF285 4.5 liter Tier 3 engine, and its specifications are provided in Table 3-2. This engine was new, as provided by the manufacturer's distributor. This engine was derated from its original horsepower (hp) level to the 115 hp level to ensure the testing could be accommodated on the available dynamometer.

Table 3-1. Test Engine Specifications

Engine Manufacturer	Kubota
Engine Model	V2203-DIB
Model Year	1998
Engine Type	In-line 4 cylinders, 4 strokes (Pre Tier 1)
Displacement (liter)	2.197
Power Rating (hp)	37.8 hp (actual power ~ 27.6 hp)
Speed Rating (rpm)	2200 rpm (actual rated speed ~ 1900 rpm)
Fuel Type	Diesel
Induction	Naturally aspirated

Table 3-2. Test Engine Specifications

Engine Manufacturer	John Deere
Engine Model	4045HF285
Model Year	2009
Engine Family	4045HF285 C,D,E,F,G
Engine Type	In-line 4 cylinder, 4-stroke (Tier 3)
Displacement (liter)	4.5
Power Rating (hp)	115 hp (86 kW)
Speed Rating (rpm)	2400 rpm
Fuel Type	Diesel
Induction	Turbocharged

3.3 Test Cycles

The test protocol used for testing these engines was the ISO 8178, Part 4 "Test Cycle Type C1 off-road vehicles, industrial and Medium/High load." This test cycle is composed of 8 steady states modes. The speed, torque, and weighting factor parameters for the eight-mode test are summarized in Table 3-3. The duration of each mode was 300 seconds.

Table 3-3. 8-mode Test Parameters

Mode	Speed	Torque %	Weight Factor
1	Rated*	100	0.15
2	Rated	75	0.15
3	Rated	50	0.15
4	Rated	10	0.1
5	Intermediate**	100	0.1
6	Intermediate	75	0.1
7	Intermediate	50	0.1
8	Idle***	0	0.15

*Rated speed ~ 1900 rpm Kubota, 2400 rpm John Deere
**Intermediate speed ~ 1430 rpm Kubota, 1500 rpm John Deere
***Idle ~ 1035 rpm Kubota, 800 rpm John Deere

3.4 Test Matrix

The test matrix for the TRU and John Deere engine testing was designed to provide randomization between the different fuels tested and a measure to testing reproducibility.

The TRU testing was conducted in two series. The test sequences for the two series are shown in Table 3-4. A single full 8 mode test was conducted each test day on a single fuel. Nominally, eight replicates of each fuel were performed for each series. Some additional tests were also conducted toward the end of each series to provide supplemental data for tests that were invalidated or might otherwise have provided insufficient information.

Table 3-4. Test Matrix for the TRU Testing

Test Series 1 - Soy based biodiesel

Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
CARB	B50	B100	CARB	B50	B100	CARB	B50	B100	CARB	B50	B100
Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
CARB	B50	B100	CARB	B50	B100	CARB	B50	B100	CARB	B50	B100

Test Series 2 - Soy based biodiesel

Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
CARB	B5	B20	CARB	B5	B20	CARB	B5	B20	CARB	B5	B20
Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
CARB	B5	B20	CARB	B5	B20	CARB	B5	B20	CARB	B5	B20

The John Deere utilized a similar randomization between different fuels on different test days. This test sequence was closer to the test sequence for the heavy-duty engine testing, with the CARB fuel being tested at the beginning and the end of the test sequence, with a fuel change generally occurring during the middle of the day. This test sequence is shown in Table 3-5.

Two full 8 mode tests were conducted each test day. Nominally, six replicates of each fuel were performed for each series. The testing sequence was run in two series corresponding to the soy-based and animal-based feedstocks. Some additional tests were also conducted toward the end of each series to provide supplemental data for tests that were invalidated or might otherwise have provided insufficient information.

Table 3-5. Test Matrix for the John Deere Testing

Test Series 1 – Soy based biodiesel

Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
Cal.	C-1	S20-2	S50-2	S100-2	Cal.	C-3	S20-4	S50-4	S100-4
Ck.	FC	FC	FC	FC	Ck.	FC	FC	FC	FC
	S20-1	S50-1	S100-1	C-2		S20-3	S50-3	S100-3	C-4
Day 11	Day 12	Day 13	Day 14	Day 15	Day 16				
Cal.	C-5	S20-6	S50-6	S100-6	Cal.				
Ck.	FC	FC	FC	FC	Ck.				
	S20-5	S50-5	S100-5	C-6					

Test Series 2 – Animal based biodiesel

Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 19	Day 20	Day 21	Day 22
Cal.	C-1	A5-2	A20-2	A100-2	Cal.	C-3	A5-4	A20-4	A100-4
Ck.	FC	FC	FC	FC	Ck.	FC	FC	FC	FC
	A5-1	A20-1	A100-1	C-2		A5-3	A20-3	A100-3	C-4
Day 23	Day 24	Day 25	Day 26	Day 27	Day 28				
Cal.	C-5	A5-6	A20-6	A100-6	Cal.				
Ck.	FC	FC	FC	FC	Ck.				
	A5-5	A20-5	A100-5	C-6					

3.5 Emissions Testing

The TRU engine testing was conducted at CARB's Haagen-Smit Laboratory in El Monte. The TRU engine was installed on a Midwest & Dynamatic 50 hp Eddy Current Dynamometer, Model # 758, Serial # 0702. Emission measurements followed CFR title 40, part 89. Average tailpipe concentrations (ppm) of NO_X, CO, CO_2, and CH_4 in each mode were measured from Tedlar bags using a Horiba constant volume sampling (CVS) system and an AVL AMA 4000 analyzer. The average THC concentration (ppmC) in each mode was measured using a Horiba CVS system and an AVL Heated FID analyzer. N_2O samples of each mode were collected in Tedlar bags and measured offline with a gas chromatograph equipped with an electron capture detector (ECD), but only for the first test series. The PM mass in the diluted exhaust was collected on 47 mm Teflon filter, and calculated as the difference of the buoyancy corrected pre-test and post-test filter weights (following CFR 1065 and ARB Monitoring and Laboratory Division SOP MLD # 145). Average emission concentrations (ppm) were converted to average emission rates in (g/h). Weighted specific emissions (g/kWh) were calculated based on weighting factor and engine power of each mode. Figure 3-1 shows a schematic of the setup for the TRU testing.

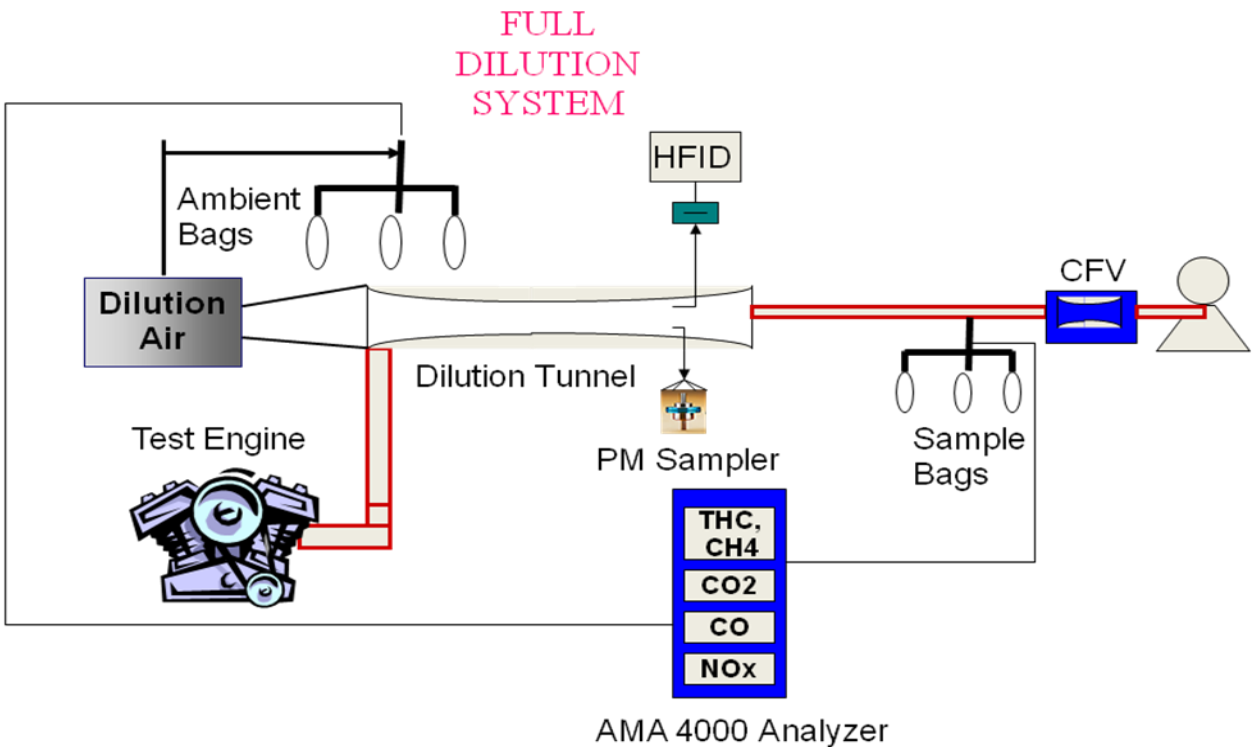


Figure 3-1. Schematic of Engine Testing

The John Deere, non-road engine was tested at the CARB's Laboratory in Stockton, CA. Upon receipt, the engine was mounted to a Midwest eddy current engine dynamometer rated at 125 hp at 4000 rpm. Prior to testing, the new engine was run for approximately 150 hours to degreen it. During degreening, the engine was run on CARB diesel with varied speeds and loads applied. After degreening, the engine oil, oil filter, and fuel filter were replaced and the engine was then operated an additional 20 hours to stabilize the new oil.

For testing, the engine and dynamometer were instrumented. The dynamometer and other analytical equipment received calibration checks approximately weekly, using traceable avoirdupois calibration weights. Emissions measurements were made using an AVL AMA i60 emissions bench. The AMA i60 measures NO_x, NO, THC, CO, CO_2, and O_2. Raw exhaust samples were transferred to the analyzer bench via heated lines. Engine intake combustion air was measured using a calibrated air turbine manufactured by Superflow, Inc. (model 1200A-0855), and fuel consumption was measured using a gravimetric fuel measurement system made by Superflow,Inc. PM samples were collected utilizing a Sierra Instruments BG-2 mini dilutor. For each test mode, PM samples were collected on double 90 mm T60A20 fiberfilm filters. Following temperature and humidity stabilization, the filters were weighted using a Mettler Toledo, UMX 2 mictrobalance housed in an environmentally controlled room. For each test cycle, modal second-by-second data was collected and then post processed to determine average emission rates in (g/hr). Combining brake horsepower measurements, ISO weighting factors (Table 3-3), and average emission rates (g/hr), weighted brake specific emissions (g/bhp-hr) were calculated.

4.0 Experimental Procedures – Heavy-Duty Chassis Dynamometer Testing

4.1 Test Fuels

The primary fuels for the chassis dynamometer testing were the same as those used for the engine dynamometer testing. This includes the CARB baseline diesel, and the soy- and animal-based biodiesels and the renewable diesel blend stocks. These fuels were obtained from the same batches of primary fuels as used for the engine dynamometer testing, and the fuels were blended at the same time as well. The fuel properties for the neat and blended fuels are provided above in section 2.1, along with the blending procedures. The detailed properties for the neat and blended fuels are provided in Appendix A. For the chassis testing, the blends were tested at only the 20%, 50%, and 100% blend levels because the typically greater variability for the chassis dynamometer testing would make it difficult to identify trends for lower 5-10% blend levels.

4.2 Vehicle Selection

A total of 4 vehicles are being tested for this program. The test vehicles include the following:

- 2006 International Truck equipped with a 2006 11 liter Cummins ISM engine.
- 2008 Freightliner Truck equipped with a 2007 MBE4000 engine.
- 2000 Freightliner Truck equipped with a 2000 Caterpillar C-15 engine.
- Kenworth model T800 truck equipped with a 2010 Cummins ISX15 engine.

The first two vehicles were equipped with the same engines that were used in the engine dynamometer testing. The specifications for these engines are provided in Section 3.2. The third vehicle was CE-CERT's in-house, 2000 Caterpillar C-15 14.6 liter engine equipped, Freightliner Class 8 Truck. This engine is certified to EPA 2000 model year standards, with a NO_x certification level of 3.7 g/bhp-hr and a PM certification level of 0.08 g/bhp-hr without a DPF. The specifications for this engine are provided in Table 4-1. The final vehicle was equipped with a 2010 Cummins ISX15 equipped with a OEM DPF with a selective catalytic reduction (SCR) system. This engine is certified to EPA 2010 model year standards, with a NO_x certification level of 0.22 g/bhp-hr and a PM certification level of 0.08 g/bhp-hr without a DPF. The specifications for this engine are provided in Table 4-2. The data analysis for this vehicle has not been completed, so results from this vehicle are not included in this report.

Table 4-1. Test Engine Specifications

Engine Manufacturer	Caterpillar
Engine Model	C-15
Model Year	2000
Engine Family Name	XH0893ERK
Engine Type	In-line 6 cylinder, 4 stroke
Displacement (liter)	14.6
Power Rating (hp)	475 hp @ 2100
Fuel Type	Diesel
Induction	Turbocharger with after cooler

Table 4-2. Test Engine Specifications

Engine Manufacturer	Cummins
Engine Model	ISX15
Model Year	2010
Engine Family Name	ACEXH0912XAP
Engine Type	In-line 6 cylinder, 4 stroke
Displacement (liter)	14.9
Power Rating (hp)	450 hp @ 1800
Fuel Type	Diesel
Induction	Turbocharger with after cooler

4.3 Test Cycles

Two test cycles were utilized for the chassis dynamometer testing, an Urban Dynamometer Driving Schedule (UDDS) and a CARB Heavy Heavy-Duty Diesel Truck (HHDDT) 50 mph Cruise cycle. The UDDS is designed to simulate urban driving while the 50 mph cruise cycle is designed to simulate highway driving up to ~65 mph. These test cycles are described in Appendix B. For the UDDS cycle, back-to-back UDDS's were run to provide a longer sampling period for cumulative samples for the toxic and other unregulated emissions.

The test cycles were performed at different test weights to provide a broader range of load over which the impacts of biodiesel could be investigated. The test weights used for each vehicle and cycle are summarized in Table 4-3.

Table 4-3. Test Weights for Different Vehicle/Cycle Combinations

Vehicle/Engine	Mileage	Test Weight
Freightliner Truck with 2000 Caterpillar C-15 engine	34,000	UDDS: 43,861 lbs. 50-mph Cruise: 58,744 lbs.
International Truck with 2006 Cummins ISM engine	93,000	UDDS: 43,480 lbs. 50-mph Cruise: 61,189 lbs.
Freightliner Truck with 2007 MBE4000 engine	8,000	UDDS: 43,480 lbs. 50-mph Cruise: 57,490 lbs.

Preconditioning

The engine was warmed up for 5 minutes at 50 mph prior to running the first cruise cycle each day. The vehicle was turned off, or "hot soaked", in between tests throughout the remainder of the day, including the period between the cruise cycle and the UDDS tests. The hot soak corresponded to a period of approximately 40 minutes, which is approximately the time needed to reset the analyzers and complete the preparation for the next test. If there was a longer break in the test sequence, i.e., for lunch or repairs, preconditioning of 5 minutes at 50 mph was performed again prior to restarting testing.

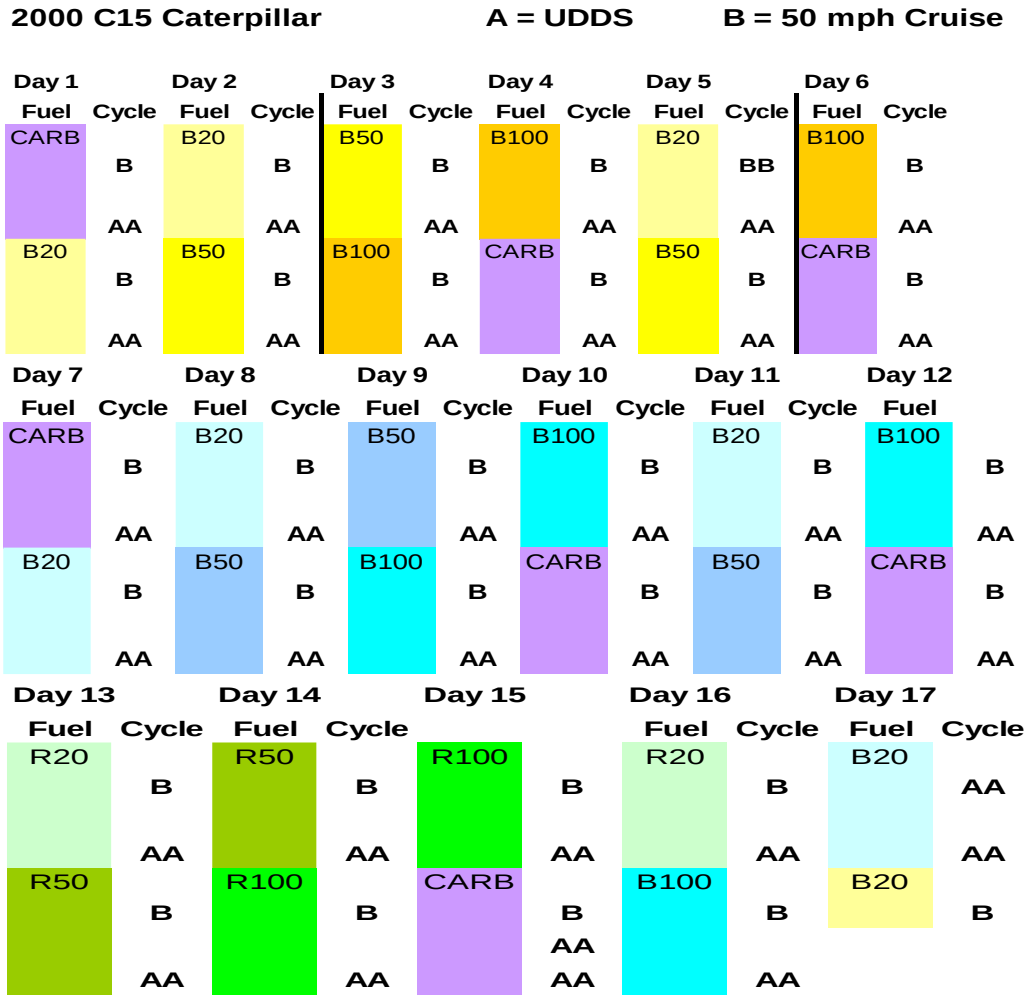
For the 2007 MBE4000, the engine was equipped with a OEM–DPF that utilized active regeneration including an extra fuel injector in the exhaust. To ensure that the DPF would not regenerate in the middle of a testing sequence, and to minimize carryover of PM and

toxics trapped during a previous fuel into the testing of a subsequent fuel, the DPF was regenerated after each fuel change prior to beginning the test on the new fuel. This forced regeneration schedule resulted in a regeneration at least once per day or every four emissions tests. An OEM service tool was used to request the stationary parked regereneration (which lasts approximately 45 minutes).

4.4 Test Matrix

The test matrix was designed to provide a randomized test matrix with long range replication. The test matrix was designed to provide at least 6 replicates of the UDDS and 3 replicates of the 50 mph cruise on each biodiesel blend. For the renewable blends, at least 4 iterations of the UDDS and 2 iterations of the 50 mph cruise were conducted. Some additional tests were also conducted toward the end of the test program to provide supplemental data for tests that were invalidated or might otherwise have provided insufficient information.

Table 4-4 : Vehicle 2000 C-15 Caterpillar



4.5 Emissions Testing

The laboratory portion of the project was conducted at CARB's Heavy-Duty Engine Emissions Testing Laboratory (HDEETL) located at the Metropolitan Transit Authority facility in Los Angeles, CA. This facility has a Schenck-Pegasus chassis dynamometer with a single 72 inch diameter roller. The dynamometer is driven by a direct current 675 hp motor that can absorb up to 660 hp. The dynamometer has a range of simulated inertial weights from 5,000 to 100,000 lbs. This facility is described in greater detail in Ayala et al. [2002].

The emissions sampling included regulated emissions, filter-based PM mass, additional real-time PM sizers, and sampling for PM composition, toxicity, and health effects. A summary of the emissions measurements for this portion of the program is provided Table 4-5.

Table 4-5. Sample Collection Test Matrix for Chassis Dynamometer Testing

Analyte	Collection media	Analysis
THC	Modal, Bag	FID
NMHC	Modal, Bag	FID
NO_x, NO_2	Modal, Bag	Clemiluminescence
CO, CO_2	Modal, Bag	NDIR
BTEX	Tedlar Bags	GC-FID
Carbonyls	2,4-DNPH cartridges	HPLC
PM Mass	Teflon 47mm (Teflo)	gravimetric
Organic/Elemental Carbon	Quartz fiber filter 47mm	Thermo/Optical Carbon Analysis IMPROVE_A protocol
Elements	Teflon filter	ICP-MS
PAH	Teflon Filter/PUF/XAD	GC-MS
N_2O	Tedlar Bags	FTIR

4.5.1. Regulated Emissions

Standard emissions measurements were made for the regulated emissions (NO_x, NO_2, THC, NMHC, CO) and CO_2. NO_x and NO_2 were measured over a heated sampling path. Emissions measurements were made using the standard laboratory instruments at the CARB chassis dynamometer facility in Los Angeles, CA. For each test cycle, for gaseous emissions, both modal (second-by-second) and bag data were collected.

4.5.2. Filter-based PM Mass Emissions

Filter-based PM mass measurements were collected for all tests. Over double iterations of the UDDS, and over each of the segments of sampling for the cruise and idle tests, PM mass samples were collected cumulatively.

Samples were collected from a secondary dilution tunnel off the primary CVS. Samples were collected using 47mm Teflo filters and the sampling conditions specified in the 2007 regulations. This includes collection of PM samples at the appropriate 47°C±5°C, and with the appropriate filter face velocities. The dilution was set such that a total dilution ratio (primary + secondary) of

approximately 20 to 1 for the PM mass was achieved under fully loaded vehicle test conditions. Pre- and post-filter mass measurements were made using a Mettler Toledo UMX2 microbalance with a static neutralizer in a 2007 compliant glove box.

4.5.3 1,3 Butadiene, BTEX, Styrene, Carbonyl, and N_2O Sampling and Analysis

Exhaust samples were collected in Tedlar bags, 0.002 inches in thickness, for benzene, toluene, ethylbenzene, and xylenes (BTEX) and 1,3-butadiene, N_2O analysis at the CARB's Haagen Smit Laboratory in El Monte, CA. BTEX were quantified using a Varian GC (Model 3800 or equivalent, designated for C_5-C_{12}) with a flame ionization detector (GC/FID) maintained at 300°C (CARB SOP MLD 102/103, 2007). The sample was injected into a fixed volume loop in the GC using an automated, gas phase sampling valve system. The GC is equipped with a cryogenic pre-concentration system (nickel tubing, 0.32mm ID x 50m) operated at -180°C and using a DB-1 WCOT column (0.32mm ID x 60m).

A Fourier Transform Infrared system (FTIR, Thermo/Nicolet Magna-IR 560) with a 10 meter long, 2ℓ cell was used to quantify N_2O (CARB SOP MLD 136, 2004). The FTIR is annually recalibrated with N_2O, CO, and CO_2 in the 2187.6 cm^{-1} to 2205.2 cm^{-1} region, using primary gas standards at CARB. The calibration is a multipoint linear calibration using a least squares fit algorithm. Other pollutants such as formaldehyde, acetaldehyde and 1,3-butadiene can be measured simultaneously, but the diluted concentration levels for the vehicles tested in this program are below the detection limits for the emissions.

Dilute exhaust gas carbonyls were collected at a flow rate of 1 ℓ per minute (LPM) through a heated line onto silica gel cartridges coated with 2,4-dinitrophenyl-hydrazine (2,4-DNPH). Two 6 mg-load DNPH cartridges (Supelco) were collected in series to reduce potential break through. The 2,4-DNPH cartridges were subsequently eluted using acetonitrile to provide samples for analysis. The resulting extract was analyzed using a Waters Alliance 2690/2690D Series high performance liquid chromatograph (HPLC) with a dual ultraviolet (UV) detector. The HPLC sample injection, column, and operating conditions were set up according to the specifications of the CARB SOP MLD 104 (2006).

Reactive carbonyls were collected and analyzed as previously described (Seaman et. al., 2006) and analyses conducted by Arizona State University. Briefly, reactive carbonyl samples were collected from the dilution tunnel into a "mist chamber" bisulfite solution (0.1M) that derivatized the carbonyl compounds. The collection period was for a single UDDS test cycle (the first of two). A "clean dilution air" sample was also collected in parallel for an identical period of time. Once samples were collected, hydrogen peroxide (1.04 mmol) was added followed by pentafluorohydroxylamine (PFBHA) (1 mM final concentration). This PFBHA derivative was extracted twice with hexane that was placed in the freezer for at least 1 month. Analyses of the PFBHA-carbonyl oximes were conducted using a 6890N gas chromatograph coupled with a Agilent 5973 mass selective detector. The GC was equipped with a DB-5 fused silica capillary column (30 m, 0.25 mm i.d., 0.25 umμm film thickness). The detector was operated in the negative chemical ionization mode with methane as the reagent gas. Deuterated internal standards were used throughout to determine recovery and quantitate the derivatized carbonyls. A more detailed discussion for the QA/QC procedure for this method are provided in Appendix F.

4.5.4 PM Composition Sampling and Analysis

The diluted exhaust air stream was drawn through a 2.5 cm stainless steel tube in the CVS, and split into three airstreams for PM speciation: 1) organic and elemental carbon, 2) cation and anions, and 3) elements. Each PM speciation sample was set up at a nominal flow rate of 30 LPM. The flow rate was measured at the beginning and the end of the sampling cycle.

Samples for organic and elemental carbon analyses were collected on 47mm quartz fiber filters (7202, Tissuquartz, Pall Corp). The quartz fiber filters were pre-baked at 900°C for four hours to reduce background carbon levels. Elemental and organic carbon analyses were performed using a DRI Thermo/Optical Carbon Analyzer Model 2001, following the IMPROVE_A protocol (Chow et al., 2007; CARB MLD SOP 139, 2006). The method is based on the preferential oxidation of OC and EC at different temperatures and under different conditions. A 5/16 inch diameter punch is taken from a quartz filter deposited with vehicular exhaust PM, placed inside the analyzer, and heated to selected temperatures under selected conditions. At low temperatures and in a helium (He) atmosphere, OC is volatilized and removed from the quartz filter, while EC is not. The volatilized OC is swept by helium over a hot oxidizer (manganese dioxide, MnO_2) and converted to CO_2. The CO_2 is then reduced to CH_4 by passing the flow through a methanator (a nickel catalyst). A flame ionization detector (FID) is used to quantify the CH_4. After all the OC is removed from the sample, the filter is further heated to higher temperatures in a controlled oxygen atmosphere. EC is pyrolyzed to CO_2, converted to CH_4, and quantified with the FID. With an appropriate calibration factor, the amounts of OC and EC can be calculated from the FID peak areas.

Samples for trace elements and ions were collected on 47mm Teflo filters (R2PJ047 Teflo 47 mm Pall Corp, Ann Habor, MI). The filters were extracted in deionized water by sonicating and storing extracts overnight in a refrigerator to settle particles. The extract was analyzed by an ion chromatography system (Dionex IC LC20 for anions and Dionex ICS-2000 for cations) comprised of a guard column, an analytical column, a self-regenerating suppressor, and a conductivity detector. The peak integrations were conducted by a software program based on conductivity. Then, concentrations of selected particulate anions (nitrate and sulfate) and cations (sodium, ammonium, and potassium) were calculated based on peak areas using external standards (CARB MLD SOP 142, 2007).

4.5.5. PM Real-Time PM Measurements

Real-Time PM measurements were made to characterize the size distribution and number concentration, the particle length/diameter concentration, and the particle-bound PAH concentration. A description of the instruments used for these measurements and their characteristics is provided as follows:

- Differential Mobility Spectrometer (DMS 500, Cambustion Ltd)
    - Characterizes size distribution and number concentration
    - Classifies particles (4.5 nm-1000nm) according to their electrical mobility
- Engine Exhaust Particle Sizer (EEPS 3090, TSI Inc)

    - Size distribution and number concentration
    - Electrical mobility analyzer (6.04 nm-523nm) – similar to the DMS.
- Electrical Aerosol Detector (EAD 3070A, TSI Inc)
    - Particle length/diameter concentration (the total length of all the particles if placed in a line)
    - Diffusion Charger (10- ~1000nm)
- Photoelectric Aerosol Sensor (PAS 2000, Eco Chem)
    - Particle bound polycyclic aromatic hydrocarbons (pPAH)
    - Photoionization of particle-bound PAH

Different real-time particle instruments were employed, depending on the instrument availability and other testing logistics. For the Caterpillar C-15 equipped vehicle, only the DMS 500 was utilized. For the 2006 Cummins ISM-equipped vehicle, the EEPS 3090, EAD 3070A, and PAS 2000 were used. For the 2007 MBE4000-equipped vehicle, the DMS 500, EAD 3070A, and PAS 2000 were utilized. The number of tests where the physical properties of particles were measured also differed between vehicles. The number of driving runs used for the real-time PM analysis is provided in Table 4-6 for each test vehicle and each instrument. For the Caterpillar C-15 mostly one validated test run was available for analysis (except the CARB fuel). Therefore, the results described later for this vehicle are not conclusive, and should be considered only a snapshot.

Table 4-6. Number of Driving Runs Used for the Real-Time PM Data Analysis

	2000 C15 Caterpillar		2006 Cummins ISM						2007 MBE 4000					
	Particle Number/ Size Dist.		Particle Number/ Size Dist.		Particle Length (PL, EAD)		pPAH (PAS)		Particle Number/ Size Dist.		Particle Length (PL, EAD)		pPAH (PAS)	
Fuel	Cruise	UDDS	Cruise	UDDS	Cruise	UDDS	Cruise	UDDS	Cruise	UDDS	Cruise	UDDS	Cruise	UDDS
CARB	2	2	6	6	6	6	6	6	6	12	6	12	6	12
Soy B20	NA	NA	3	3	3	3	3	2	3	8	3	8	3	8
Soy B50	1	1	3	3	3	3	3	3	3	9	3	8	2	8
Soy B100	1	1	3	3	3	3	3	3	3	7	3	9	3	9
AnB20	1	2	3	3	3	3	2	3	5	4(2)	4	4(2)	4	3(2)
An B50	1	NA	3	3	3	3	3	3	4	3	3	3	4	4(1)
An B100	1	1	3	3	3	3	3	3	4	4(1)	4(1)	4(1)	4	4(1)
R20	1	1	Renewable fuel was not tested for International and MBE 4000 trucks											
R50	1	NA												
R100	1	1												

All the instruments were directly connected to the CVS through a common stainless steel tube (1/2 inch ID, total length ~7ft) having multiple ports. A picture of the instruments (DMS not shown here) and the steel tube are shown below in Figure 4-1.

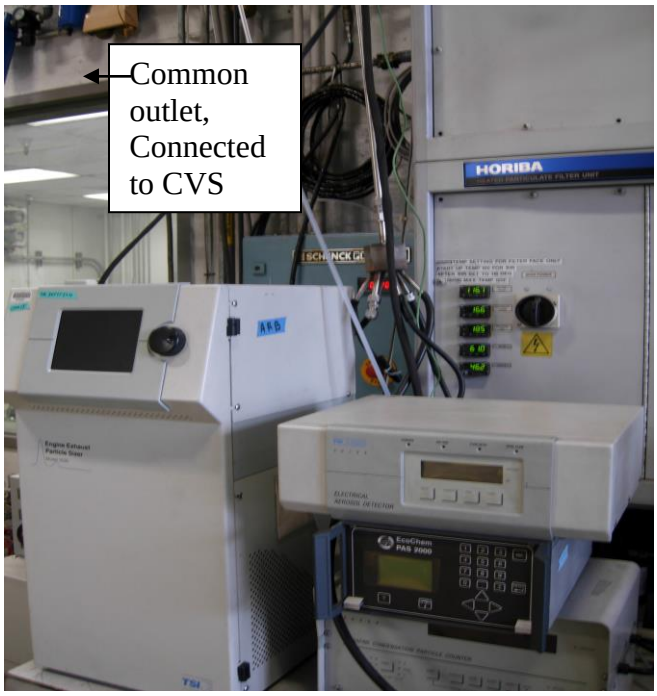


Figure 4-1. Picture of Sampling for Real-Time PM instruments.

4.5.6. PAH and Nitro PAH Speciation Sampling and Analysis

Particle and vapor-phase samples for associated PAHs were collected using a combination of a 90 mm Teflon filter (Pall Life Sciences, Ann Arbor, MI, Zefluor) placed in series with polyurethane foam (PUF) plugs - XAD-2 resin (polystyrene divinylbenzene polymer) cartridge. For the C-15 vehicle, at least triplicate samples were taken each for CARB, soy biodiesel, animal biodiesel, renewable diesel, and the respective blends (20% and 50%), and the tunnel blanks, and they were analyzed separately. For the MBE4000 vehicle, triplicate samples were taken each for CARB, soy biodiesel and the blends (20% and 50%), but combined for analysis due to low concentrations of PAHs and nitro-PAHs. The samples were taken over 4 repeated driving cycles for the C-15 vehicle, and 6 cycles for the MBE4000.

The samples were prepared and analyzed at the University of California, Davis (UCD). PUF plugs were precleaned in acetone and a mixture of acetone/hexane by sonication followed by pressurized fluid extraction (PFE). XAD-2 resin was obtained precleaned by the manufacturer (Supelpak 2, Sigma-Aldrich, Saint Luis, MO) and was used throughout. After sampling, the filters and the PUF/XAD cartridges were wrapped in foil, inventoried, and packed and transported in blue ice to the UCD lab for chemical analyses. For samples taken from the C15 vehicle, internal deuterated standards were added to each filter, PUF, and XAD sample prior to extraction. Filters were extracted in dichloromethane (DCM) followed by a DCM/toluene mixture with PFE. PUF plugs were extracted in an acetone/hexane mixture by PFE. XAD samples were extracted in separatory funnels with DCM. Each extract was solvent-exchanged to hexane and subjected to a mini column cleanup containing silica. PAHs were isolated in a hexane/DCM mixture for the analysis. Analysis for the PAHs was conducted by gas chromatography/mass spectrometry using a Hewlett-Packard (HP) 5890 Series II gas chromatograph interfaced to a HP5972 mass selective detector run in selective ion monitoring mode. The GC was equipped with a DB-5ms, fused-silica

capillary column (30 m, 0.25 mmi.d., 0.25 μm film thickness). PAH standard reference materials 2260, 2260a and 14941a (National Institute of Standards and Technology, Gaithersburg, MD) were used to prepare calibration solutions.

After PAHs were quantitated, the GC/MS sample was combined with the third fraction from the mini silica column, and further purified using an aminopropyl SPE column for nitroPAHs. Nitro PAH analysis was conducted by GC/MS using an Agilent 6890 GC interfaced to an Agilent 5975 MS operated in negative ion chemical ionization and selective ion monitoring mode. The GC was equipped with a DB-17ms fused silica capillary column (30 m, 0.25 mm i.d., 0.25 μm film thickness). SRM 2264 and 2265 were used to prepare calibration solutions.

For the MBE4000 vehicle, the triplicate samples were combined for the analysis due to low concentrations of PAHs and nitroPAHs. The internal deuterated standards were added to the composite triplicate samples and the extraction was conducted in the same manner as for the C15 samples. Each extract was solvent-exchanged to hexane and added to a column of 10 g silica that separated PAHs in a DCM/hexane mixture (1:5, v/v) and nitroPAHs in a DCM/hexane mixture (1:1, v/v). The GC/MS analyses of PAHs and nitroPAHs were conducted in the same manner as for the samples from the C15 vehicle.

4.5.7. Genotoxicity Analysis

The analyses of genotoxicity or damage to DNA was conducted using the short-term test *Salmonella/typhimurium* (Ames) Assay. A number of short-term tests for genotoxicity have been developed over the years, but the *Salmonella* test is the most validated and has the largest database when comparing to animal or human carcinogens as well as non-carcinogens (Ames et. al. 1975; McCann and Ames, 1975a, 1975b). In the current study, a simple modification of the plate incorporation procedure called the "microsuspension" assay was used. The assay procedure is approximately 10 times more sensitive, and therefore conserves samples, both as standard substances or complex mixtures (Kado et al., 1983; 1986). A number of tester strains are available for use in testing mutagenic activity of samples. In the current study, based on historical values of diesel and airborne complex mixtures, tester strains TA98 and TA100 were used, which measure frame-shift and base-pair substitutions, respectively. To account for possible metabolism or metabolic activation of the test substance or complex mixture, a liver homogenate (referred to as S-9) was used. This was a rat liver homogenate, where the animal is induced with compounds that enhance the enzyme levels.

Filters and PUF for the bioassay analyses of the emissions were treated and handled as described for the PAH analyses. For the bioassays, a hi-volume sample consisting of an 8" x 10" Zefluor filter was used throughout. The filter was pre-cleaned, as described for the PAH analyses. Mutagenic activity was determined from the linear portion of dose response curves for each extract and tested in duplicate. Briefly, for the microsuspension procedure, bacteria, S-9, and test compounds are added in liquid incubation protocol, as previously reported (Kado et al. 1986; 2005). The results are reported as "revertants", which represent cells that were mutated back (reverted) to a parent type where they could grow independently of any added amino acid histidine. All emission samples for all CARB, biodiesel, and renewable fuels were sampled and tested in triplicate.

4.5.8. Inflammation and Oxidative Stress Analysis

Expressions of inflammatory and oxidative stress markers were measured. The *in vitro* human cell model consists of two main target cell types for PM, human macrophage cells and lung cells. U937 macrophages were found to be the most sensitive of the cell types tested. NCI-H441, a bronchiolar Clara cell line, was found to be the most sensitive lung cell type when compared to the human alveolar lung cell line, A549, and HPL1 cells, and a normal lung epithelial cell line. The macrophage and the Clara cell lines were then used for the biodiesel samples throughout this study.

In this model, PM-mediated cellular toxicity is due to the ability of a number of PM-related components, such as polycyclic aromatic hydrocarbons (PAHs), to bind to the aryl hydrocarbon receptor (AhR). At this point, the "activated" AhR has been shown to increase the protein concentration of a number of metabolic enzymes, such as cytochrome P450 1A1 (CYP1A1), through increased transcription via direct DNA binding. We have also previously shown that interleukin-8 (IL-8), an inflammatory cytokine, is regulated by a similar mechanism.

Oxidative Stress is evaluated via a biological assay where in vitro cells are exposed to the pollutant being evaluated. In this case, extracts were used to treat human macrophages (U937), which are phagocytotic cells used as a first line of defense, and lung Clara cells from the pulmonary epithelium (NCI-H441). Several biomarkers of PAH exposure, inflammation, and oxidative stress were monitored from the assays. These include:

- CYP1A1: Cytochrome P450 monooxygenase, a xenobiotic metabolizing enzyme, bioactiviation, Ah-Receptor regulated.
- COX-2: Cyclooxygense, a key enzyme for the production of prostaglandins involved in inflammation, upregulated in cancer cells.
- IL-8: Interleukin 8, chemoattractant peptide for neutrophils, major mediator of inflammatory response.
- HO-1: Hemooxygenase 1, an essential enzyme in heme catabolism, which protects cells against oxidative injury. HO-1 is a stress-responsive protein and induced by exposure to various forms of oxidative stress.
- MUC5AC: mucin 5AC, oligomeric mucus/gel-forming compounds in Homo sapiens. Mucins are a large family of glycoproteins expressed by many epithelial cells and their malignant counterparts.

4.5.9. DNA Damage/Comet Assay Analysis

The Single Cell Gel Electrophoresis assay (also known as Comet Assay) is a sensitive technique for the detection of DNA damage at the level of the individual eukaryotic cell. This is one of the techniques used in the area of cancer research for the evaluation of genotoxicity and effectiveness of chemoprevention. Swedish researchers Östling & Johansson developed this technique in 1984. It involves the encapsulation of cells in a low-melting-point agarose suspension, lysis of the cells in neutral or alkaline (pH>13) conditions, and electrophoresis of the suspended lysed cells. This is followed by visual analysis with staining of DNA and calculating fluorescence to determine the

extent of DNA damage. The resulting image that is obtained resembles a "comet" with a distinct head and tail. The head is composed of intact DNA, while the tail consists of damaged (single-strand or double-strand breaks) or broken pieces of DNA. The DNA damage is evaluated by manual scoring or automatically by an imaging software.

We used human U937 monocytic cells to evaluate the potential damage to DNA for biodiesel fuels emissions. The cells were individually embedded in a thin agarose gel on a microscope slide. All cellular proteins are then removed from the cells by lysing. The DNA is allowed to unwind under alkaline/neutral conditions. Following the unwinding, the DNA undergoes electrophoresis, allowing the broken DNA fragments or damaged DNA to migrate away from the nucleus. After staining with a DNA-specific the fluorescent dye ethidium bromide, the gel is read for amount of fluorescence in head and tail and length of tail. The extent of DNA liberated from the head of the comet is directly proportional to the amount of DNA damage and is used for the quantitation of the DNA damage (Singh et al. 1988). This approach has been used for detecting DNA damage to cultured human lung cells exposed to oxidants (Lee et al. 1996).

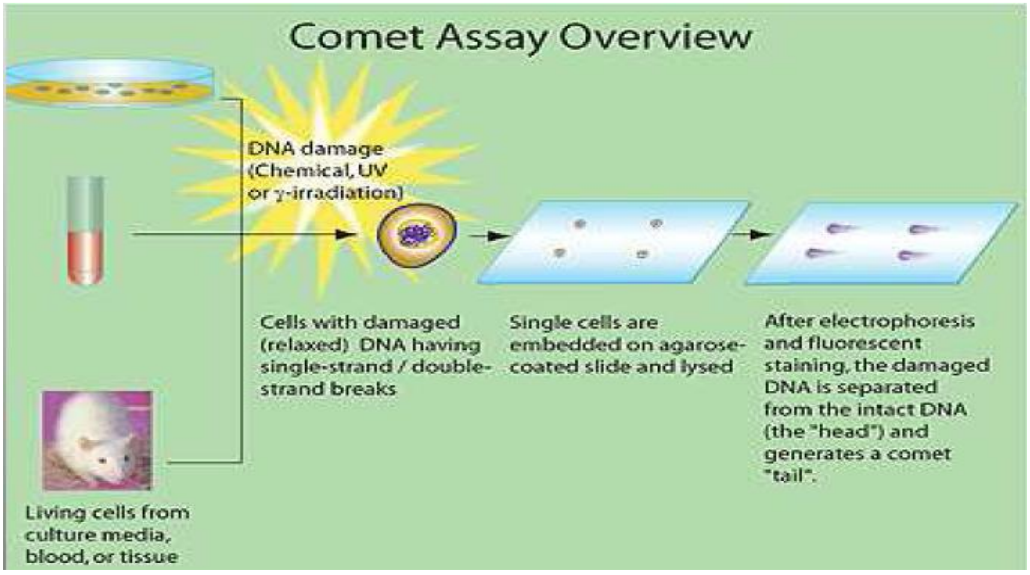


Figure 4-2. Schematic Overview of Comet Assay.

5.0 On-Road, Heavy-Duty Engine Dynamometer Biodiesel Results

5.1 NO_x Emissions

Understanding the impact of biodiesel on NO_x emissions is one of the more critical elements of this program. The NO_x emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock on two different engines are presented in Figure 5-1 to Figure 5-4, respectively, on a gram per brake horsepower hour (g/bhp-hr) basis. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination. The error bars represent one standard deviation on the average value. The CARB results were quantified separately for each feedstocks/test period to minimize the impact of any engine drift between different test periods, and since some changes in the control point for the temperature of the water to the inlet air temperature were made between different feedstocks, as discussed in section 2.7.

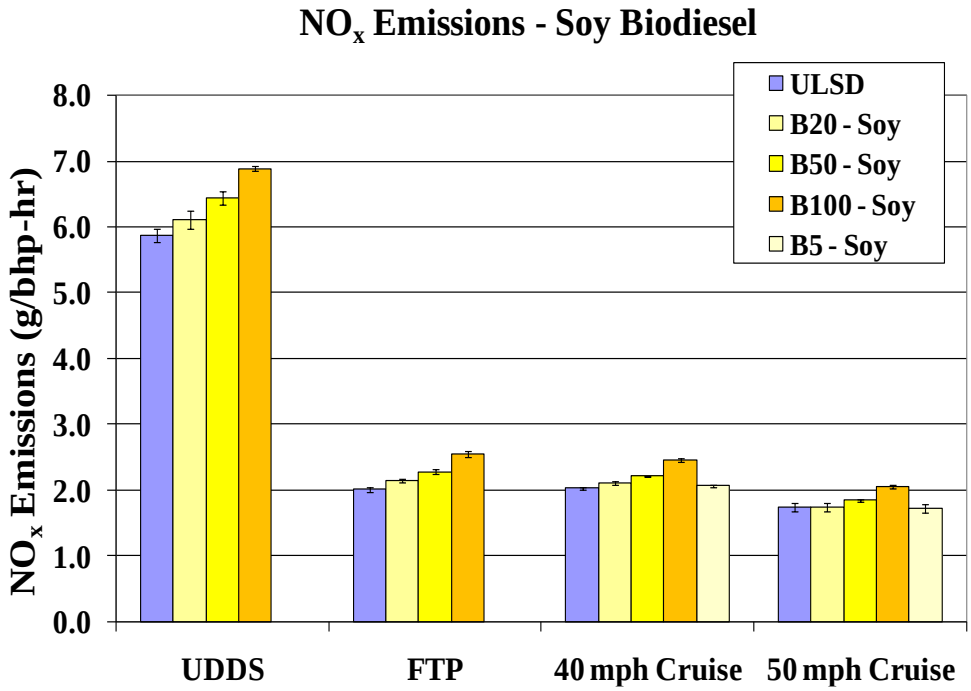


Figure 5-1. Average NO_x Emission Results for the Soy-Based Biodiesel 2006 Cummins ISM

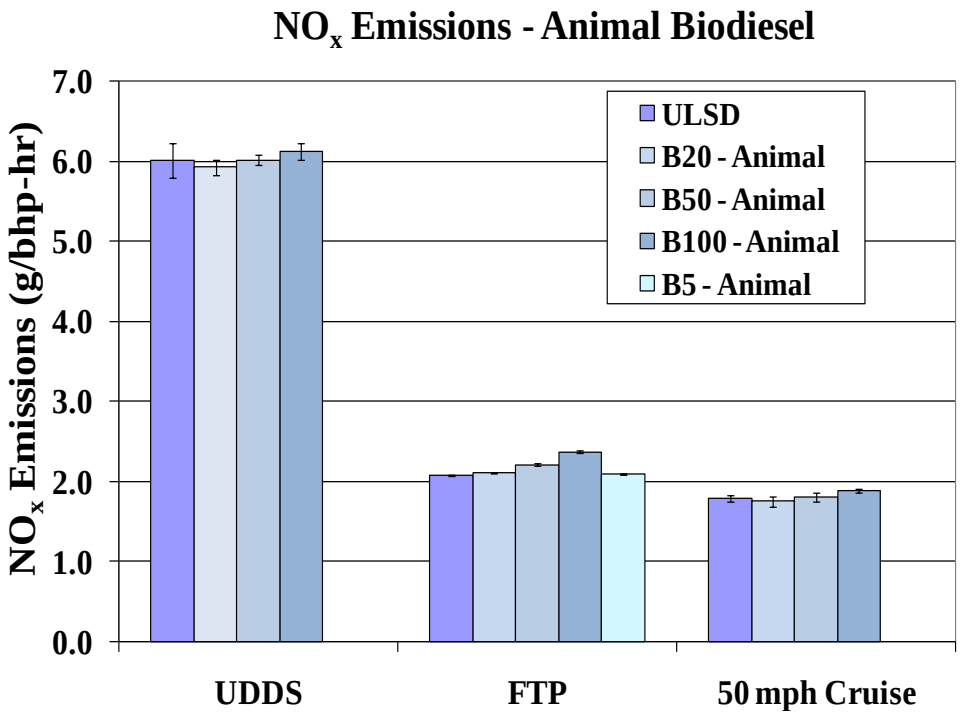


Figure 5-2. Average NO_x Emission Results for Animal-Based Biodiesel 2006 Cummins ISM

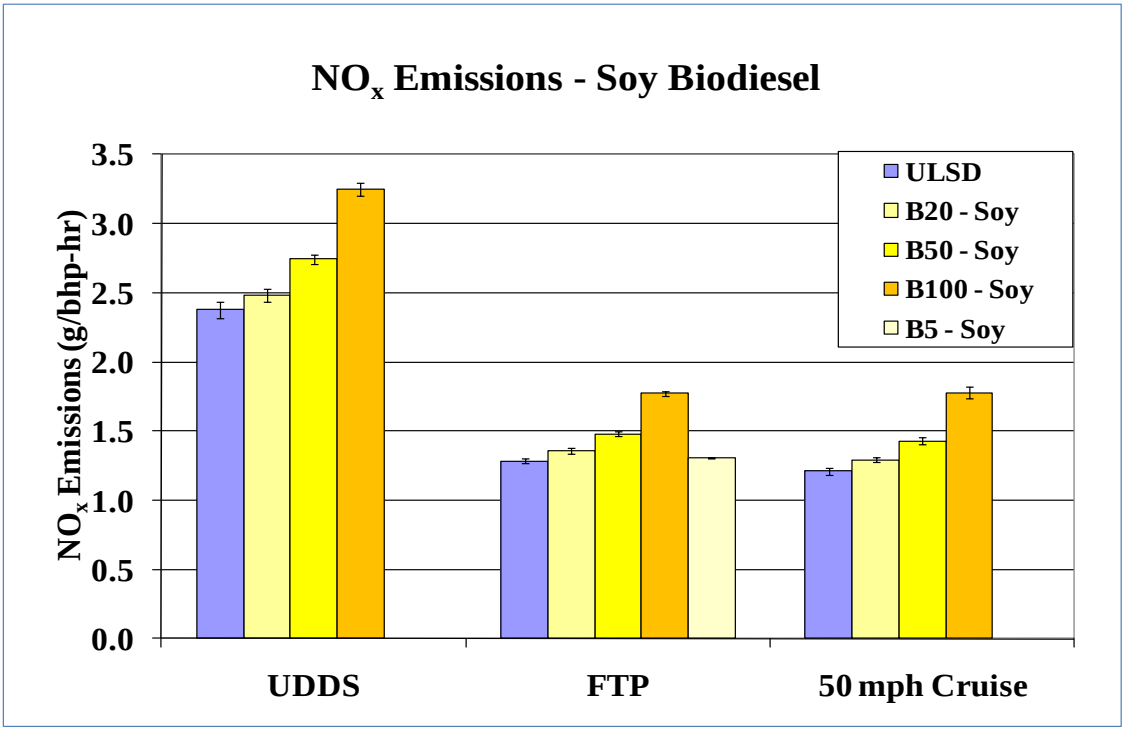


Figure 5-3. Average NO_x Emission Results for the Soy-Based Biodiesel 2007 MBE4000

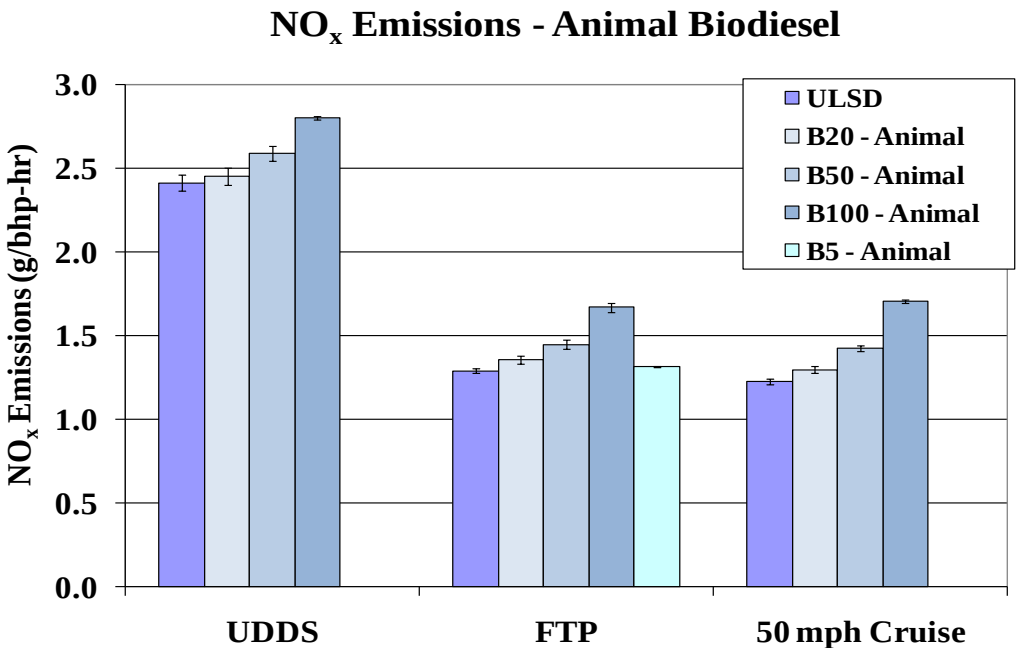


Figure 5-4. Average NO_x Emission Results for Animal-Based Biodiesel 2007 MBE4000

The average NO_x emissions show trends of increasing NO_x emissions with increasing biodiesel blend level, but the magnitude of the effects differ between the different feedstocks. Table 5-1 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a 2-tailed, 2 sample equal variance t-test. Note for completeness, this table, and subsequent tables in this section, also contain results for soy-based B5 and B10 blends on the FTP for the 2006 Cummins engine that were conducted in the NO_x mitigation portion of this program, discussed in section 7. The statistical analyses provide information on the statistical significance of the different findings. For the discussion in this memorandum, results for the on-highway heavy-duty engine dynamometer testing are considered to be statistically significant for p values ≤ 0.05, which represents a 95% confidence level. More detailed information about the average values and number of replicate tests are provided in Appendix G for the 2006 Cummins ISM and in Appendix H for the 2007 MBE4000.

For the 2006 Cummins engine, the soy-based biodiesel blends showed a higher increase in NO_x emissions for essentially all blend levels and test cycles. For the different cycles, the FTP seemed to show the strongest NO_x increases for biodiesel for both soy-based and animal-based blends. For comparison, EPA base case estimates for soy-based biodiesel from their 2002 study showed increases in NO_x of 2% at the B20 level, 5% at the B50 level, and 10% at the B100 level compared to an average federal diesel fuel. The soy-based biodiesel blends showed increases that were higher than these estimates for all of the test cycles for the 2006 Cummins engine. The NO_x impacts found for the soy-based biodiesel are consistent, however, with the EPA estimates for the "clean base fuel" case, which show increases of 5% for B20, 13% for B50, and 28% for B100 fuel against a clean base fuel. The EPA defined "clean" diesel fuels were defined as diesel fuels meeting the CARB requirements for sale in California, or diesel fuels with cetane numbers greater

than 52, aromatic contents less than 25 vol.%, and specific gravities less than 0.84. For the animal-based biodiesel feedstock for the 2006 Cummins engine, the emission increases for the FTP cycle are consistent with the EPA base case estimates.

For the UDDS cycle for the animal-based biodiesel feedstock for the Cummins engine, the emissions differences were not statistically significant for any of the blend levels. For the 50 mph Cruise cycle for the animal-based biodiesel for the Cummins engine, a statistically significant increase was only found for the B100 level that was approximately a 5% increase. For the 50 mph Cruise for the Cummins engine, however, it should be noted that the percentage changes in emissions and the statistical significance of the changes in NO_x emissions were obscured by the different engine operation that was observed for that cycle, as discussed in section 2.7 and Appendix E.

For the 2007 MBE4000 engine, the soy- and animal-based biodiesel blends both showed higher NO_x emissions with increasing biodiesel blend level for essentially all test cycles. In comparison with the 2006 Cummins engine, the magnitude of the NO_x emissions increases, on a percentage basis, were greater for the 2007 engine for nearly all biodiesel blends and test cycles. The absolute difference in the emission levels for the CARB and biodiesel fuels, however, were less for the 2007 MBE4000 due to its lower overall NO_x emission levels. For the 2007 MBE4000, the soy-based biodiesel showed higher increases in NO_x than the animal-based biodiesel for all testing conditions. The highest increases in NO_x on a percentage basis were seen for the highest load, 50 mph Cruise for the 2007 MBE4000. The emissions increases for the both the soy-based and the animal-based biodiesel were all higher than those for the EPA base case estimates. The NO_x increases for the soy-based biodiesel were also higher than those for the EPA estimates for a clean base fuel. The animal-based biodiesel showed estimates comparable to the EPA clean base fuel estimates for the FTP, but showed a lower NO_x impact for the lighter load UDDS cycle and a higher NO_x impact for the 50 mph cruise cycle.

It is also useful to look at the impacts of cycle power on NO_x emissions and the trends with biodiesel. In a recent study by the US EPA (Sze et al. 2007), it was found that NO_x emissions and the difference in NO_x emissions between a biodiesel blend and a base fuel or B0 blend both increased as the average power of the cycle increases.

For this study, NO_x emissions showed a general increasing trend as the average cycle power increased similar to the EPA study. This was seen for both engines and for both the soy- and animal-based biodiesels. This is shown in Figure 5-5 and Figure 5-6 for the 2006 Cummins engine and in Figure 5-7 and Figure 5-8 for the 2007 MBE4000 engine.

Table 5-1. NO_x Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle [g/bhp-hr basis].

		2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Soy-based		Animal-based	
	CARB vs.	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	4.1%	0.002	-1.5%	0.376	4.4%	0.005	1.6%	0.000
	B50	9.8%	0.000	0.1%	0.935	15.3%	0.000	7.3%	0.000
	B100	17.4%	0.000	1.9%	0.243	36.6%	0.000	16.0%	0.000
FTP	B5	2.2% (Mit)	0.000	0.3%	0.298	0.9%	0.001	1.3%	0.000
	B10	2.6% (Mit)	0.000						
	B20	6.6%	0.000	1.5%	0.000	5.9%	0.000	5.0%	0.000
	B50	13.2%	0.000	6.4%	0.000	15.3%	0.000	12.1%	0.000
	B100	26.6%	0.000	14.1%	0.000	38.1%	0.000	29%	0.000
40 mph Cruise	B5	1.7%	0.135						
	B20	3.9%	0.000						
	B50	9.1%	0.000						
	B100	20.9%	0.000						
50 mph Cruise	B5	-1.1%	0.588						
	B20	0.5%	0.800	-2.3%	0.151	6.9%	0.000	5.9%	0.000
	B50	6.3%	0.001	0.8%	0.588	18.2%	0.000	16.3%	0.000
	B100	18.3%	0.000	5.3%	0.000	47.1%	0.000	39.4%	0.000

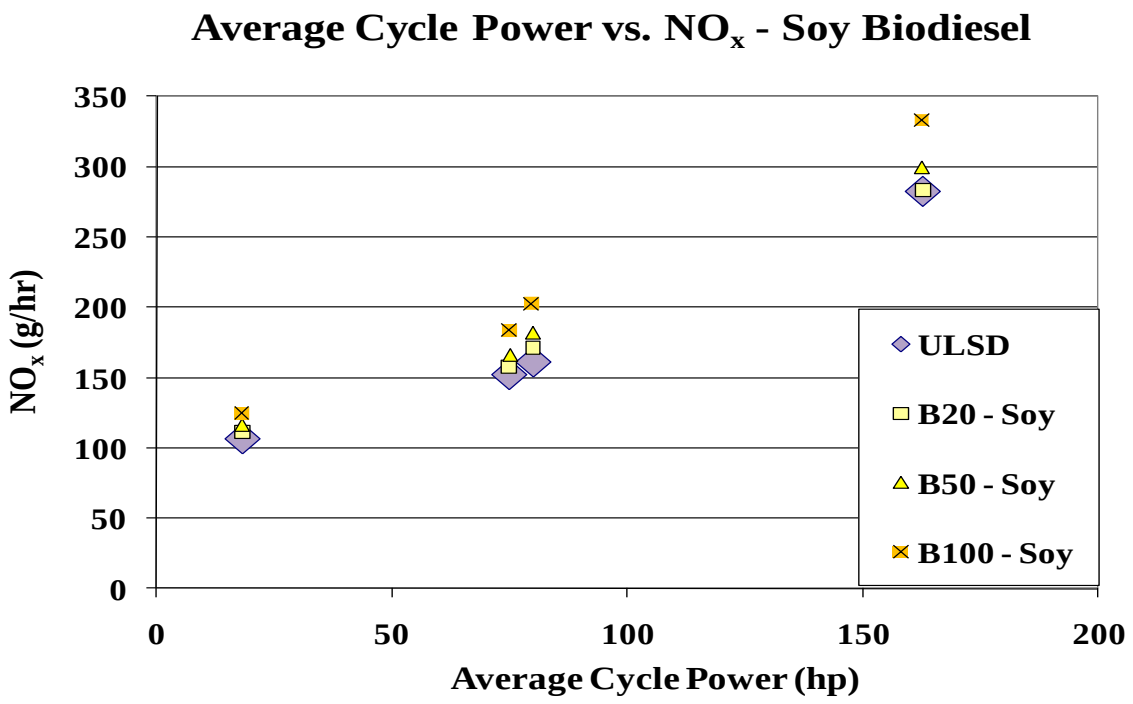


Figure 5-5. Average Cycle Power vs. NO_x Emissions for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

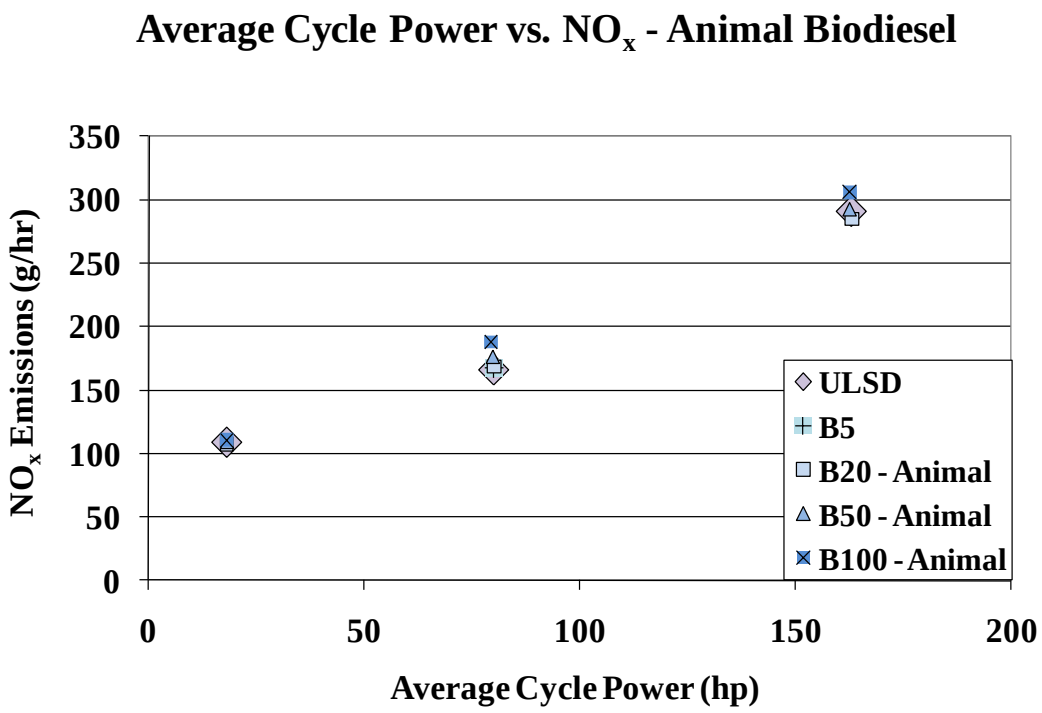


Figure 5-6. Average Cycle Power vs. NO_x Emissions for Testing on Animal-Based Biodiesel Blends 2006 Cummins ISM

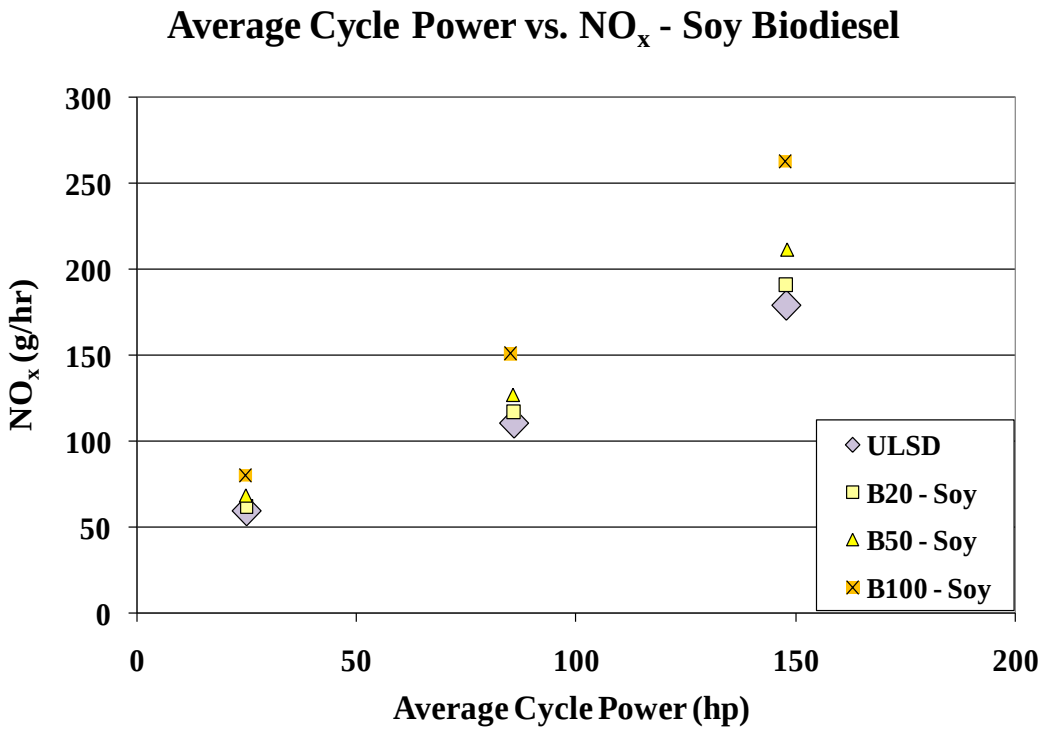


Figure 5-7. Average Cycle Power vs. NO_x Emissions for Testing on Soy-Based Biodiesel Blends 2007 MBE4000

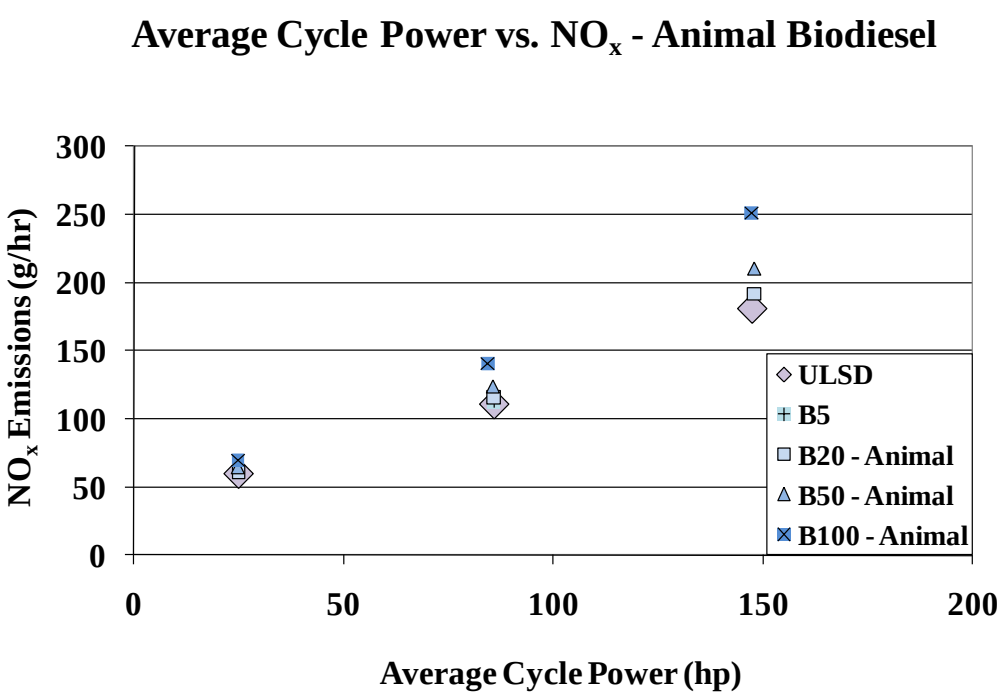


Figure 5-8. Average Cycle Power vs. NO_x Emissions for Testing on Animal-Based Biodiesel Blends 2007 MBE4000

The differential between NO_x emissions for a biodiesel blends and the base fuel showed different trends for the different engines and test fuels. This is shown in Figure 5-9 and Figure 5-10 for the 2006 Cummins engine and in Figure 5-11 and Figure 5-12 for the 2007 MBE4000 engine. For this testing, only the animal-based biodiesel testing on the 2007 MBE4000 engine showed increases in the NO_x differential with increasing cycle power. There were also some trends of a higher NO_x differential for the soy-based biodiesels on the highest load, 50 mph cruise cycle for the 2007 MBE4000, but there were not big differences between the other cycles. For the 2006 Cummins, the NO_x differential did not show increases in the NO_x differential with increasing cycle average power. This comparison was obscured, however, by the differences in the engine operation that were observed for the 50 mph cruise, as discussed above. Interestingly, the NO_x differential showed higher values for the FTP or certification test for both the soy-based and animal-based biodiesel blends for the 2006 Cummins engine in comparison with the 40 mph cruise cycle, even though these cycles have similar power levels.

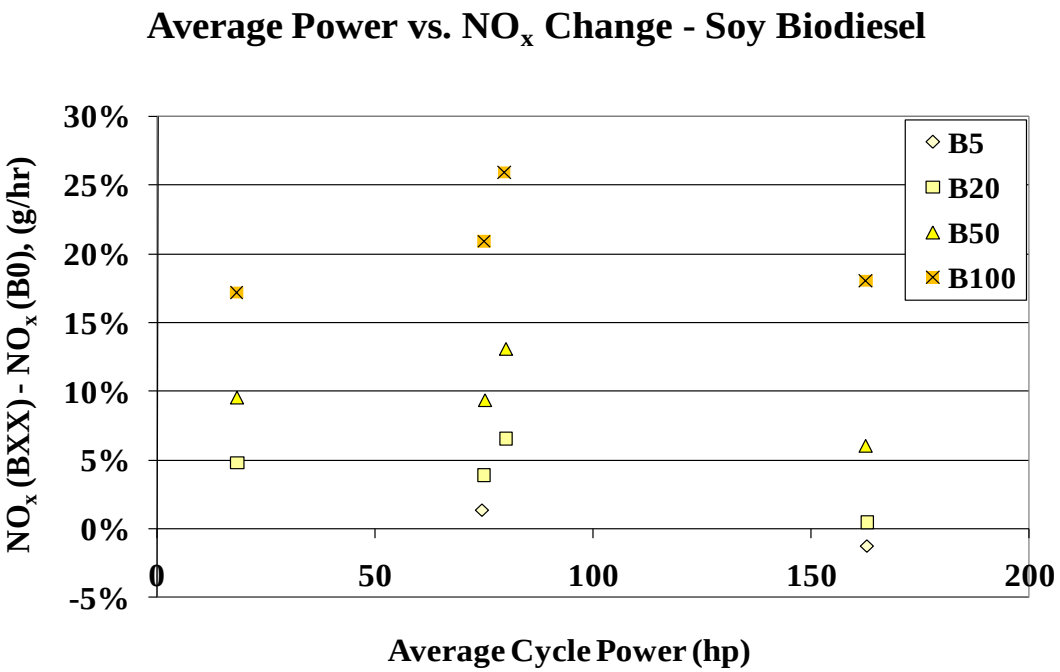


Figure 5-9. Average Cycle Power vs. NO_x Emissions Change for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

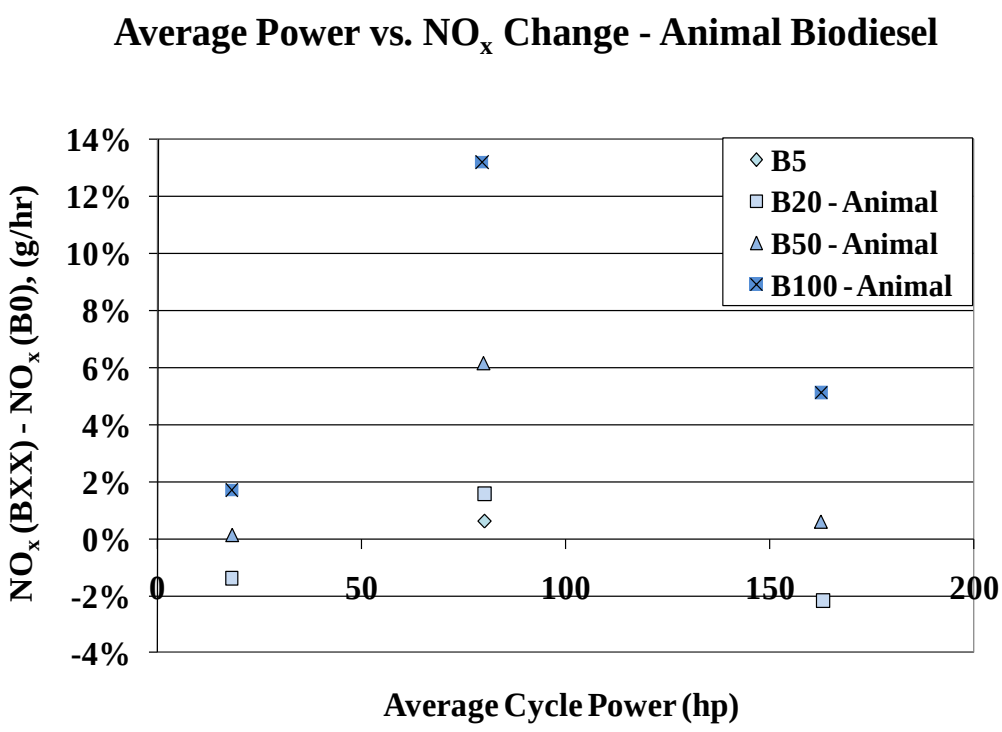


Figure 5-10. Average Cycle Power vs. NO_x Emissions Change for Testing on Animal-Based Biodiesel Blends 2006 Cummins ISM

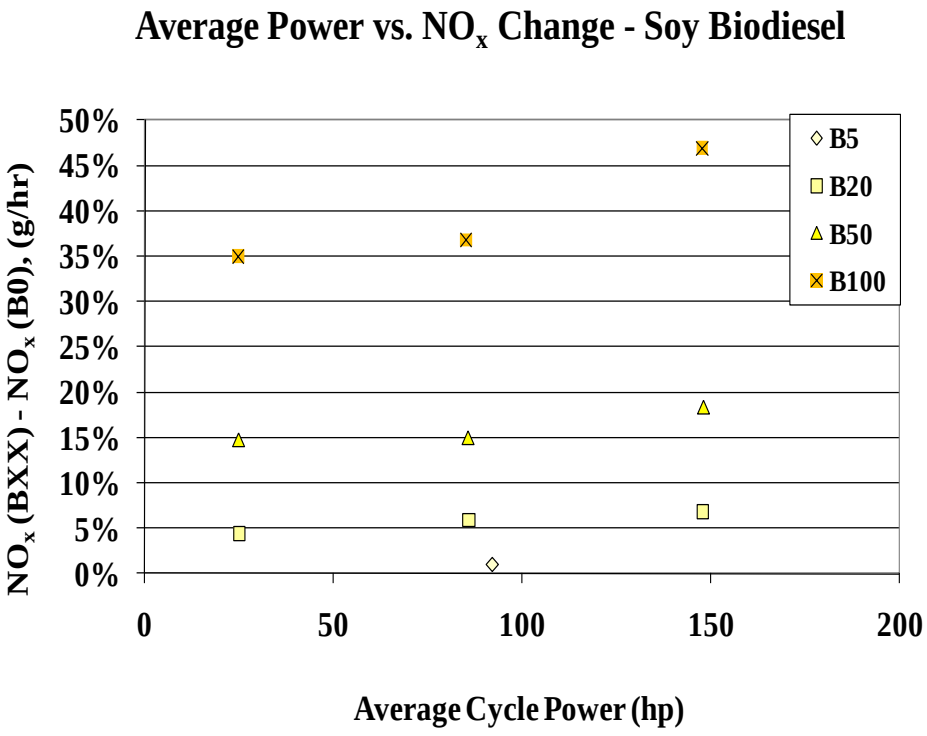


Figure 5-11. Average Cycle Power vs. NO_x Emissions for Testing on Soy-Based Biodiesel Blends 2007 MBE4000

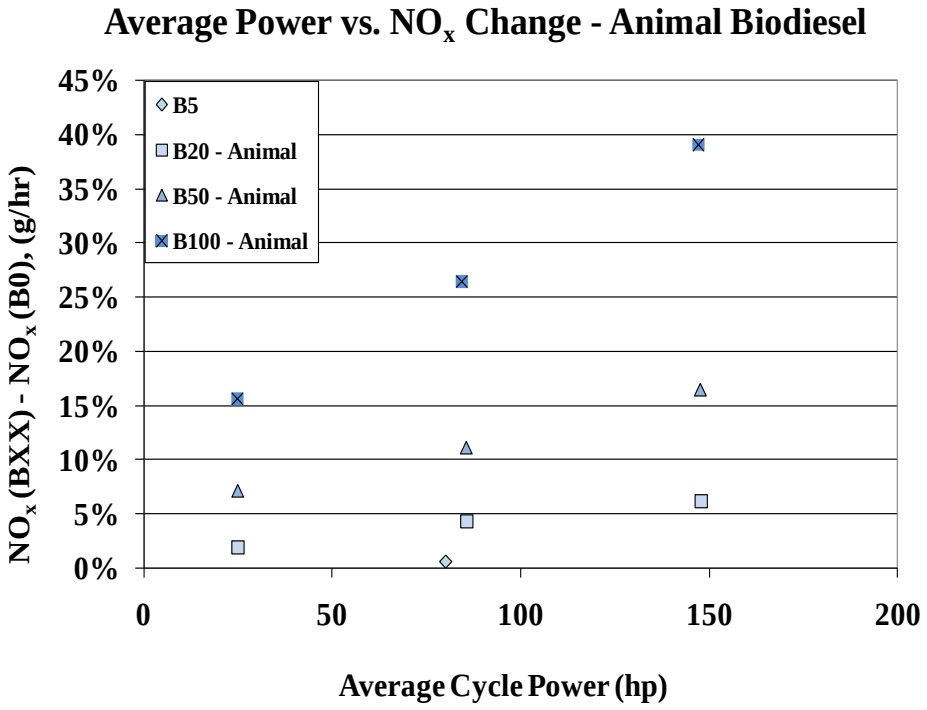


Figure 5-12. Average Cycle Power vs. NO_x Emissions for Testing on Animal-Based Biodiesel Blends 2007 MBE4000

Similar to the trends for the NO_x differential in comparison with average cycle power, the NO_x differential as a function of fuel consumption varied with biodiesel fuel and test engine. This is shown in Figure 5-13 and Figure 5-14 for the 2006 Cummins engine and in Figure 5-15 and Figure 5-16 for the 2007 MBE4000 engine. Again, only the animal-based biodiesel for the 2007 MBE4000 showed a trend of increasing NO_x differential with increasing fuel consumption, similar to the EPA study. For the soy-based biodiesel on the MBE4000 engine, the NO_x differential was highest for the fuel consumption level for the 50 mph Cruise, but showed smaller differences for the other cycles. For both the soy- and animal-based biodiesel feedstocks on the 2006 Cummins engine, the NO_x differential was not a strong function of fuel consumption. For the 2006 Cummins engine, this result could also be impacted by the change in engine operation that was observed during the 50 mph cruise.

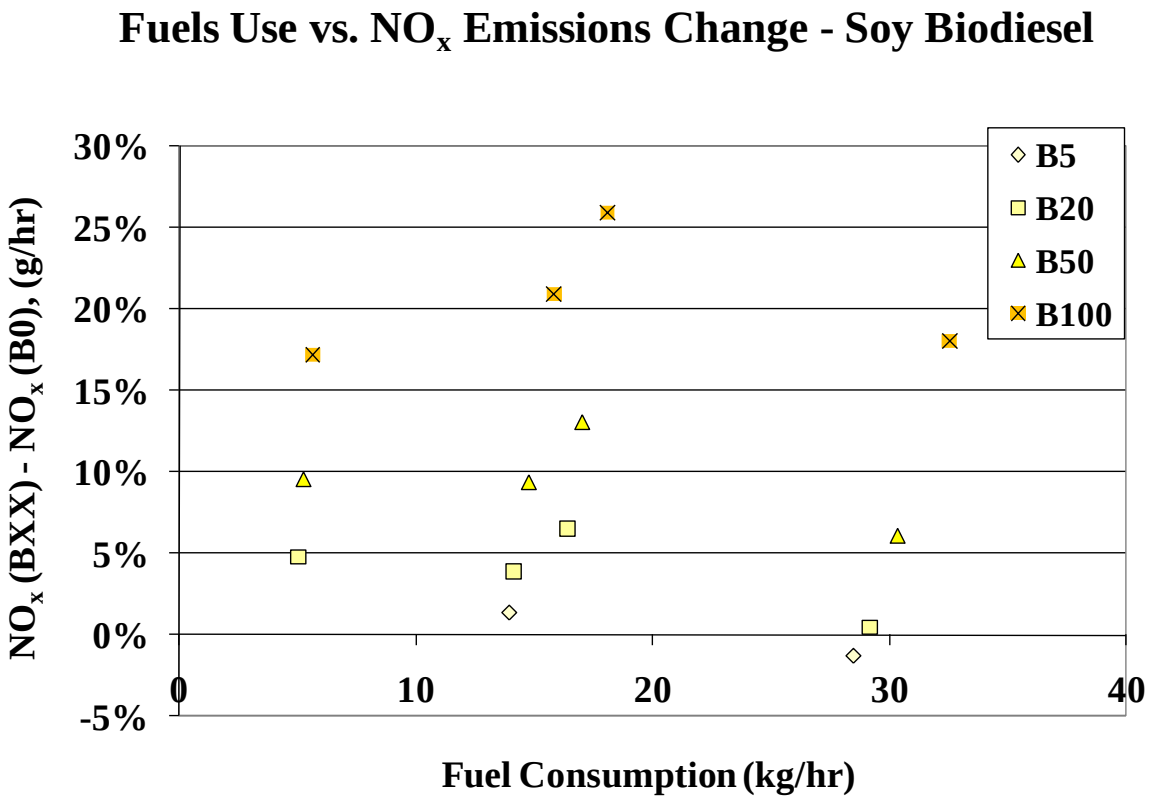


Figure 5-13. Fuel Consumption vs. NO_x Emissions Change for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

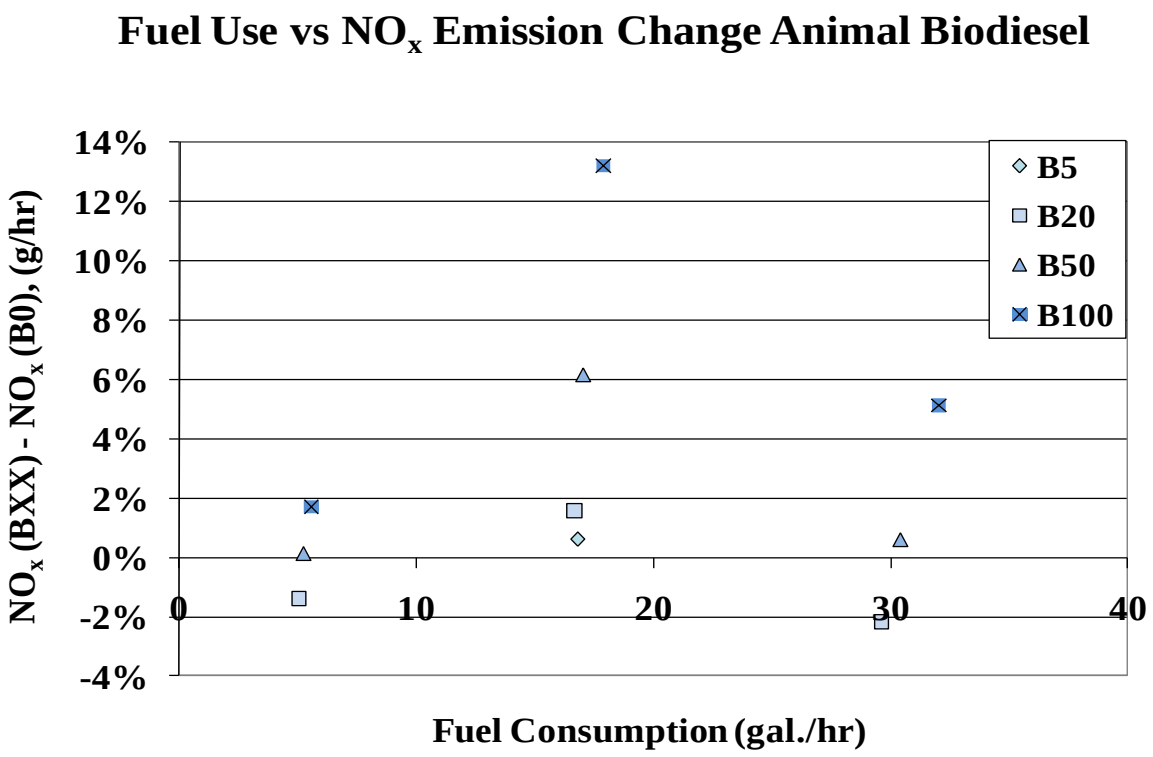


Figure 5-14. Fuel Consumption vs. NO_x Emissions Change for Testing on Animal-Based Biodiesel Blends 2006 Cummins ISM

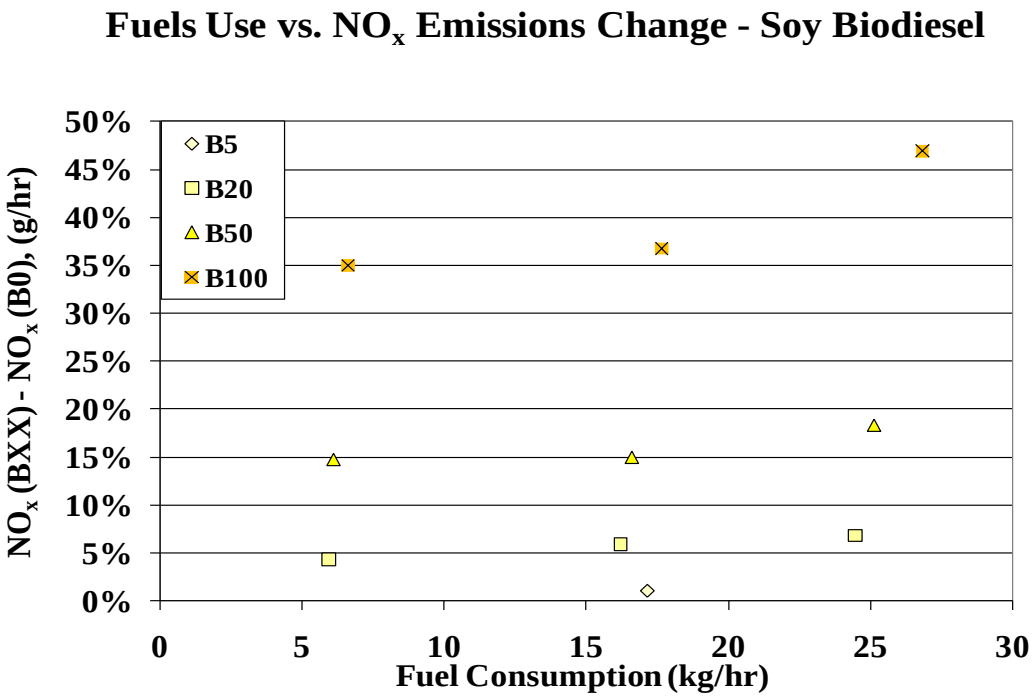


Figure 5-15. Fuel Consumption vs. NO_x Emissions Change for Testing on Soy-Based Biodiesel Blends 2007 MBE4000

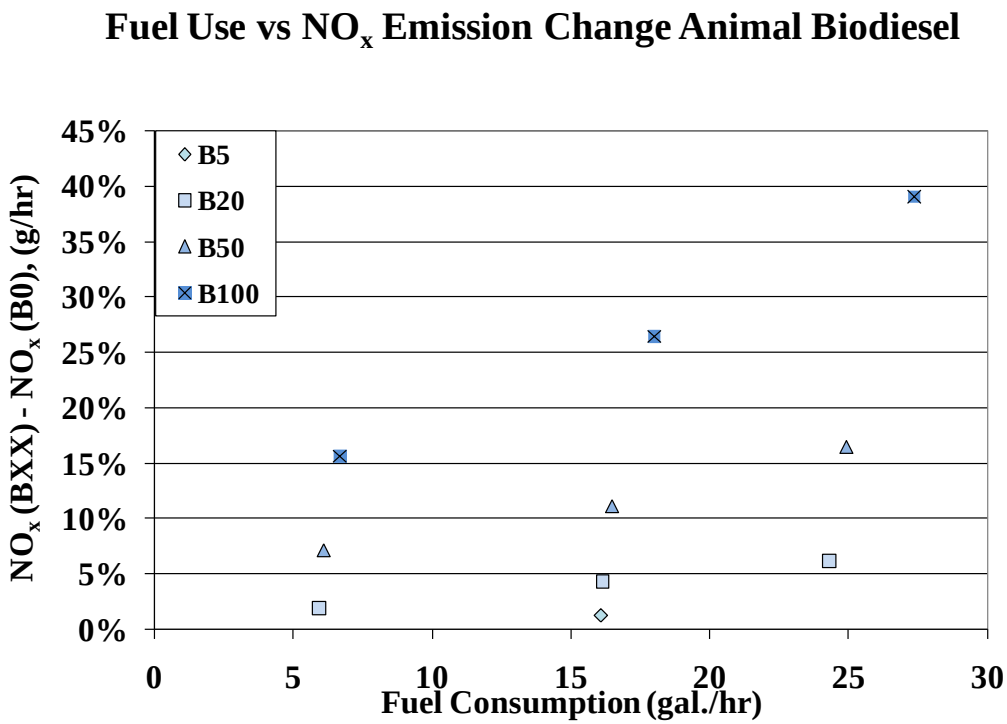


Figure 5-16. Fuel Consumption vs. NO_x Emissions Change for Testing on Animal-Based Biodiesel Blends 2007 MBE4000

5.2 PM Emissions

The PM emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock for both test engines are presented in Figure 5-17 to Figure 5-20, respectively, on a g/bhp-hr basis. Table 5-2 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles for both engines, along with the associated p-values for statistical comparisons using a t-test.

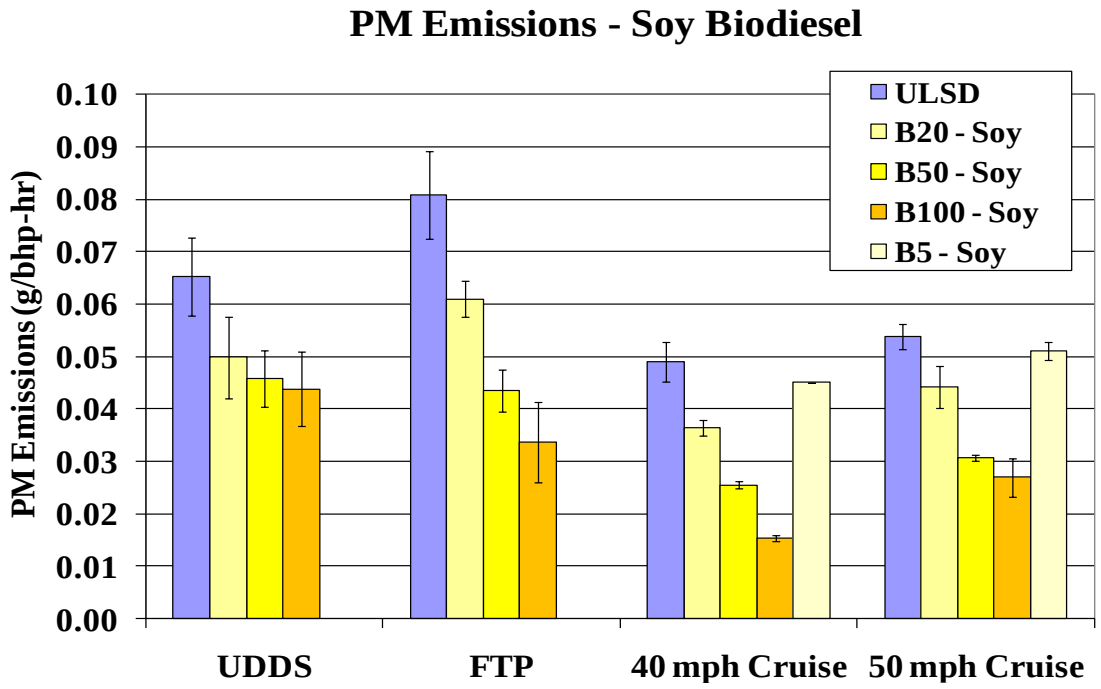


Figure 5-17. Average PM Emission Results for the Soy-Based Biodiesel Feedstock 2006 Cummins ISM

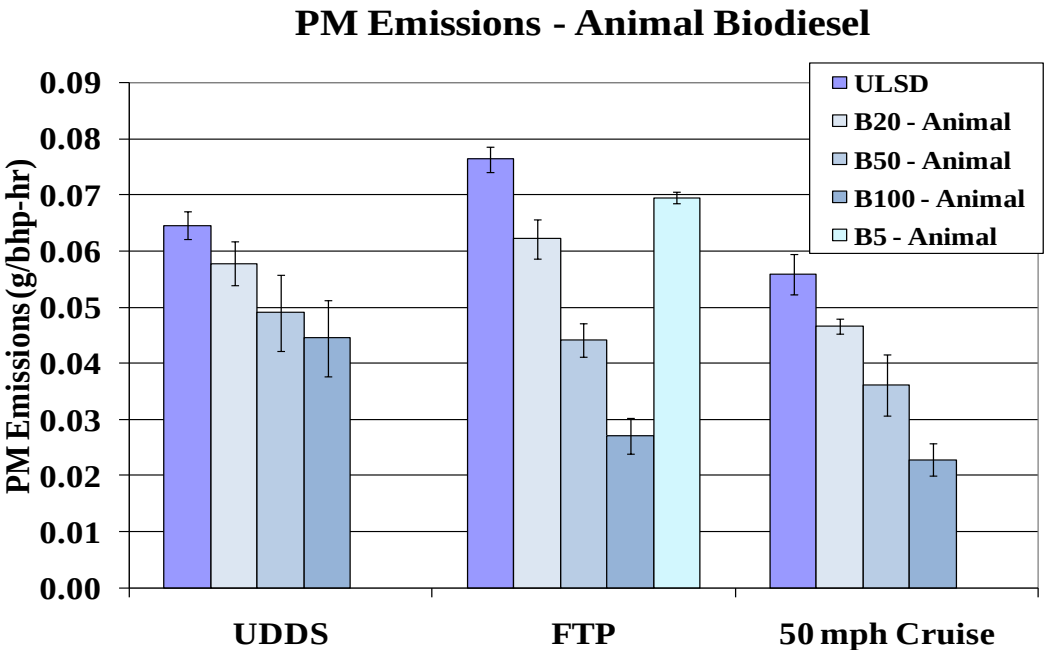


Figure 5-18. Average PM Emission Results for the Animal-Based Biodiesel Feedstock 2006 Cummins ISM

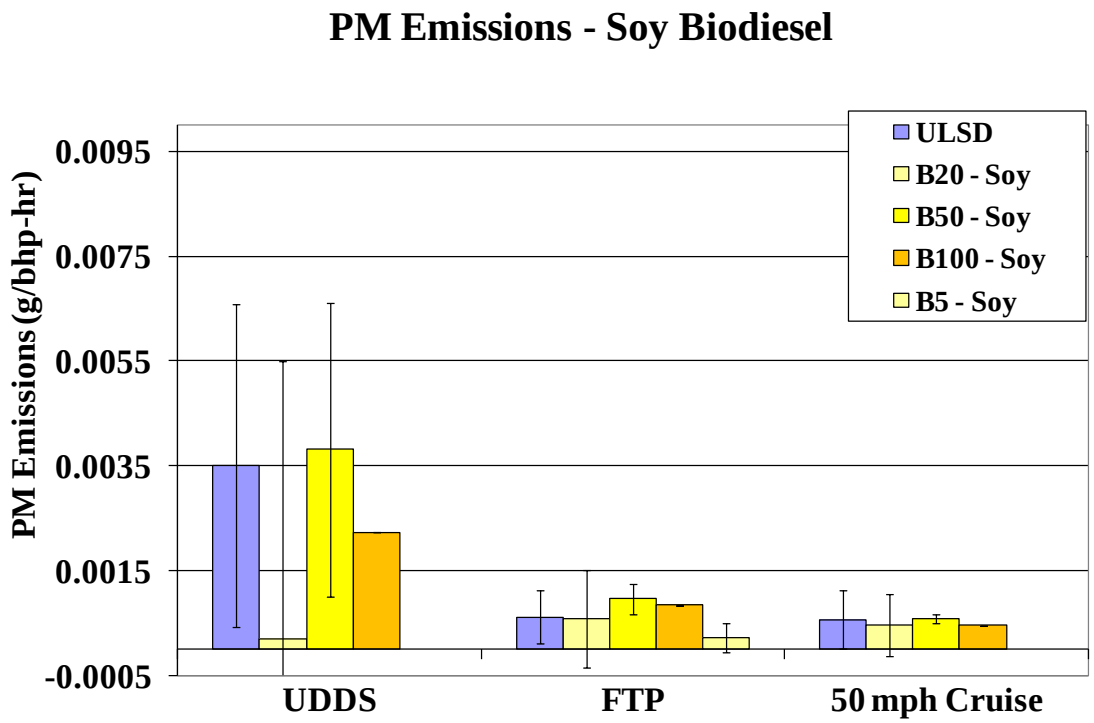


Figure 5-19. Average PM Emission Results for the Soy-Based Biodiesel Feedstock 2007 MBE4000

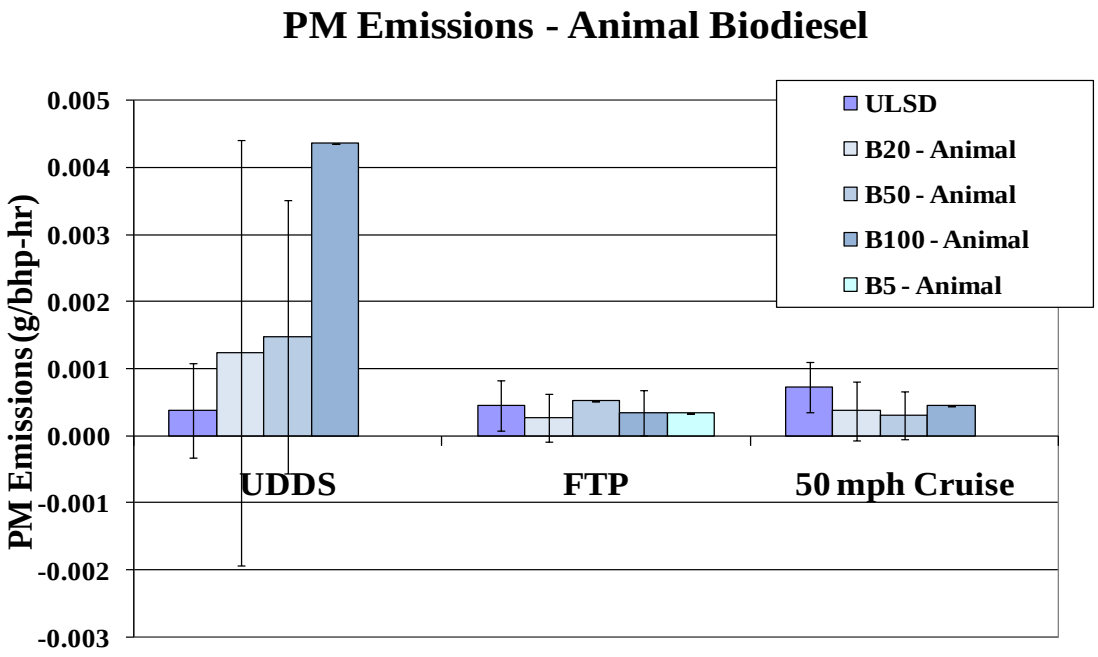


Figure 5-20. Average PM Emission Results for the Animal-Based Biodiesel Feedstock 2007 MBE4000

For the 2006 Cummins engines, PM emissions showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. This is consistent with a majority of the previous studies of emissions from biodiesel blends. For comparison, the EPA estimated reductions for the base case were 12% at a B20 level, 27% for a B50 level, and 47% at the B100 level. EPA estimates for the PM reductions expected for a clean base fuel are smaller, with reductions of less than 10% for B20, ~20% for the B50 level, and ~35% for B100. The PM reductions for both the soy-based and animal-based biodiesel blends for the 2006 Cummins engine were generally larger than those found in the EPA study, and are closer to the estimates for an average base fuel than a clean base fuel. The smallest reductions were seen for the UDDS, or the lightest loaded cycle. The reductions for the FTP and the cruise cycles were comparable for both fuels. Although there were some differences in the percent reductions seen for the soy-based and animal-based biodiesel fuels, there were no consistent differences in the PM reductions for these two feedstocks over the range of blend levels and cycles tested here.

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 detection limit of the PM measurement. While some differences are seen in the PM emissions for different fuel blends and test cycles, for the most part, the differences in PM emissions between the various biodiesel blends and the CARB ULSD were not statistically different. This is not unexpected since the efficiency of the DPF in removing particles from the exhaust would mask any fuel differences.

Table 5-2. PM Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Soy-based		Animal-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	-24%	0.002	-10%	0.009	-94%	0.187	224%	0.779
	B50	-30%	0.000	-24%	0.001	9%	0.874	285%	0.219
	B100	-33%	0.000	-31%	0.000	-37%	0.470	1043%	0.000
FTP	B5	-6% (Mit)	0.000	-9%	0.000	-61%	0.250	-32%	0.477
	B10	-17% (Mit)	0.000		0.000				
	B20	-25%	0.000	-19%	0.000	-4%	0.944	40%	0.341
	B50	-46%	0.000	-42%	0.000	58%	0.216	15%	0.757
	B100	-58%	0.000	-64%	0.000	64%	0.403	-24%	0.611
40 mph Cruise	B5	-6%	0.101						
	B20	-26%	0.000						
	B50	-48%	0.000						
	B100	-69%	0.000						
50 mph Cruise	B5	-5%	0.036						
	B20	-18%	0.000	-16%	0.000	-19%	0.746	-49%	0.143
	B50	-43%	0.000	-35%	0.000	2%	0.970	-58%	0.103
	B100	-50%	0.000	-59%	0.000	-100%	0.704	-39%	0.237

Similar to the NO_x emissions, PM emissions for the 2006 Cummins engine also showed a general trend of increasing emissions with increased average cycle power. This is shown in Figure 5-21 for the soy-based biodiesel and in Figure 5-22 for the animal-based biodiesel. This trend was not necessarily linear, however, as demonstrated by the differences in the emissions for the FTP and 40 mph cruise for the soy-based results. For the 2007 MBE4000 engine, the PM emissions

showed no real trends as a function of average cycle power due to the DPF eliminating nearly all the PM. This is shown in Figure 5-23 for the soy-based biodiesel and in Figure 5-24 for the animal-based biodiesel.

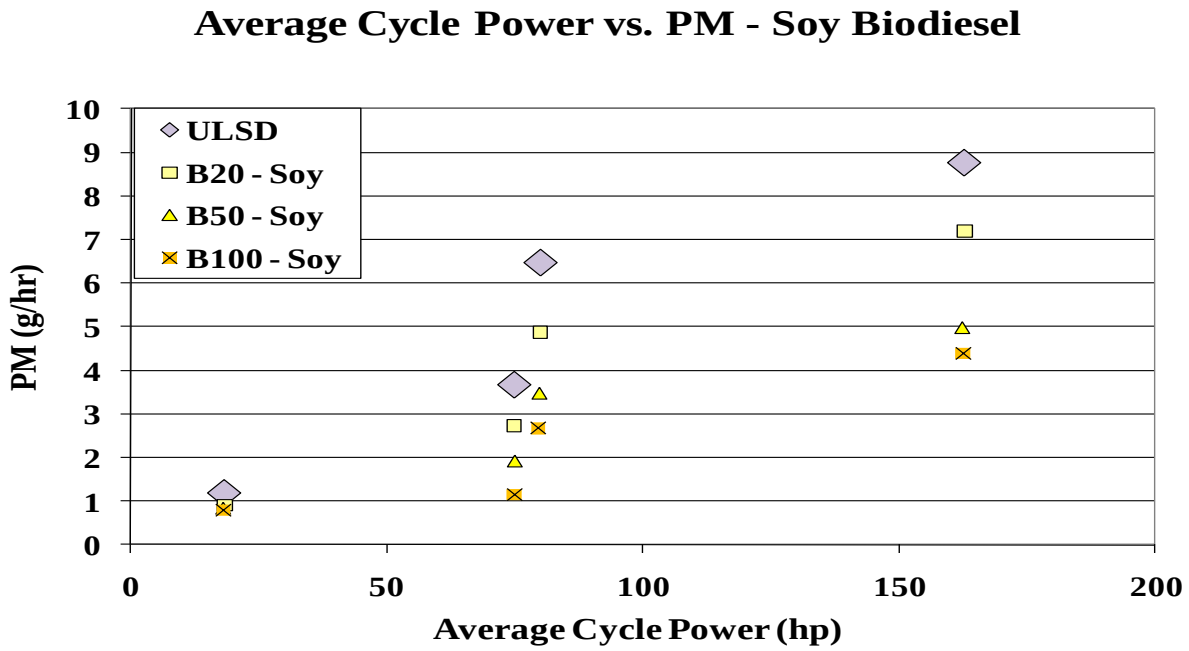


Figure 5-21. Average Cycle Power vs. PM Emissions for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

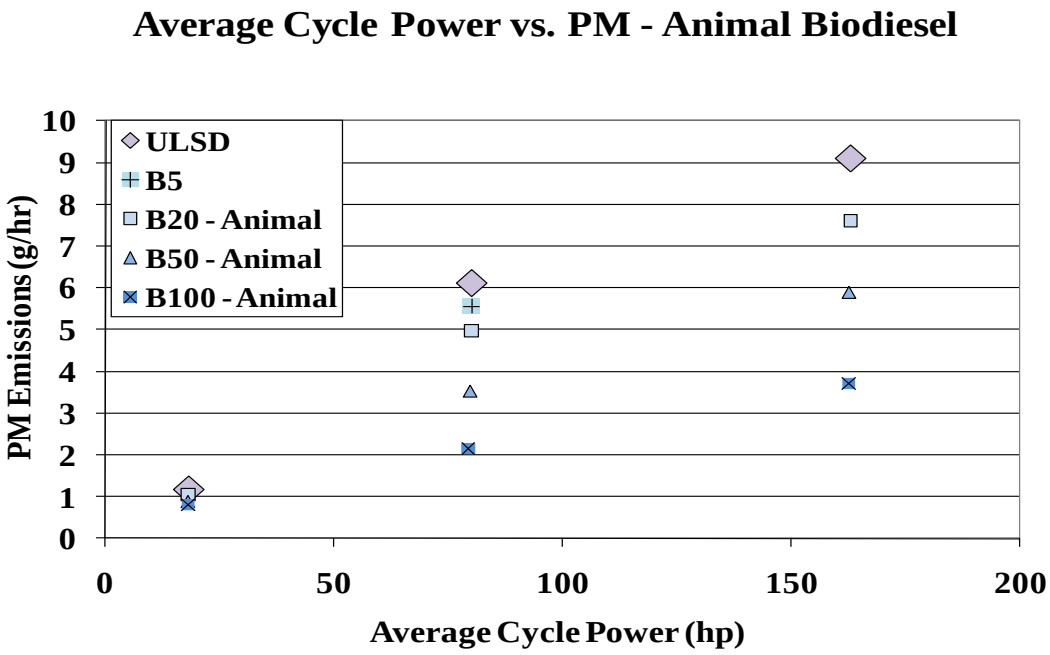


Figure 5-22. Average Cycle Power vs. PM Emissions for Testing on Animal-Based Biodiesel Blends 2006 Cummins ISM

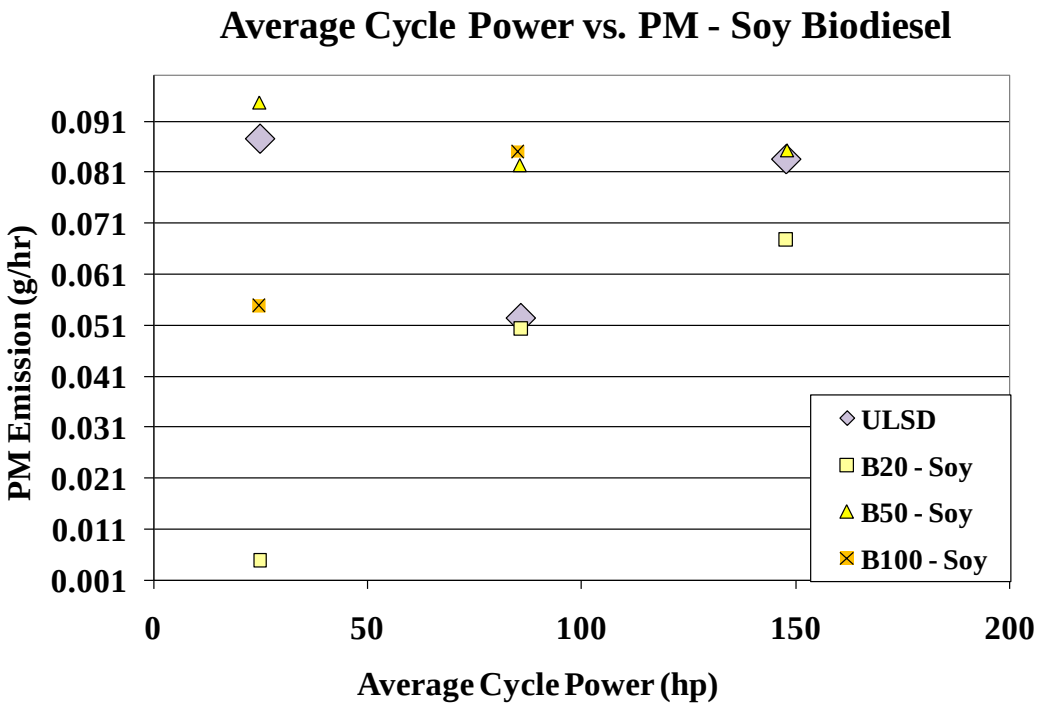


Figure 5-23. Average Cycle Power vs. PM Emissions for Testing on Soy-Based Biodiesel Blends 2007 MBE4000

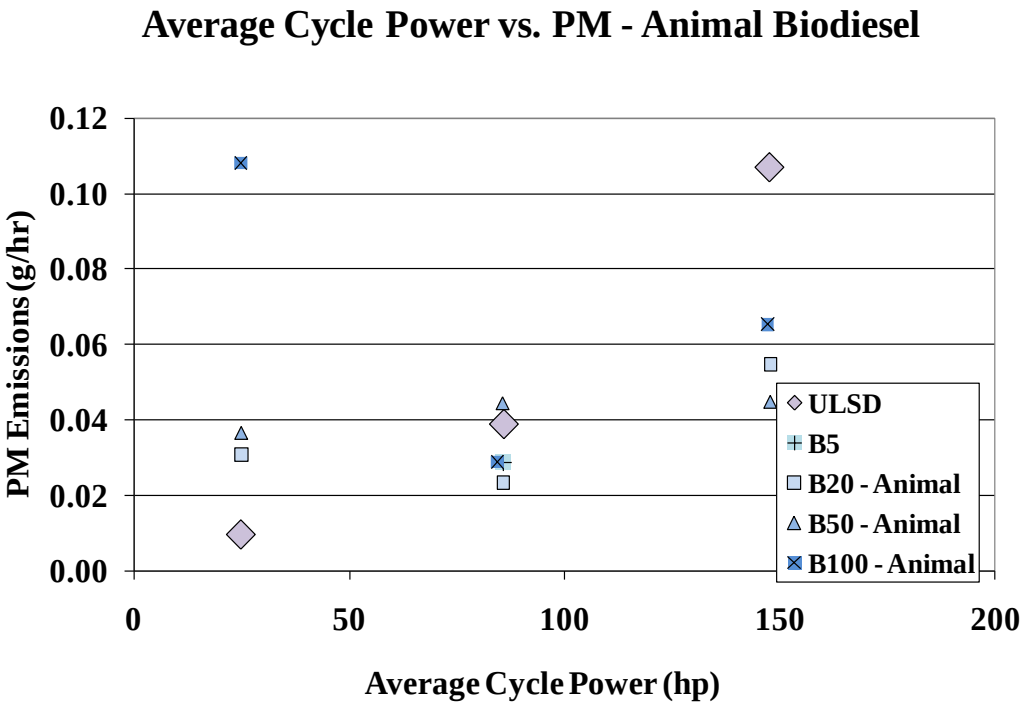


Figure 5-24. Average Cycle Power vs. PM Emissions for Testing on Animal-Based Biodiesel Blends 2007 MBE4000

For the 2006 Cummins engine, the differential between PM emissions for a biodiesel blend and the base fuel is shown as a function of power in Figure 5-25 for the soy-based biodiesel and in Figure 5-26 for the animal-based biodiesel, and as function of fuel consumption in Figure 5-27 for the soy-based biodiesel and in Figure 5-28 for the animal-based biodiesel. The data show a tendency for higher PM reductions for the FTP and 50 mph Cruise compared to the light-UDDS, but there is not a linear trend changes in emission reductions with either power or fuel use. As no statistically significant changes in PM were found as a function of either average cycle power or biodiesel blend level for the 2007 MBE4000 engine, these data are not presented here.

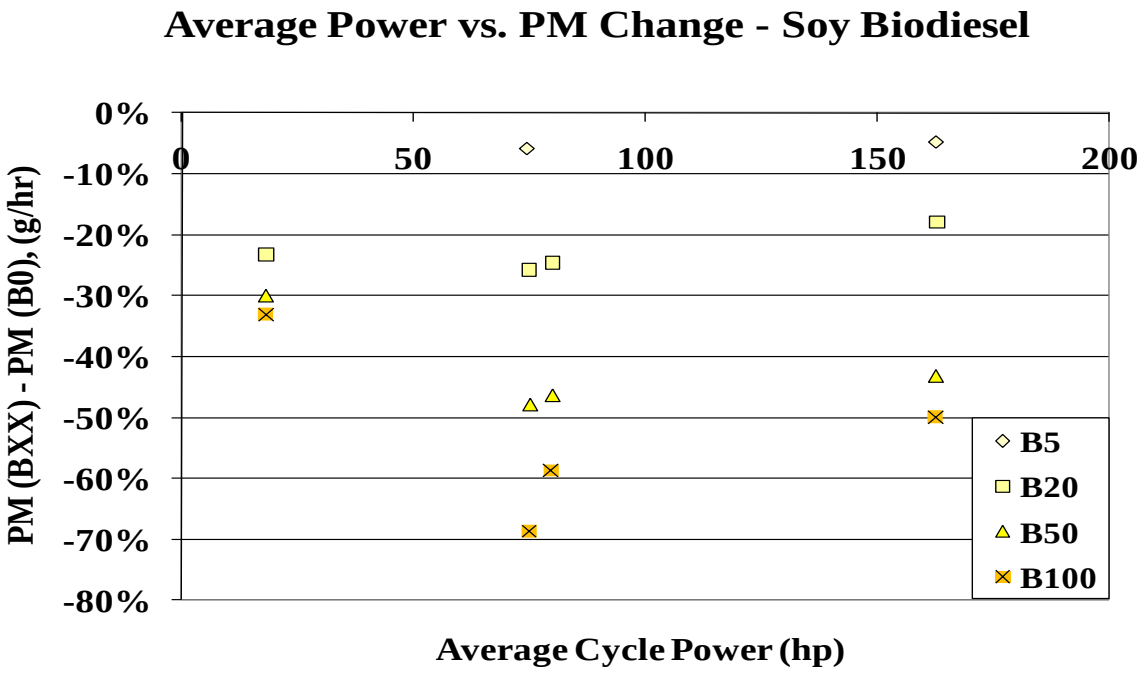


Figure 5-25. Average Cycle Power vs. PM Emissions Change for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

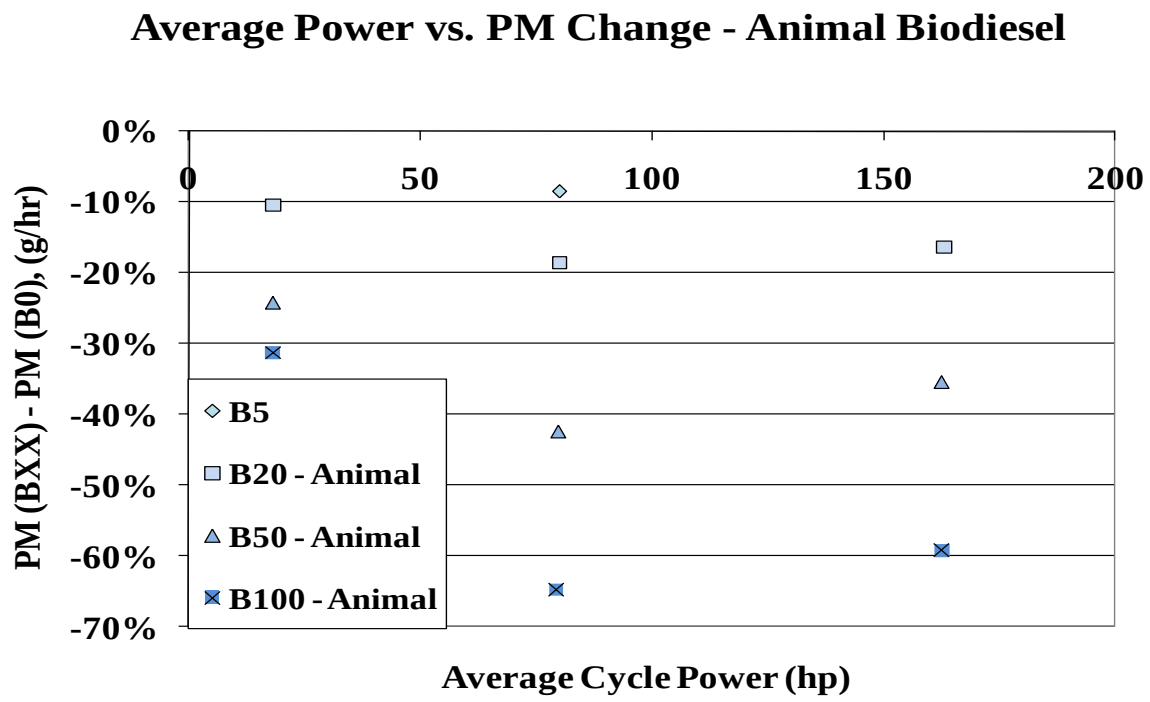


Figure 5-26. Average Cycle Power vs. PM Emissions Change for Testing on Animal-Based Biodiesel Blends 2006 Cummins ISM

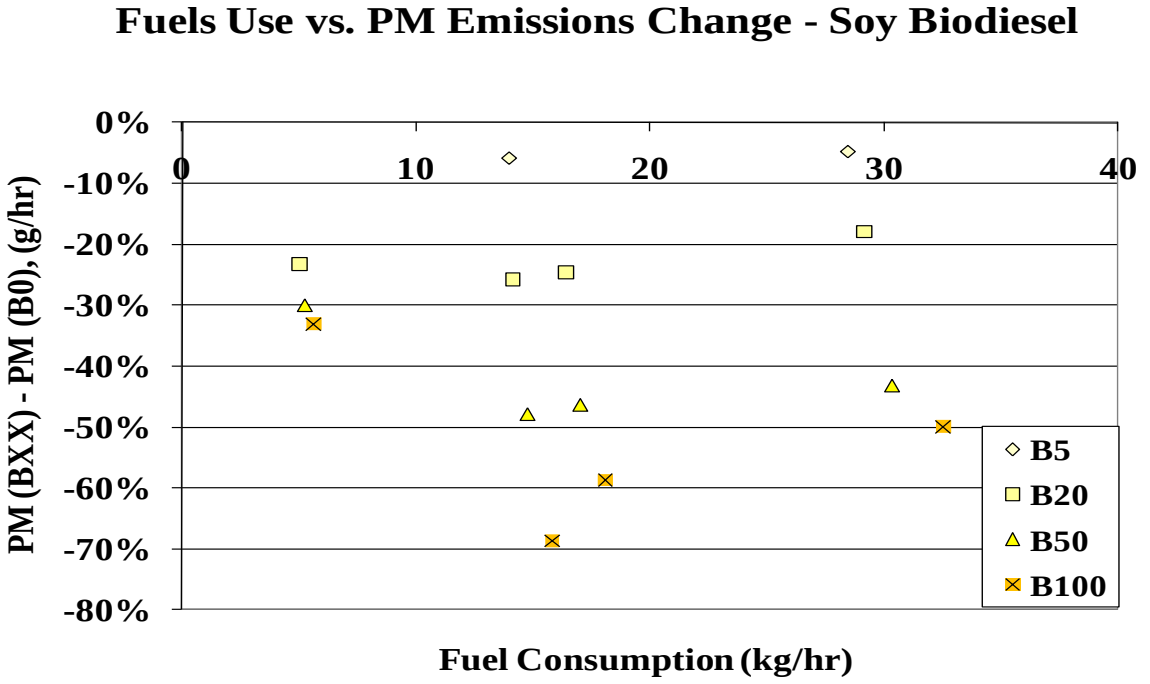


Figure 5-27. Fuel Consumption vs. PM Emissions Change for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

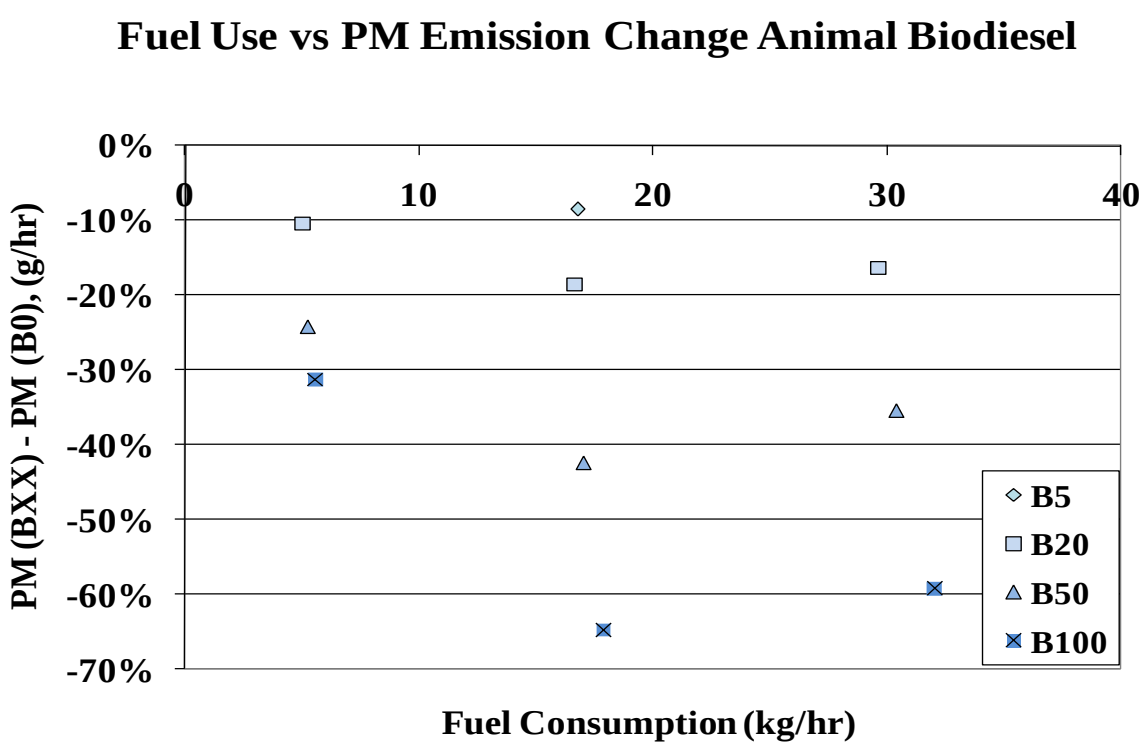


Figure 5-28. Fuel Consumption vs. PM Emissions Change for Testing on Animal-Based Biodiesel Blends 2006 Cummins ISM

5.3 THC Emissions

The THC emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock for the two test engines are presented in Figure 5-29 to Figure 5-32, respectively, on a g/bhp-hr basis. Table 5-3 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles and types of engines, along with the associated p-values for statistical comparisons using a t-test.

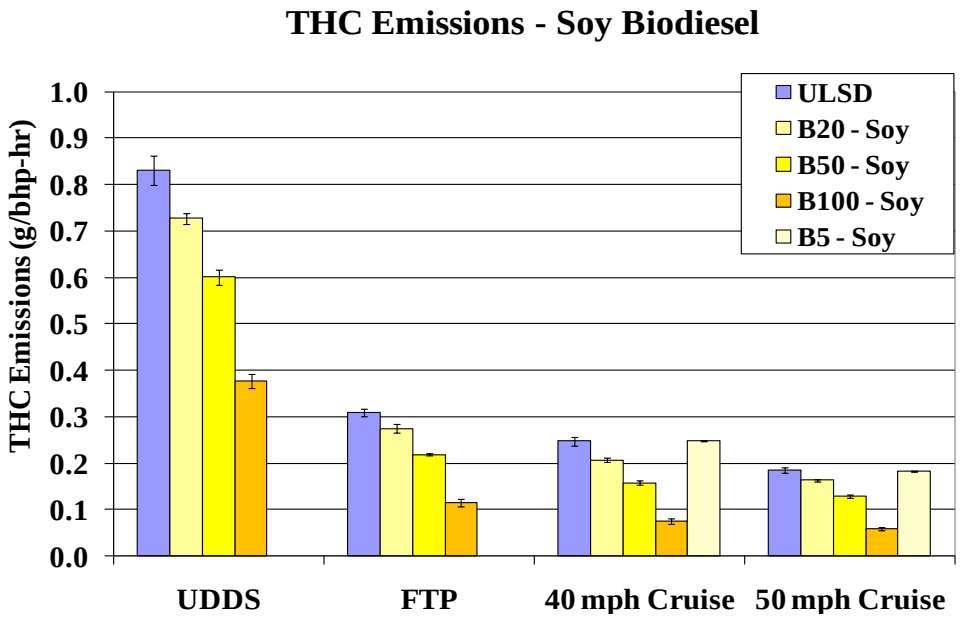


Figure 5-29. Average THC Emission Results for the Soy-Based Biodiesel Feedstock 2006 Cummins ISM

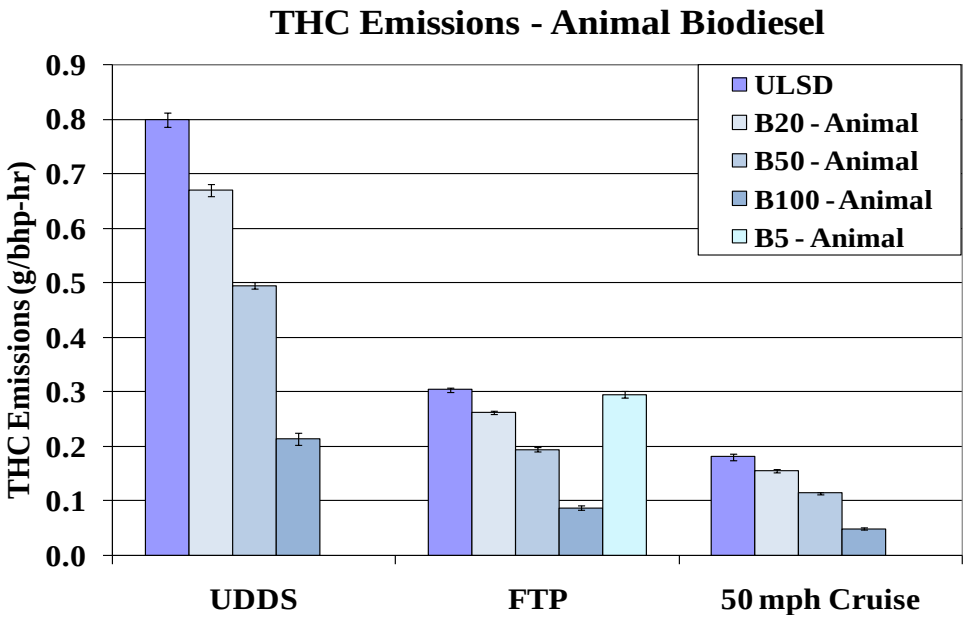


Figure 5-30. Average THC Emission Results for the Animal-Based Biodiesel Feedstock 2006 Cummins ISM

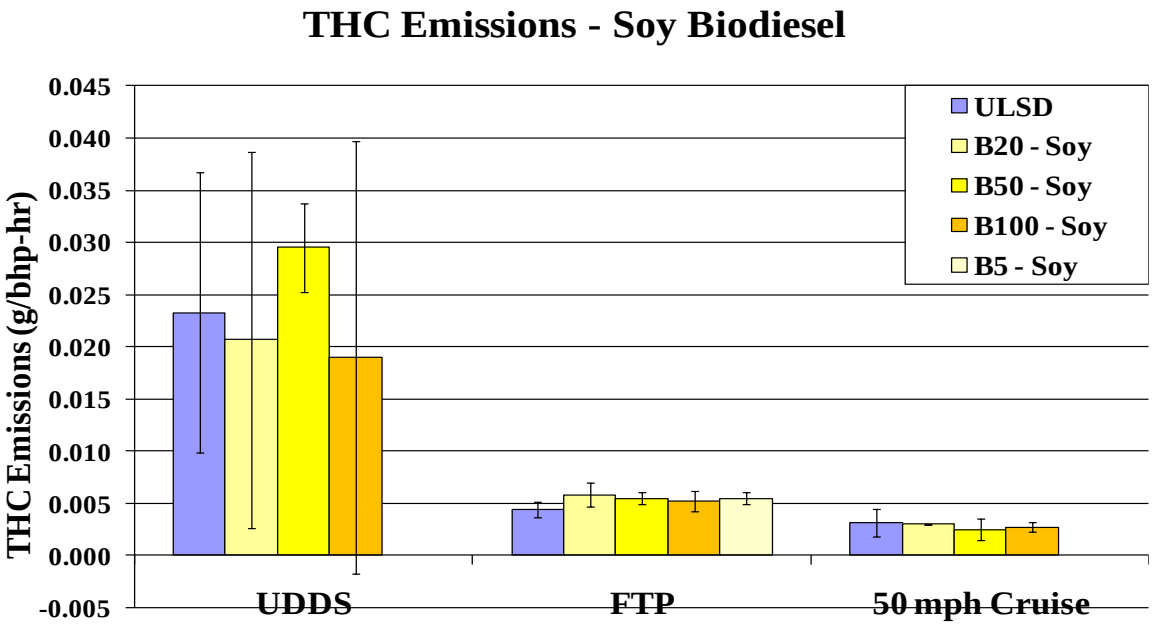


Figure 5-31. Average THC Emission Results for the Soy-Based Biodiesel Feedstock 2007 MBE4000

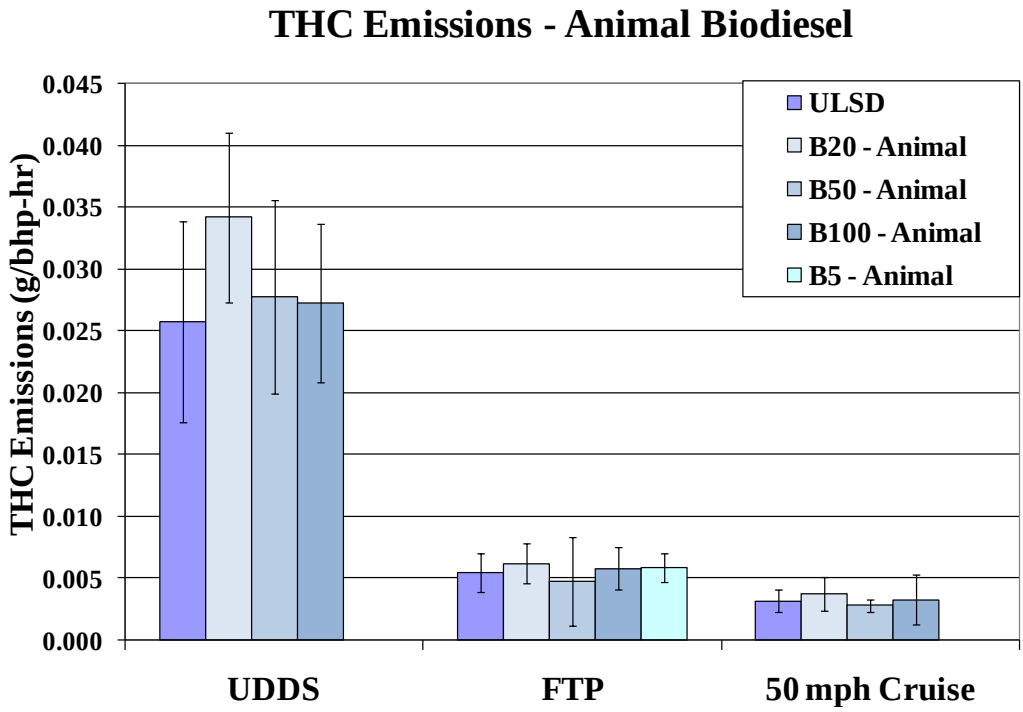


Figure 5-32. Average THC Emission Results for the Animal-Based Biodiesel Feedstock 2007 MBE4000

For 2006 Cummins engine, THC emissions showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. This is again consistent with a majority of the previous studies of emissions from biodiesel blends. For comparison, the EPA base case estimated reductions were 20% at a B20 level, ~43% for a B50 level, and ~67% at the B100 level. EPA estimates for the THC reductions expected for a clean base fuel are smaller, with reductions of ~13% for B20, ~30% for the B50 level, and ~51% for B100. Overall, the THC reductions for 2006 Cummins engine seen in this study are consistent with and similar to those found by EPA. The THC reductions for both the soy-based and animal-based biodiesel blends for B100 were closer to those found in the EPA study for the B100 level for the base case diesel fuel. The reductions for the B20 blend tended to be closer to those found for the clean diesel, while the reductions for the B50 blends were in between those estimated by EPA for the clean and average base fuels. For the soy-based biodiesel, the reductions are slightly less for the lower load UDDS, but for the animal-based biodiesel the THC reductions for all the test cycles were similar.

For 2007 MBE4000, as could be seen from the figures, the THC emissions do not show consistent and statistically significant trends. This can be attributed to the efficiency of the DPF and the associated low emissions. Interestingly, for FTP the THC emissions for soy-based biodiesel actually showed statistically significant increases ranging from 20 to 33% compared to the CARB diesel. While these tests showed differences, these differences represent small changes in the actual THC emissions level. Additional testing would be needed to further clarify this observation.

Table 5-3. THC Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Soy-based		Animal-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	-12%	0.000	-16%	0.000	-11%	0.770	33%	0.000
	B50	-28%	0.000	-38%	0.000	27%	0.400	8%	0.695
	B100	-55%	0.000	-73%	0.000	-18%	0.683	6%	0.755
FTP	B5	-1% (Mit)	0.136	-3%	0.011	38%	0.006	13%	0.429
	B10	-6% (Mit)	0.000						
	B20	-11%	0.000	-13%	0.000	33%	0.005	13%	0.376
	B50	-29%	0.000	-36%	0.000	25%	0.018	-13%	0.568
	B100	-63%	0.000	-71%	0.000	20%	0.081	5%	0.756
40 mph Cruise	B5	-1%	0.573						
	B20	-16%	0.000						
	B50	-36%	0.000						
	B100	-70%	0.000						
50 mph Cruise	B5	-2%	0.222						
	B20	-12%	0.000	-14%	0.000	-5%	0.801	17%	0.425
	B50	-31%	0.000	-37%	0.000	-20%	0.430	-13%	0.448
	B100	-68%	0.000	-73%	0.000	-13%	0.594	3%	0.905

For 2006 Cummins engine, the THC emissions show a slight trend of increasing emissions with increased average cycle power, although this trend is not as strong as for NO_x or PM. This is

shown in Figure 5-33 for the soy-based biodiesel and in Figure 5-34 for the animal-based biodiesel.

For 2007 MBE4000, the THC emissions the emissions show slightly higher values for the lower power/UDDS cycle on a g/hr basis, with the mid- and high- power cycles being essentially the same on a g/hr basis. This is shown in Figure 5-35 for soy-based and Figure 5-36 for animal-based biodiesel.

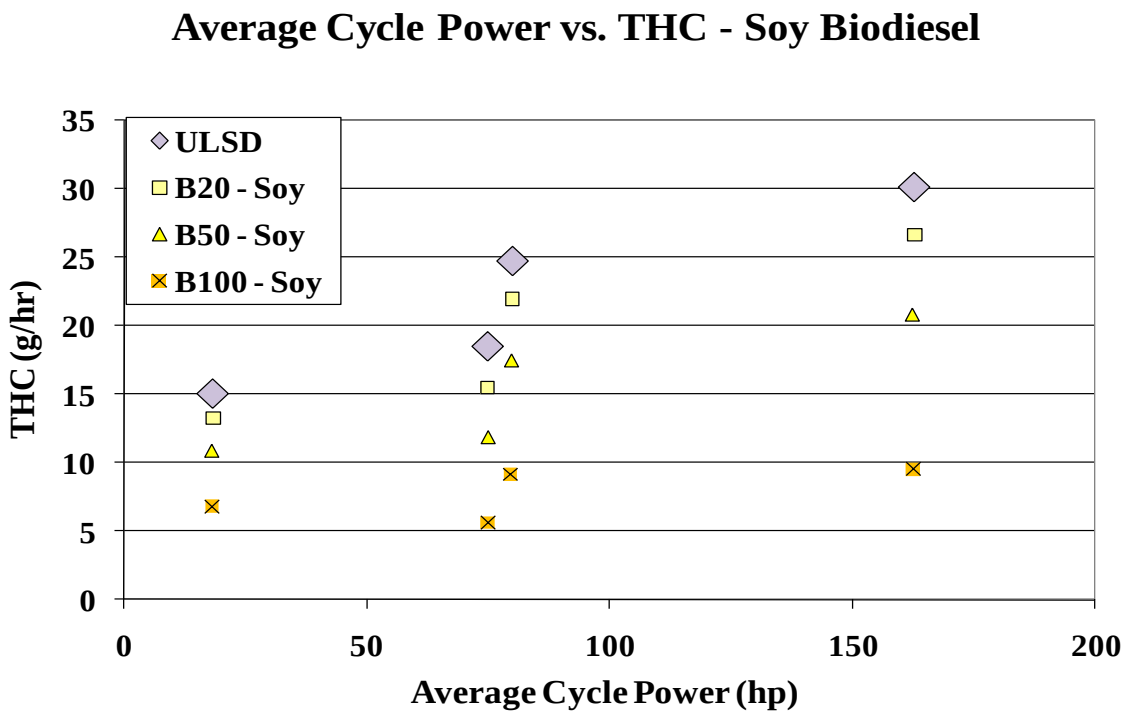


Figure 5-33. Average Cycle Power vs. THC Emissions for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

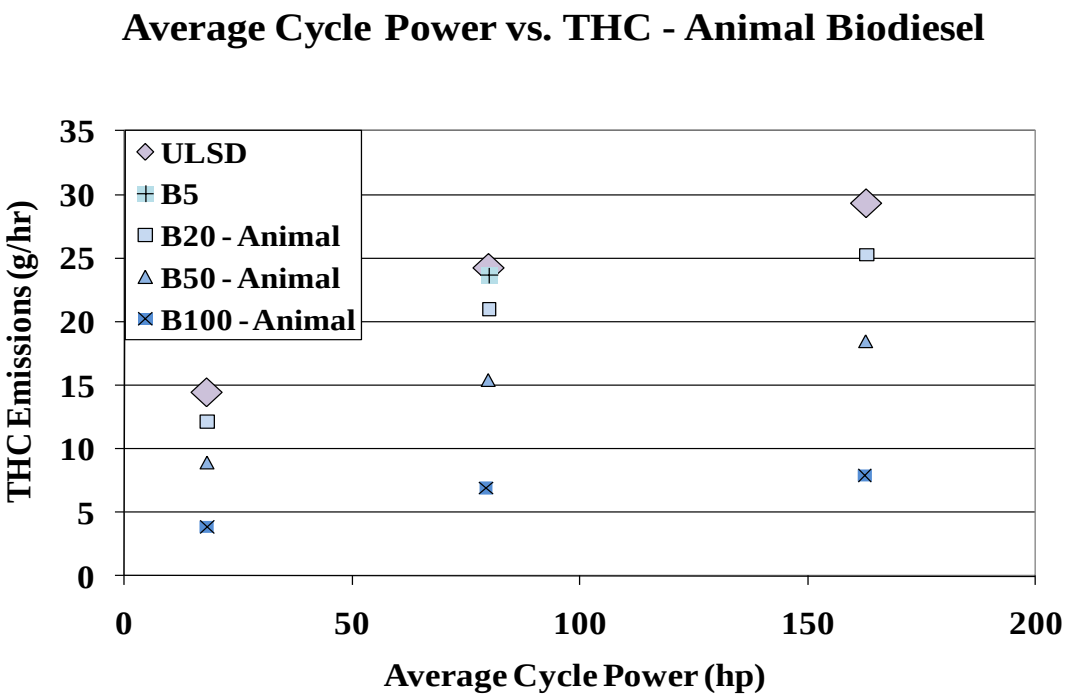


Figure 5-34. Average Cycle Power vs. THC Emissions for Testing on Animal-Based Biodiesel Blends 2006 Cummins ISM

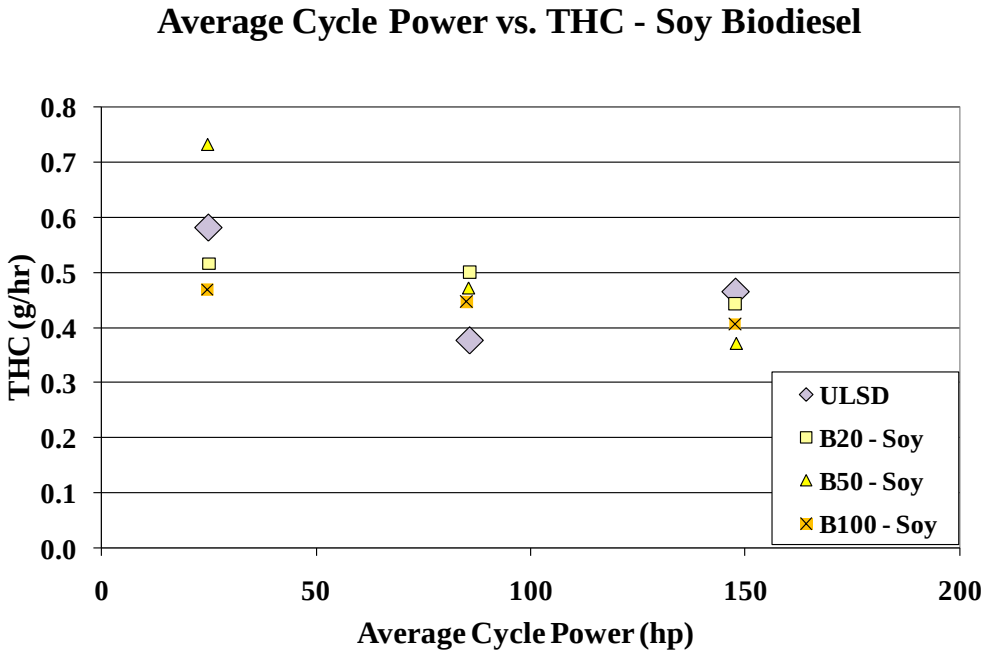


Figure 5-35 . Average Cycle Power vs. THC Emissions for Testing on Soy-Based Biodiesel Blends 2007 MBE4000

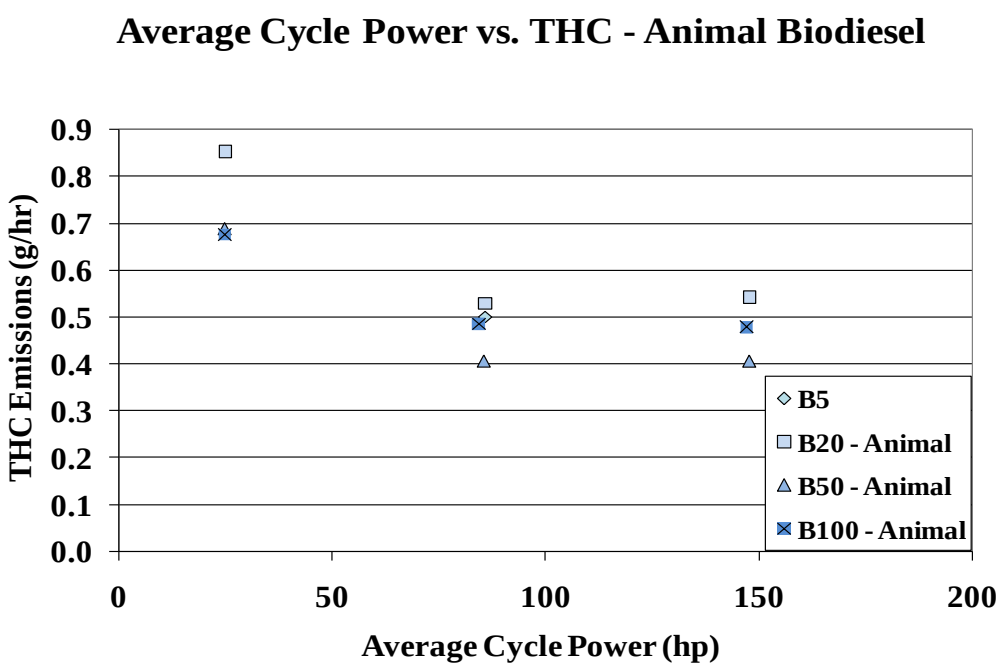


Figure 5-36. Average Cycle Power vs. THC Emissions for Testing on Animal-Based Biodiesel Blends 2007 MBE4000

For the 2006 Cummins Engine, the differential between THC emissions for a biodiesel blend and the base fuel is shown as a function of power in Figure 5-37 for the soy-based biodiesel and in Figure 5-38 for the animal-based biodiesel. The data generally show that there is not a strong trend in the THC differential for biodiesel as a function of power. For the soy-based biodiesel on the 2007 MBE4000, a trend of increasing emissions with the mid-power level FTP, as discussed above, can be seen in Figure 5-39. For the animal-based biodiesel testing on the 2007 MBE4000 there are no consistent trends in the THC differential as a function of average cycle power similar to the 2006 Cummins engine, as seen in Figure 5-40.

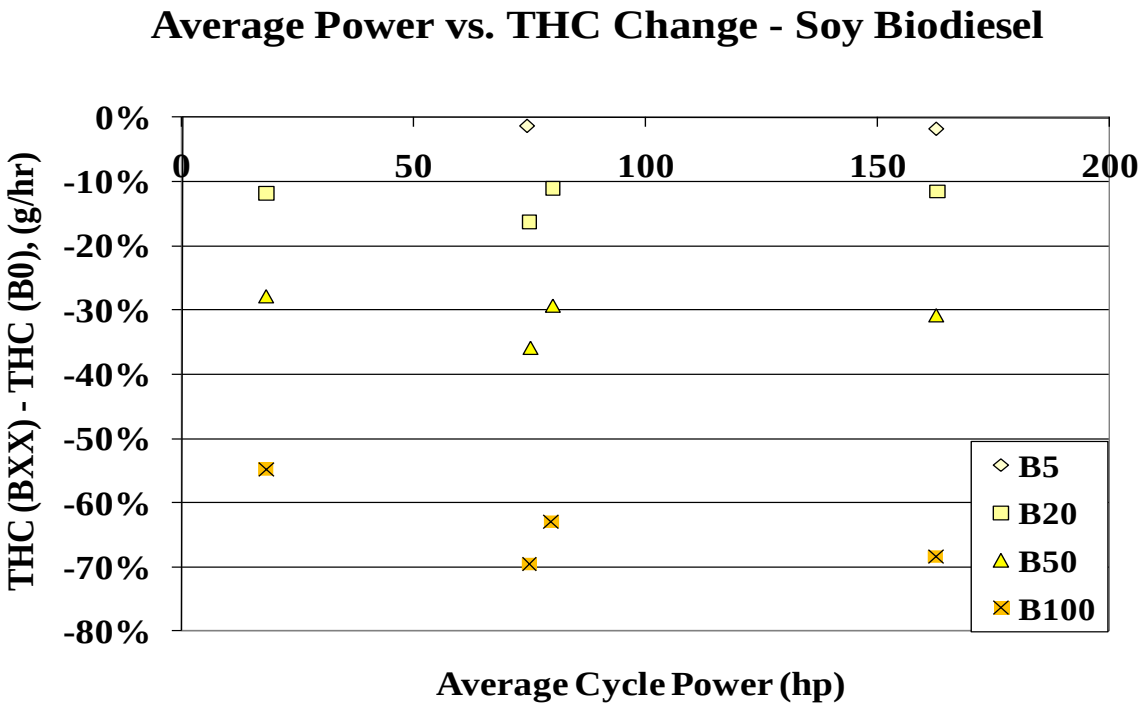


Figure 5-37 . Average Cycle Power vs. THC Emissions Change for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

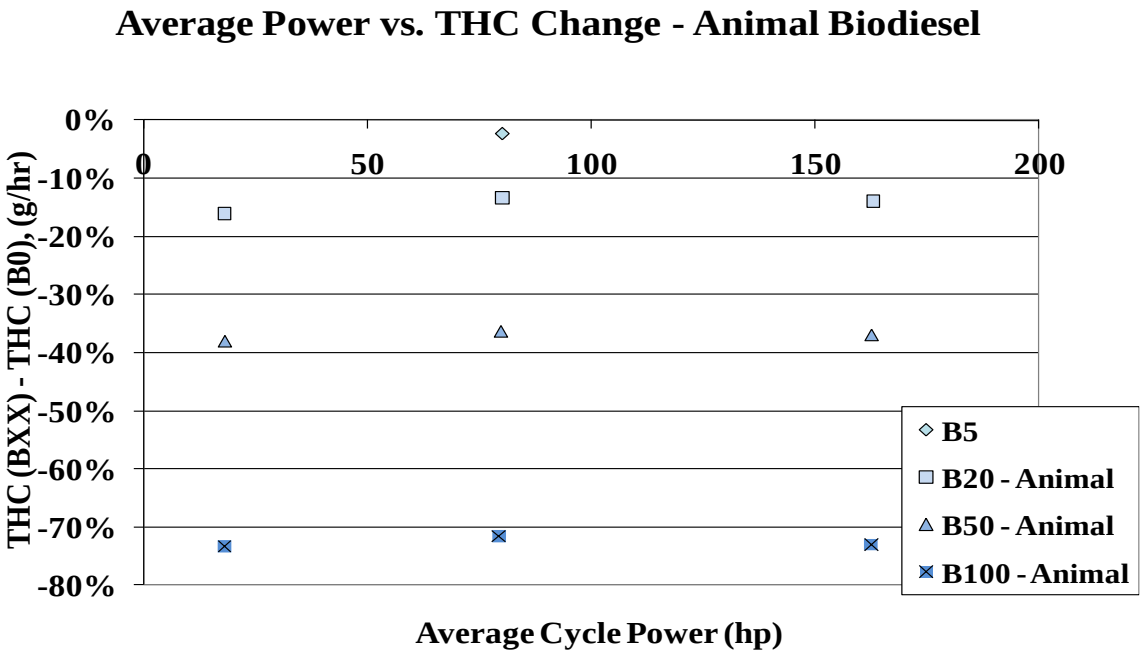


Figure 5-38. Average Cycle Power vs. THC Emissions Change for Testing on Animal-Based Biodiesel Blends 2006 Cummins ISM

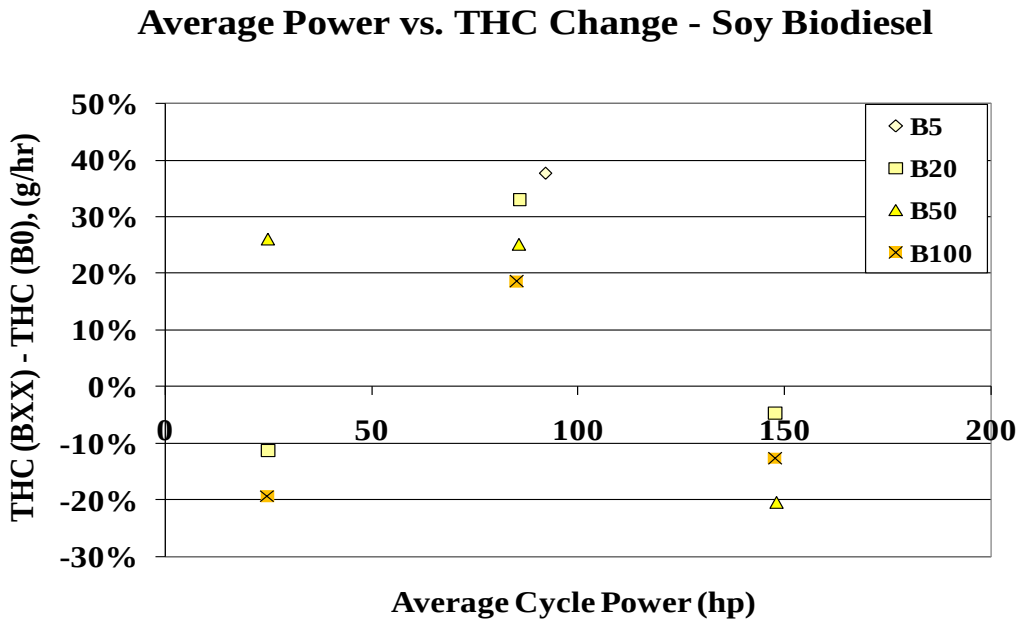


Figure 5-39.Average Cycle Power vs. THC Emissions Change for Testing on Soy-Based Biodiesel Blends 2007 MBE4000

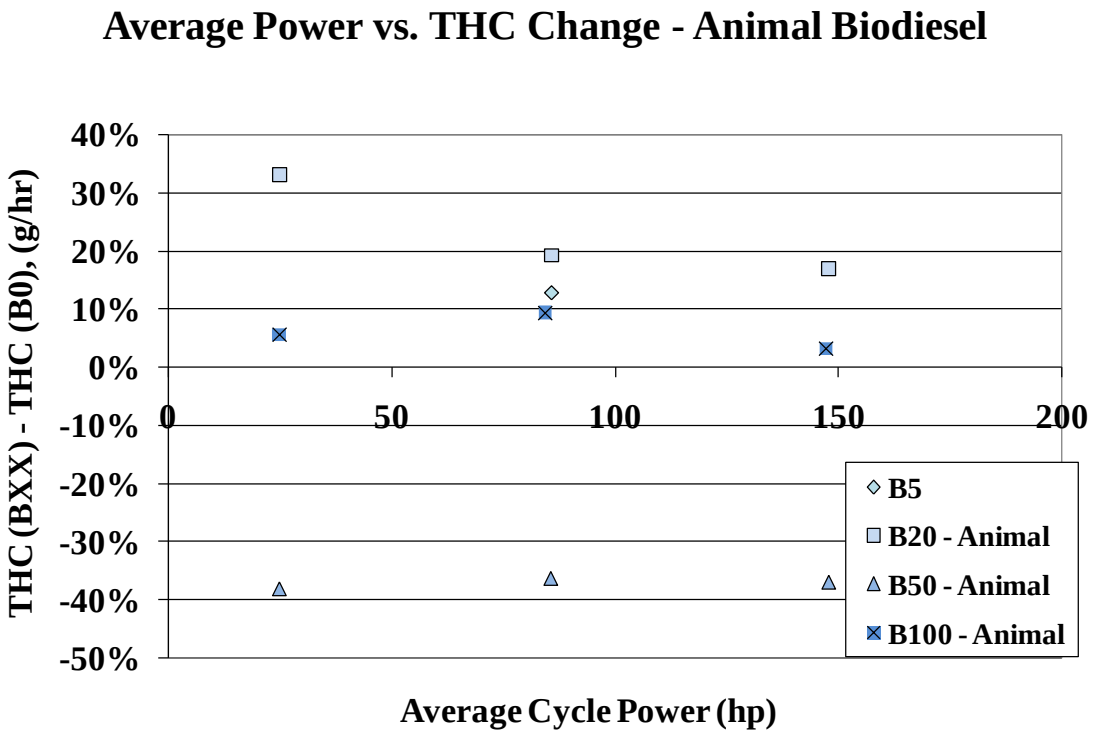


Figure 5-40.Average Cycle Power vs. THC Emissions Change for Testing on Animal-Based Biodiesel Blends 2007 MBE4000

The trends in the THC differential as a function of fuel consumption essentially followed the same trends as observed for the average cycle power, with the only significant observation being the increasing THC differential for the soy-based biodiesel on the MBE4000 over the FTP. This can be seen in Figure 5-41 to Figure 5-44.

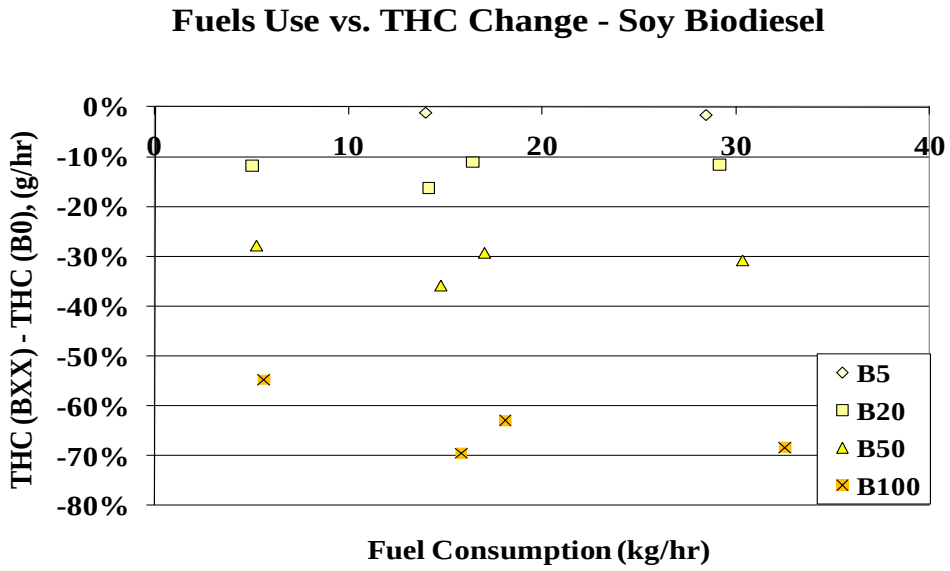


Figure 5-41. Fuel Consumption vs. THC Emissions Change for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

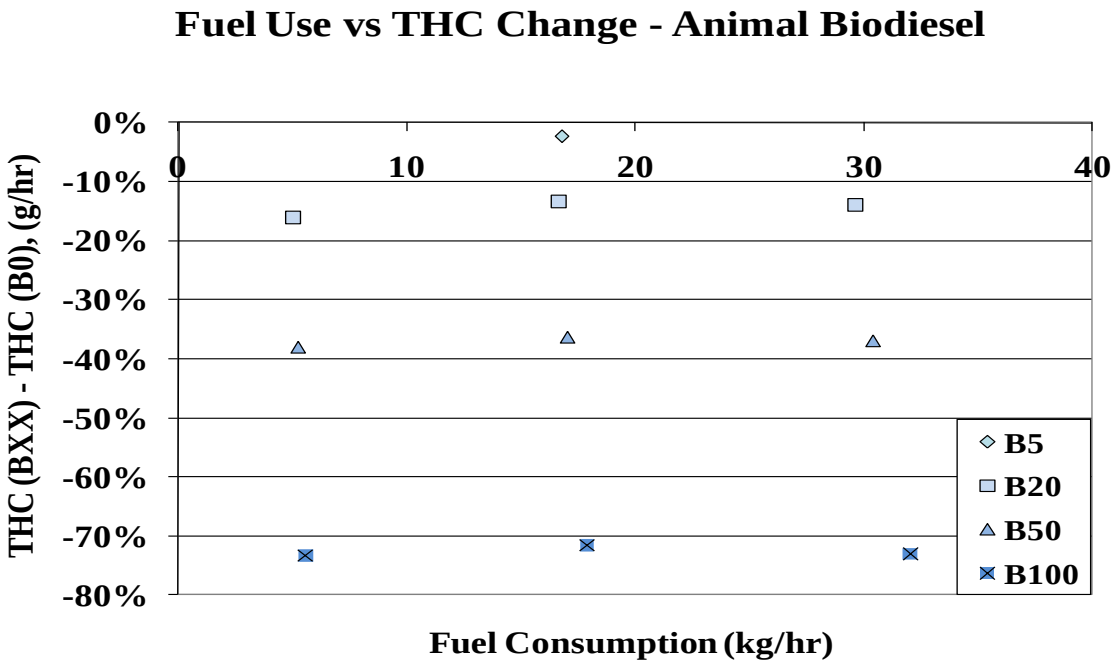


Figure 5-42. Fuel Consumption vs. THC Emissions Change for Testing on Animal -Based Biodiesel Blends 2006 Cummins ISM

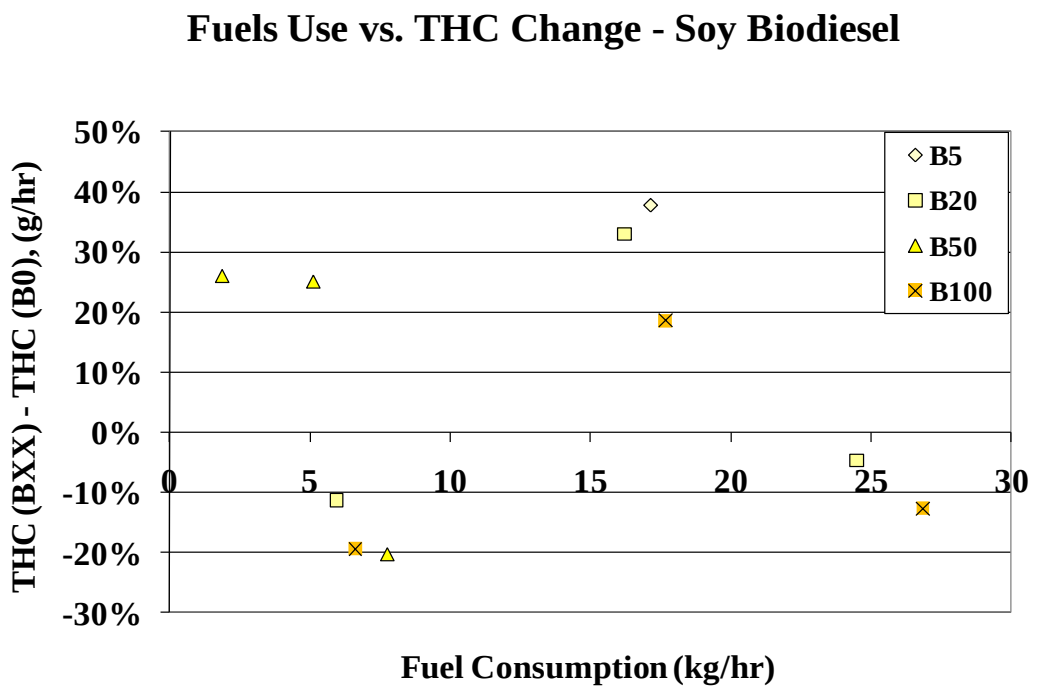


Figure 5-43.Fuel Consumption vs. THC Emissions Change for Testing on Soy-Based Biodiesel Blends 2007 MBE4000

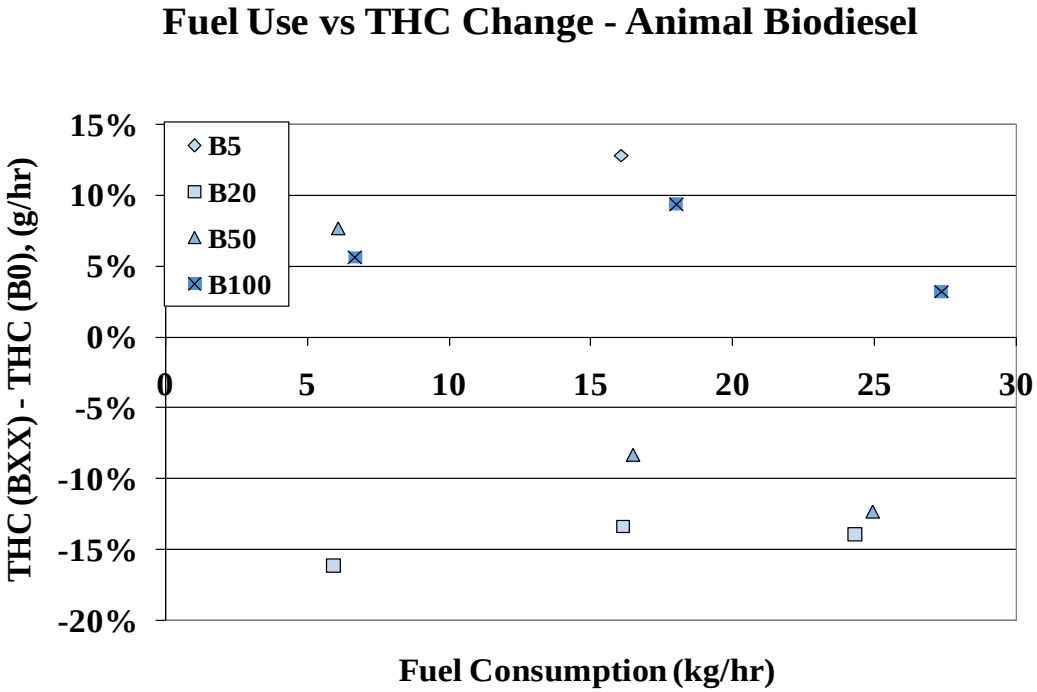


Figure 5-44.Fuel Consumption vs. THC Emissions Change for Testing on Animal -Based Biodiesel Blends 2007 MBE4000

5.4 CO Emissions

The CO emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock are presented in Figure 5-45 to Figure 5-48, respectively, on a g/bhp-hr basis. Table 5-4 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

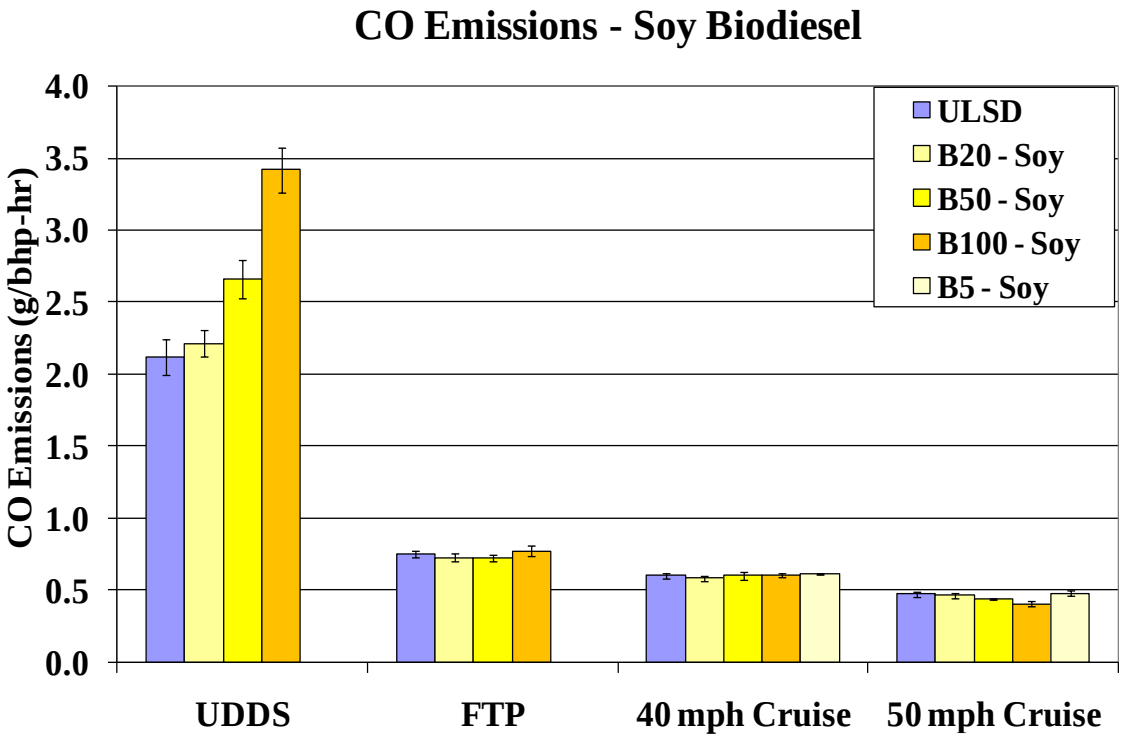


Figure 5-45. Average CO Emission Results for Soy-Based Biodiesel for 2006 Cummins ISM

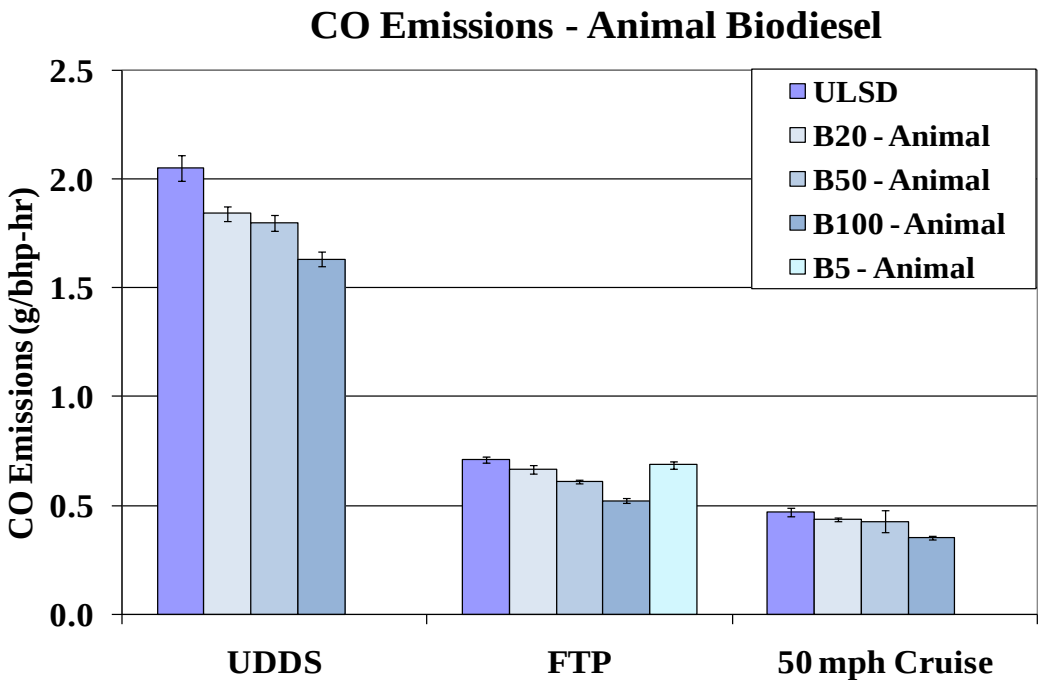


Figure 5-46. Average CO Emission Results for Animal-Based Biodiesel for 2006 Cummins ISM

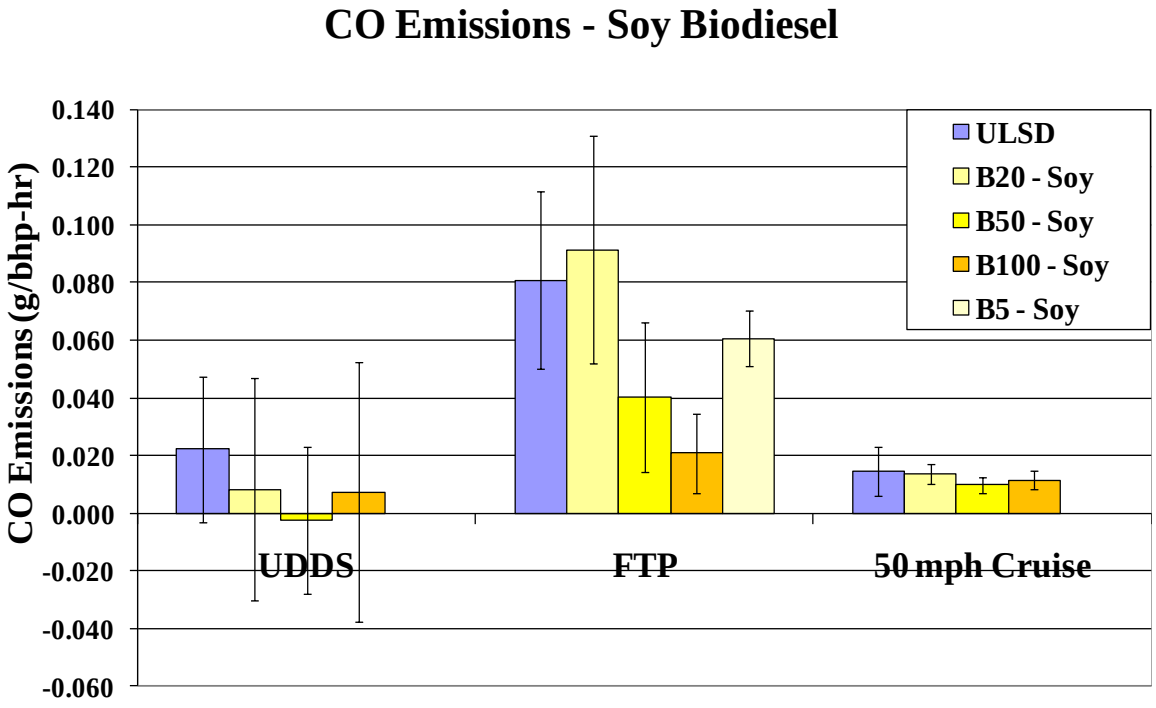


Figure 5-47. Average CO Emission Results for Soy-Based Biodiesel for 2007 MBE4000

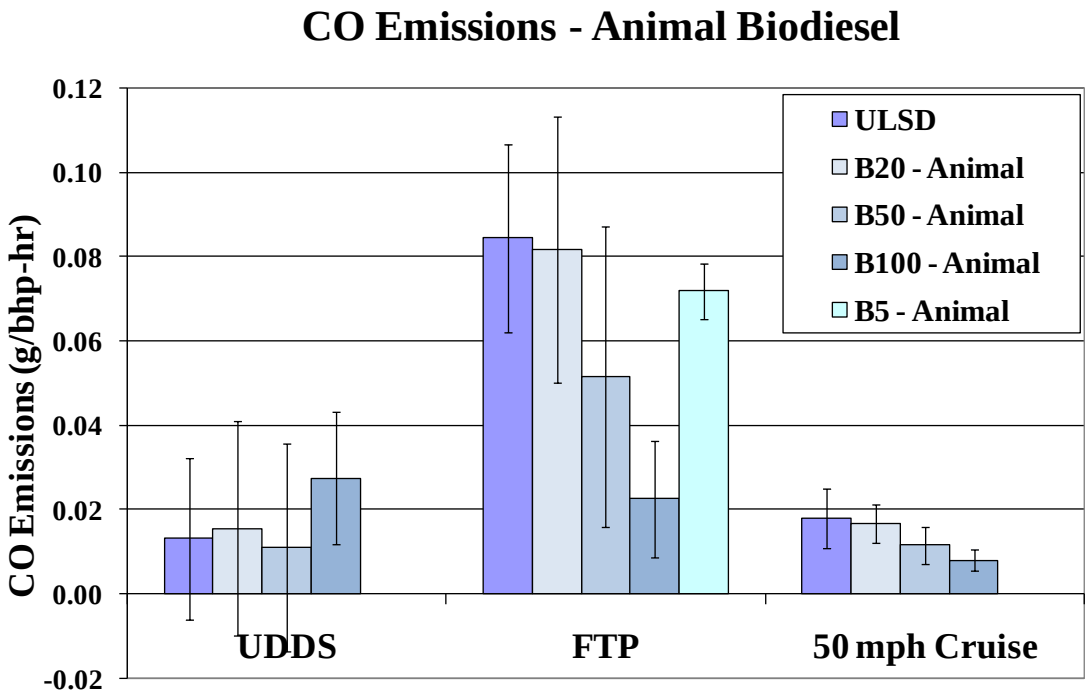


Figure 5-48. Average CO Emission Results for the Animal-Based Biodiesel Feedstock 2007 MBE4000

For the 2006 Cummins engine, the CO emissions for the animal-based biodiesel showed consistent and statistically significant reductions with increasing biodiesel blend, consistent with previous studies. For comparison, the EPA base case estimated reductions were ~12% at a B20 level, ~28% for a B50 level, and ~48% at the B100 level. EPA estimates for the CO reductions expected for a clean base fuel are smaller, with reductions of less than 10% for B20, ~20% for the B50 level, and ~37% for B100. The CO reductions seen for the animal-based biodiesel for the 2006 Cummins engine are comparable to the EPA estimates for the B20 blend, but are slightly lower than the EPA estimates for the B50 and B100 blends.

The CO trends for the soy-based biodiesel for the 2006 Cummins engine were less consistent. The CO emissions for the soy-based biodiesel did show consistent reductions with increasing biodiesel blend levels for the highest load, 50 mph cruise cycle. It should be noted that the percentage differences for the both the soy-based and animal-based biodiesel were also impacted by the engine operation differences seen for the 50 mph cruise, as discussed in Section 2.7 and Appendix E. For the FTP and 40 mph Cruise cycles for the 2006 Cummins engine, the soy-based biodiesel blends did not show any strong trends relative to the CARB ULSD and a number of differences were not statistically significant. Interestingly, the CO emissions for the lowest load UDDS cycle showed higher emissions for the Soy biodiesel blends, with the largest increases seen for the highest blend level. The increases for the UDDS cycle were all statistically significant. Additional testing would likely be needed to better understand the nature of these results, which are opposite the trends seen in most previous studies.

For the 2007 MBE4000 engine, the CO emissions were considerably lower than those for the 2006 Cummins engine due to the DPF. For most of the comparisons between the CARB fuel and the biodiesel blends, there were no statistically significant differences. For the FTP test, however, statistically significant reductions in CO were found for both the B50 and B100 blend levels in comparison with the CARB diesel. These reductions were greater than those from the EPA study, with the reductions ranging from 39-50% for the B50 blends and from 72-74% for the B100 blends, but they were very small on an absolute basis.

Table 5-4. CO Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle

		2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Soy-based		Animal-based	
	CARB vs.	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	5%	0.115	-10%	0.000	-62%	0.453	18%	0.003
	B50	26%	0.000	-12%	0.000	-111%	0.154	-16%	0.875
	B100	62%	0.000	-20%	0.000	-67%	0.491	109%	0.238
FTP	B5	-1% (Mit)	0.405	-4%	0.008	-20%	0.013	-11%	0094
	B10	-2% (Mit)	0.151						
	B20	-3%	0.078	-7%	0.000	13%	0.534	-3%	0.841
	B50	-4%	0.038	-14%	0.000	-50%	0.031	-39%	0.040
	B100	3%	0.163	-27%	0.000	-74%	0.002	-73%	0.000
40 mph Cruise	B5	2%	0.427						
	B20	-3%	0.160						
	B50	0%	0.986						
	B100	0%	0.868						
50 mph Cruise	B5	1%	0.649						
	B20	-2%	0.330	-7%	0.003	-6%	0.809	-7%	0.733
	B50	-6%	0.002	-9%	0.066	-33%	0.302	-36%	0.144
	B100	-14%	0.000	-25%	0.000	-21%	0.508	-55%	0.027

For the 2006 Cummins engine, CO emissions show a trend of increasing emissions with increased average cycle power for the animal-based biodiesel for all blends and for the soy-based biodiesel for the ULSD and the B20 and B50 blends. This is shown in Figure 5-49 for the soy-based biodiesel and in Figure 5-50 for the animal-based biodiesel. For the B100 blend for the soy-based biodiesel, the data did not show an increase with increasing power. This can be attributed in part to the increase in CO emissions for these blends on the UDDS cycle.

For the 2007 MBE4000 engine, the CO emissions were higher for the FTP than either the low load UDDS or the higher load cruise cycle. This is shown in Figure 5-51 for the soy-based biodiesel and in Figure 5-52 for the animal-based biodiesel. Thus, there were no trends as a function of average cycle power for this engine.

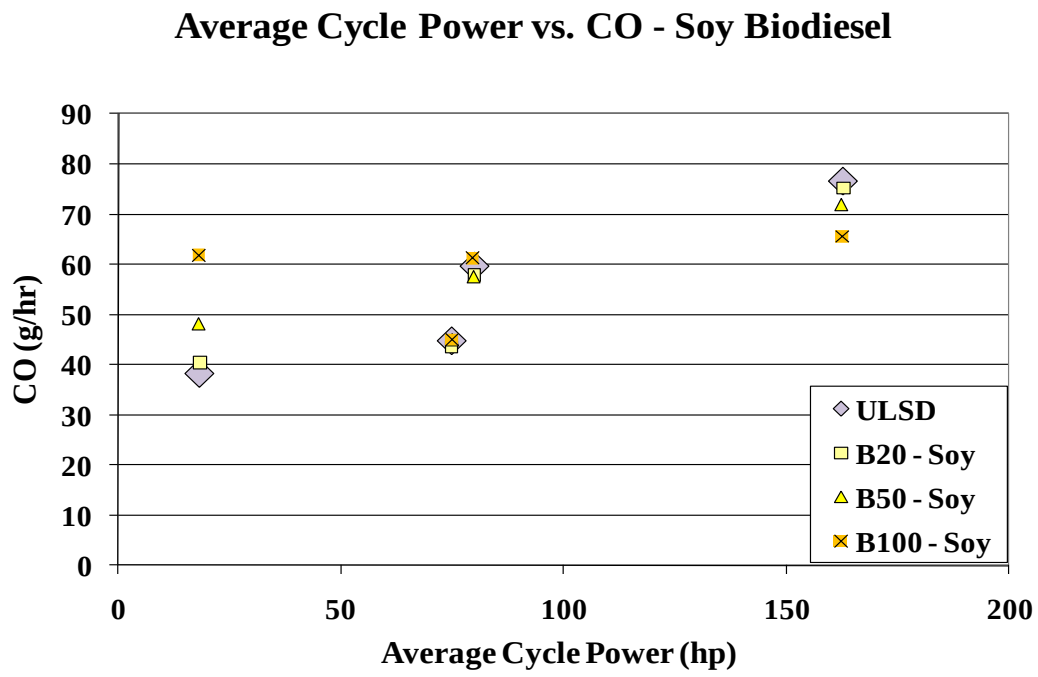


Figure 5-49. Average Cycle Power vs. CO Emissions for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

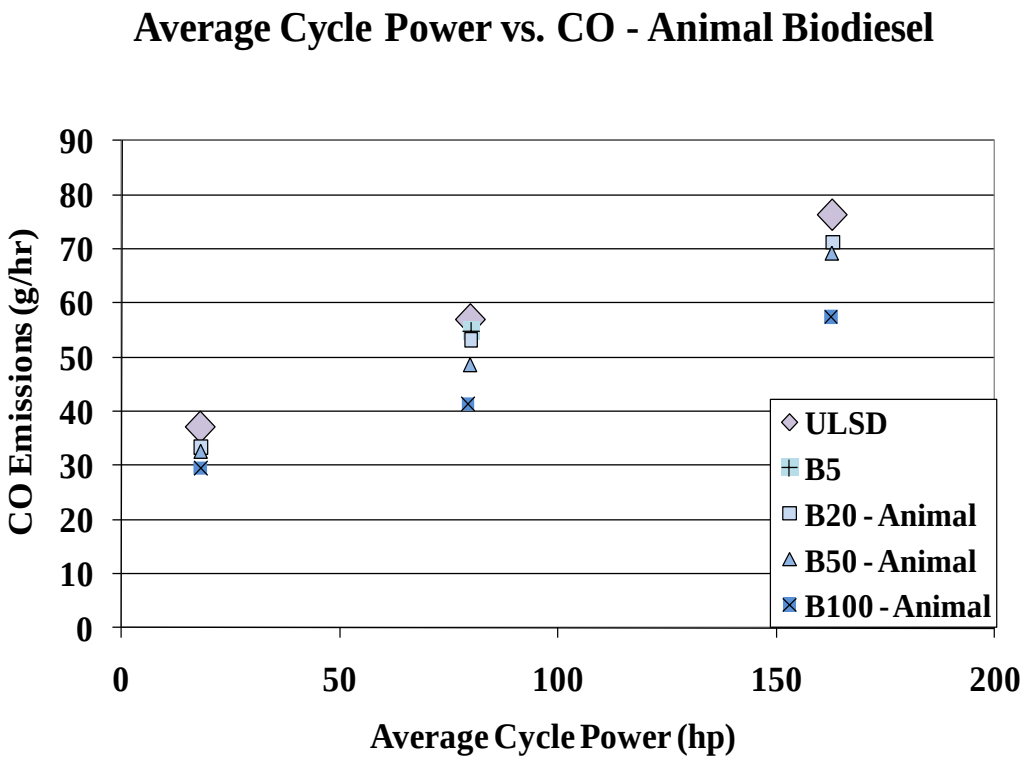


Figure 5-50. Average Cycle Power vs. CO Emissions for Testing on Animal-Based Biodiesel Blends 2006 Cummins ISM

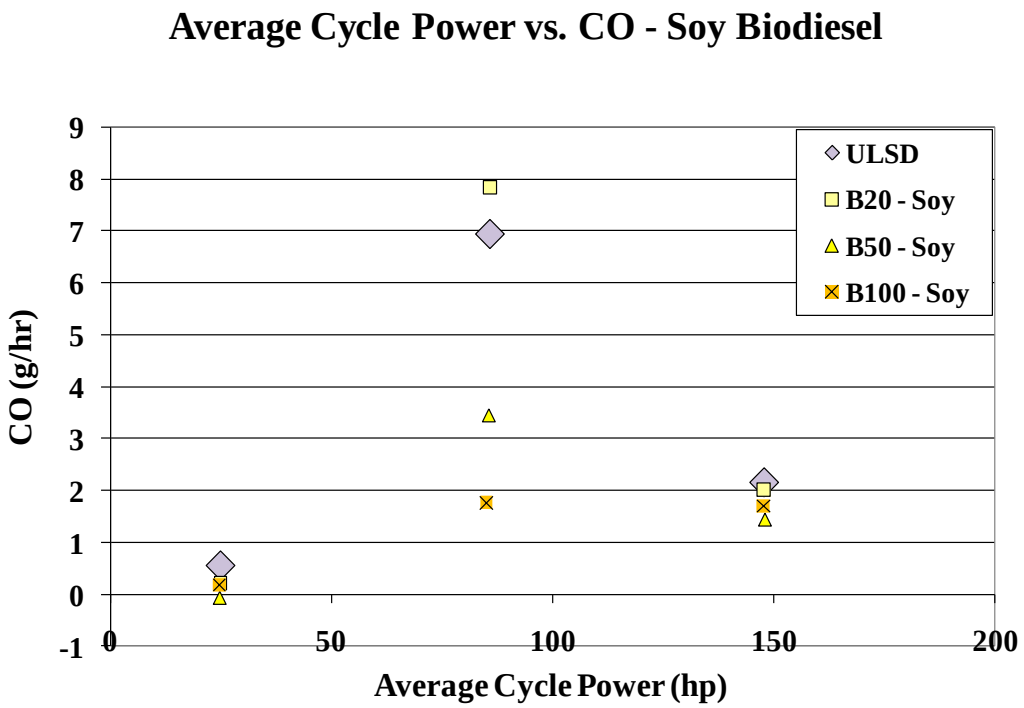


Figure 5-51. Average Cycle Power vs. CO Emissions for Testing on Soy-Based Biodiesel Blends 2007 MBE4000

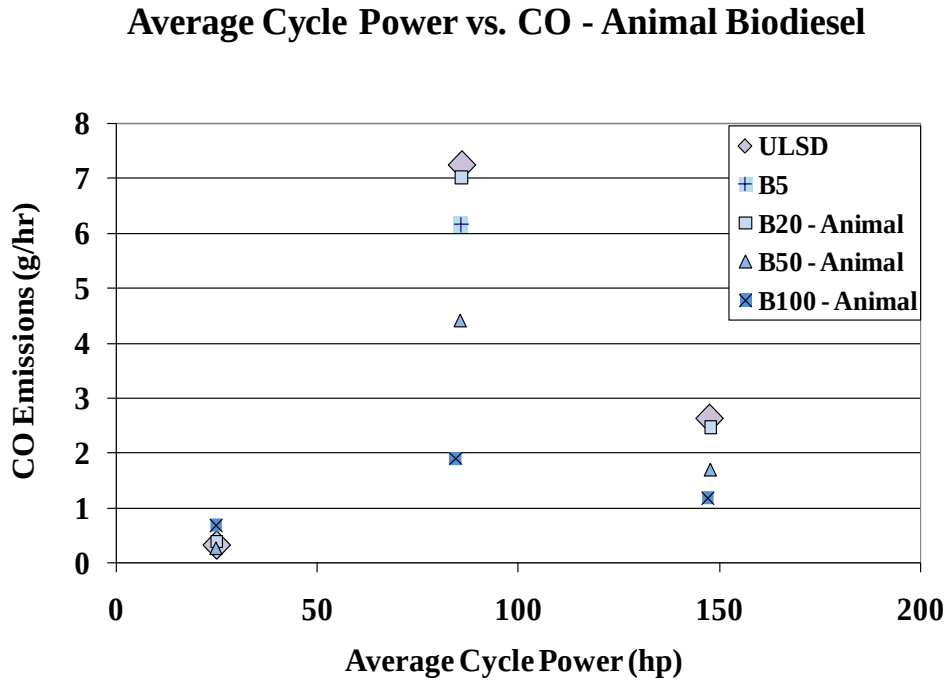


Figure 5-52. Average Cycle Power vs. CO Emissions for Testing on Animal-Based Biodiesel Blends 2007 MBE4000

The differential between CO emissions for a biodiesel blend and the base fuel for the 2006 Cummins is shown as a function of power in Figure 5-53 for the soy-based biodiesel for the 2006 Cummins ISM and in Figure 5-54 the animal-based biodiesel, and as function of fuel consumption in Figure 5-55 for the soy-based biodiesel and in Figure 5-56 for the animal-based biodiesel. For the soy-based biodiesel, the CO differentials show a reverse trend, with the highest increases seen at the lowest power/fuel use level on the UDDS. The CO differentials for the animal-based biodiesel did not show any strong trends as a function of average cycle power or fuel consumption.

For the 2007 MBE4000 engine, the emissions changes were largely not statistically significant for the UDDS and 50 mph cruise cycles, as seen in Table 3-4. As such, there were no trends as a function of average cycle power or fuel consumption, and these figures are not included here.

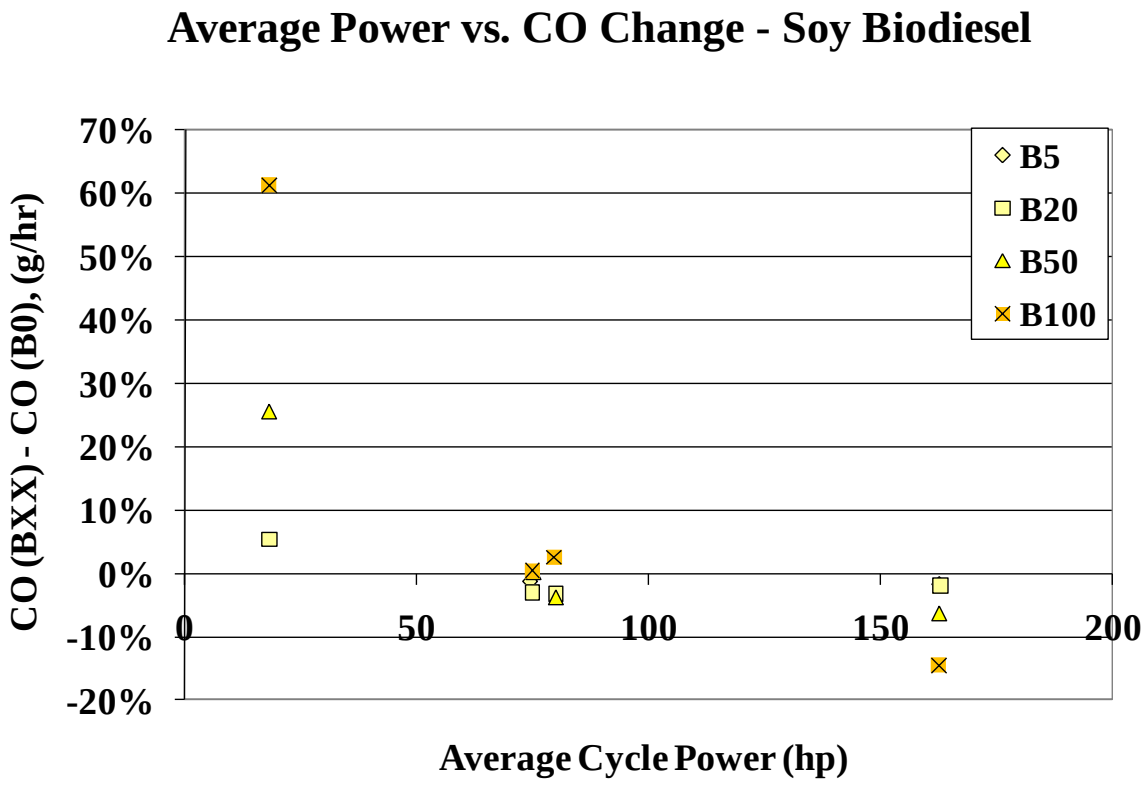


Figure 5-53. Average Cycle Power vs. CO Emissions Change for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

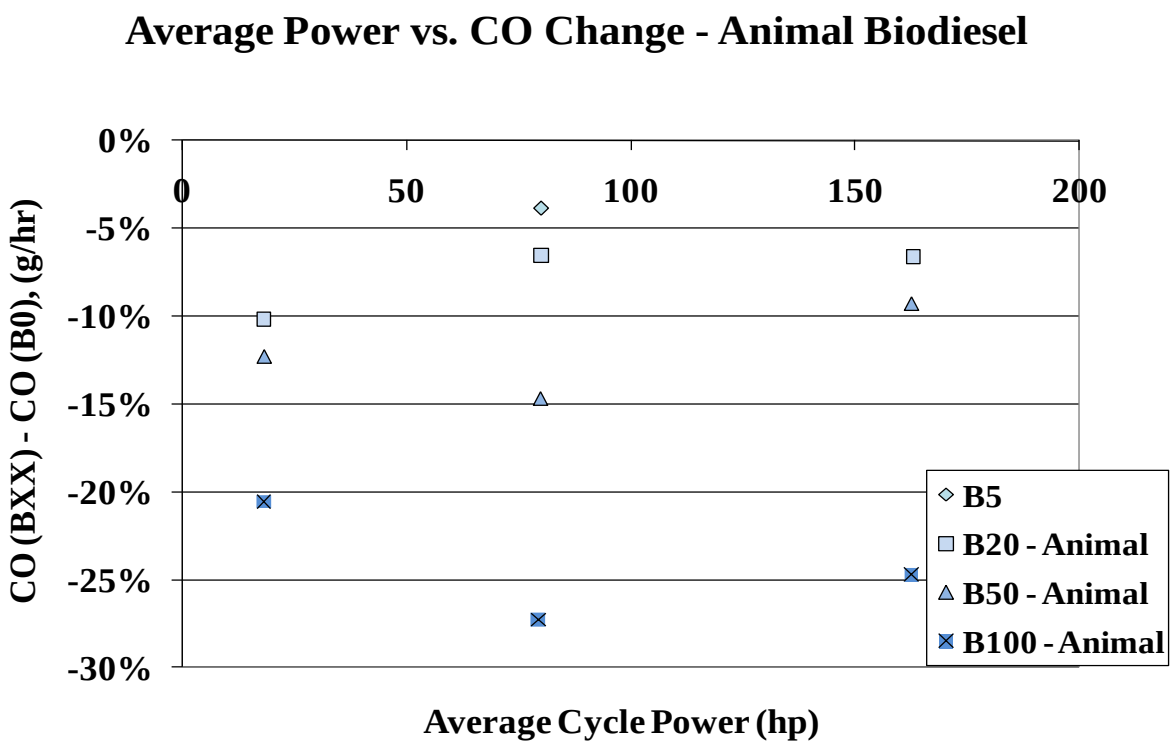


Figure 5-54. Average Cycle Power vs. CO Emissions Change for Testing on Animal-Based Biodiesel Blends 2006 Cummins ISM

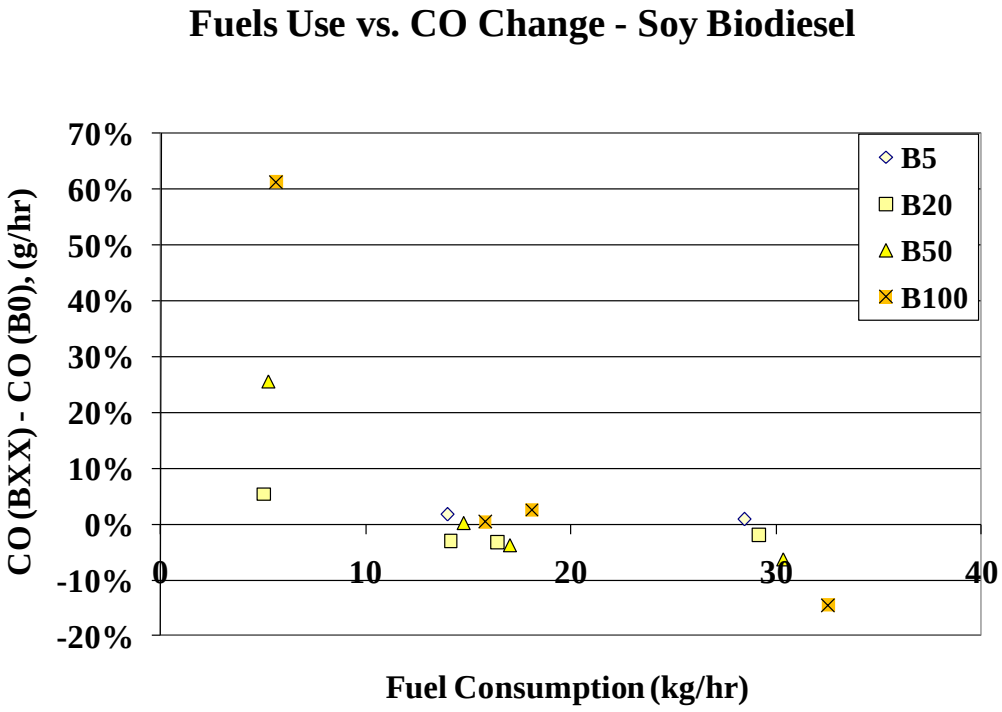


Figure 5-55.Fuel Consumption vs. CO Emissions Change for Testing on Soy-Based Biodiesel Blends 2006 Cummins ISM

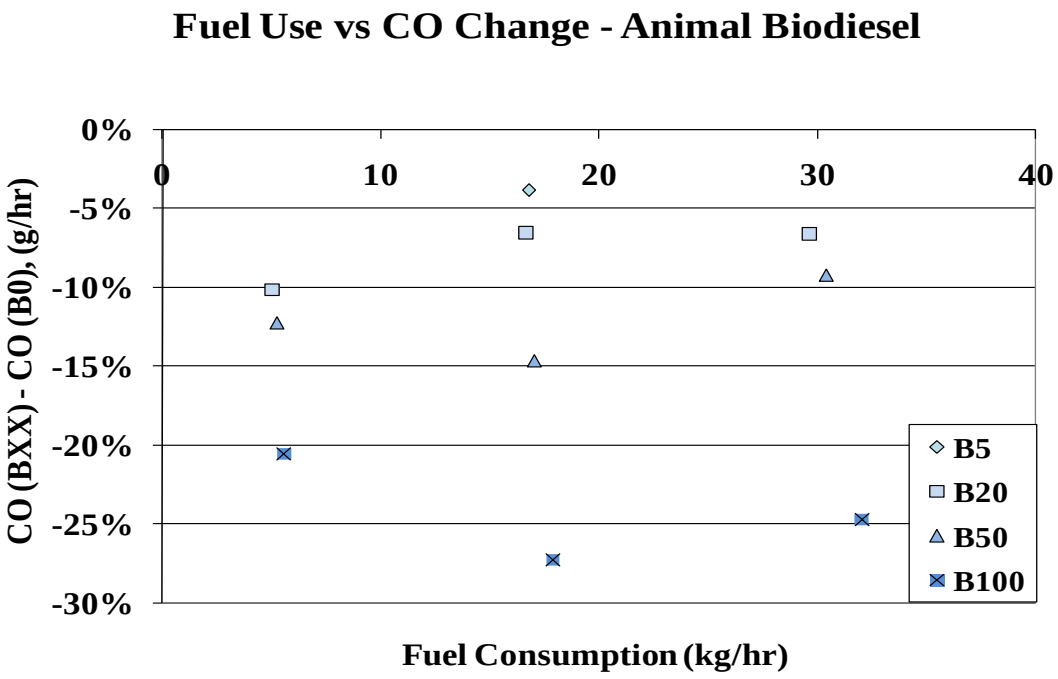


Figure 5-56.Fuel Consumption vs. CO Emissions Change for Testing on Animal-Based Biodiesel Blends 2006 Cummins ISM

5.5 CO_2 Emissions

The CO_2 emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock are presented in Figure 5-57 to Figure 5-60, respectively, on a g/bhp-hr basis. Table 5-5 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

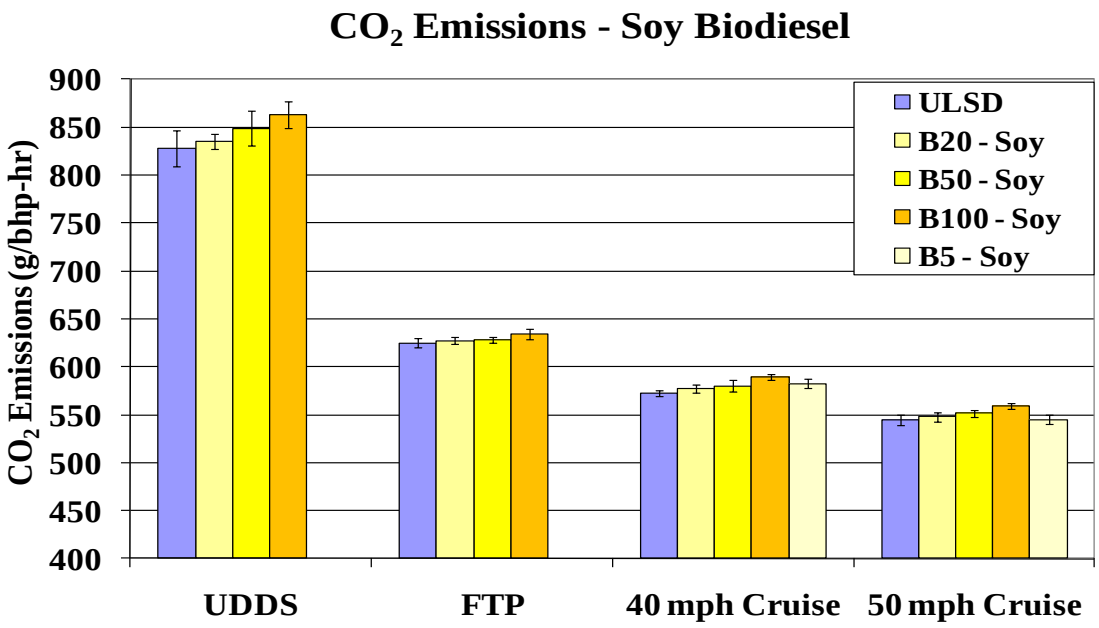


Figure 5-57. Average CO_2 Emission Results for the Soy-Based Biodiesel Feedstock 2006 Cummins ISM

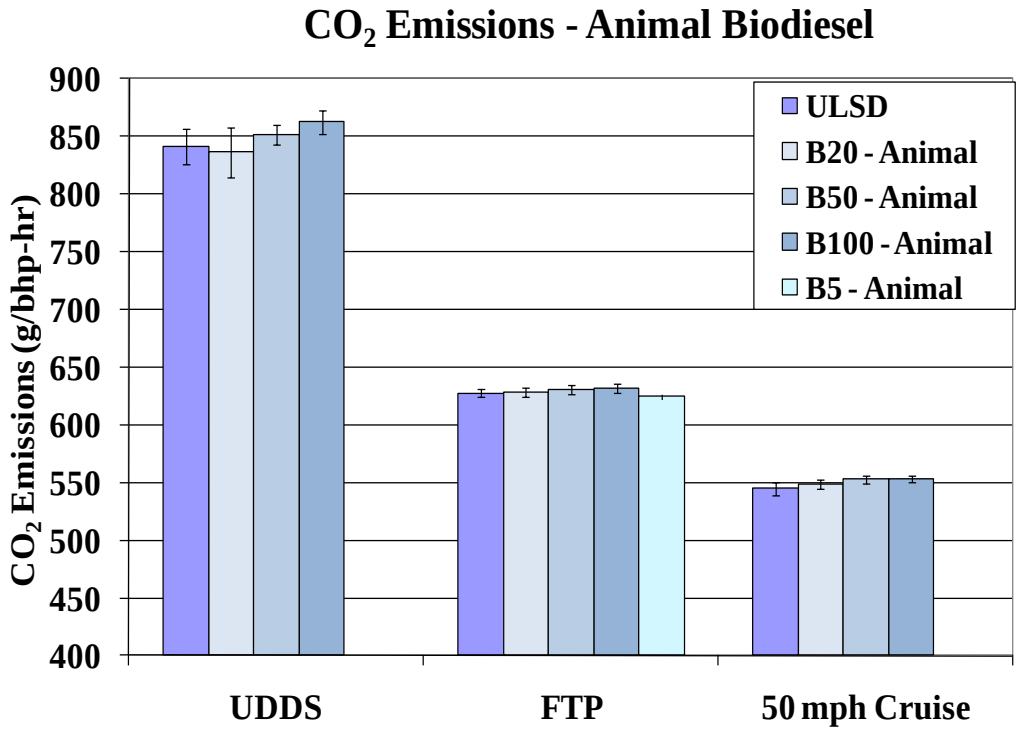


Figure 5-58. Average CO_2 Emission Results for the Animal-Based Biodiesel Feedstock 2006 Cummins ISM

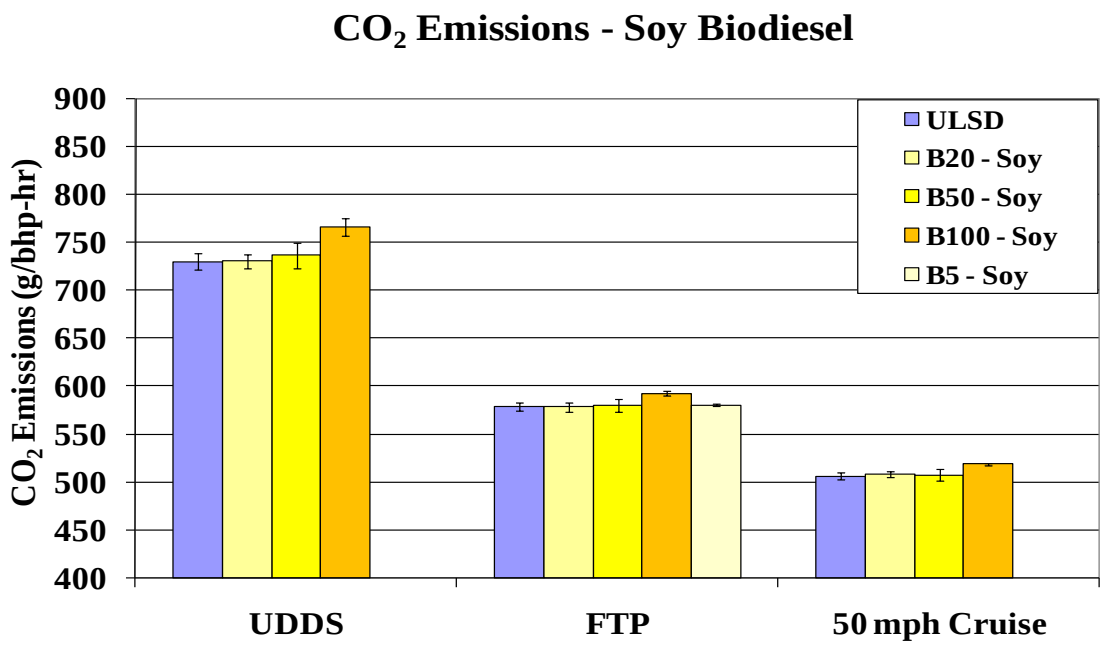


Figure 5-59. Average CO_2 Emission Results for Soy-Based Biodiesel for 2007 MBE4000

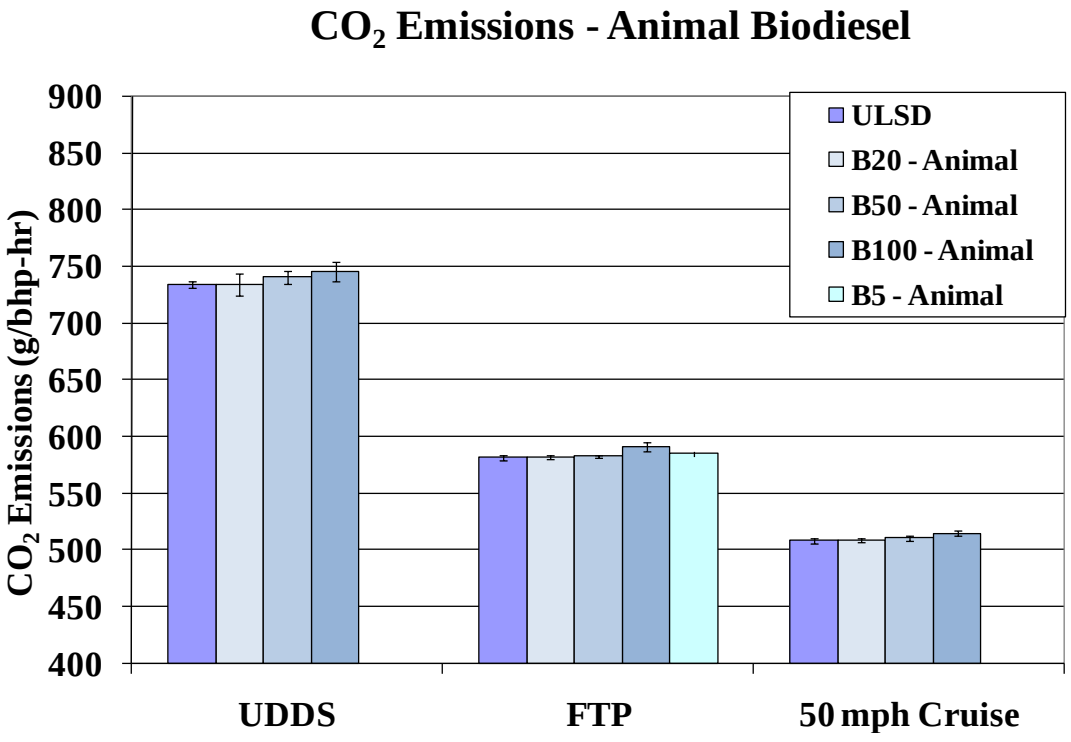


Figure 5-60. Average CO_2 Emission Results for the Animal-Based Biodiesel Feedstock 2007 MBE4000

The test results overall showed a slight increase in CO_2 emissions for the higher biodiesel blends. For the 2006 Cummins engine, this increase ranged from about 1-4%, with the increases being statistically significant for the B100 fuels for all of the tests, and for the B50 fuel for the cruise cycles and some other cycles. For the 2007 MBE4000 engine, only the B100 blends showed consistent statistically significant increases in CO_2 emissions for the different cycles, with the increases ranging from 1-5%. The differences in CO_2 emissions for the biodiesel blends can probably be attributed differences in the average carbon content per energy of the fuel. The EPA 2002 study also reported a CO_2 increase of 1-3% for B20 to B100 biodiesel blends for their "clean" base fuel. In their study, EPA compared fuels as a function of carbon content per energy of the fuel. In the US EPA study, the average carbon content per energy for typical biodiesel was 48.1 lb. carbon/million Btu compared to 47.5 lb. carbon/million Btu for the conventional diesel fuel. Given that the lower heating value of biodiesel is approximately 10-11% lower for neat biodiesel compared to typical diesel fuel on a mass basis (Hoekman et al., 2009), and the carbon contents for the present study are similar to those reported by EPA, similar differences in carbon content per energy of the fuel should be expected for this study between the CARB diesel and the biodiesel fuels.

Table 5-5. CO_2 Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Soy-based		Animal-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	0.8%	0.448	-0.6%	0.640	0.02%	0.971	0.03%	0.000
	B50	2.5%	0.055	1.2%	0.201	0.9%	0.334	1.0%	0.024
	B100	4.2%	0.003	2.5%	0.016	5.0%	0.000	1.5%	0.009
FTP	B5	0.1% (Mit)	0.816	-0.3%	0.191	0.05%	0.679	0.3%	0.145
	B10	-0.1% (Mit)	0.569						
	B20	0.4%	0.309	0.1%	0.733	-0.04%	0.909	0.1%	0.743
	B50	0.5%	0.159	0.4%	0.117	0.2%	0.722	0.2%	0.391
	B100	1.5%	0.007	0.7%	0.018	2.4%	0.000	1.6%	0.000
40 mph Cruise	B5	1.7%	0.085						
	B20	0.8%	0.056						
	B50	1.3%	0.053						
	B100	3.0%	0.000						
50 mph Cruise	B5	0.0%	0.959						
	B20	0.6%	0.227	0.7%	0.170	0.4%	0.249	0.0%	0.837
	B50	1.2%	0.008	1.5%	0.014	0.4%	0.548	0.4%	0.150
	B100	2.6%	0.000	1.6%	0.008	2.6%	0.000	1.3%	0.002

5.6 Brake Specific Fuel Consumption

The brake specific fuel consumption results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock are presented in Figure 5-61 to Figure 5-64, respectively, on a gallons per brake horsepower hour (gal./bhp-hr) basis. The brake specific fuel consumption was determined via carbon balance using the carbon weight fractions and densities of each fuel. Table 5-6 shows the percentage differences for the different biodiesel feedstocks

and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

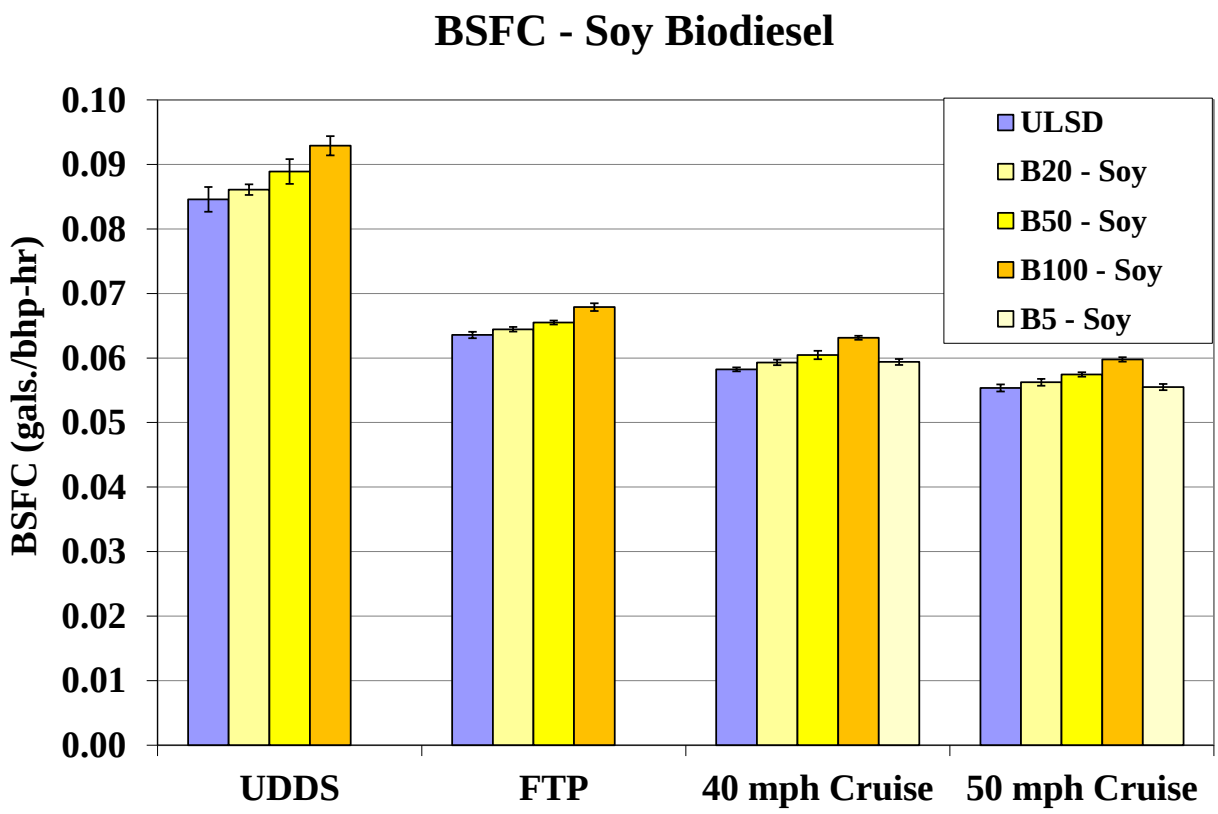


Figure 5-61. Average Brake Specific Fuel Consumption Results for the Soy-Based Biodiesel Feedstock 2006 Cummins ISM

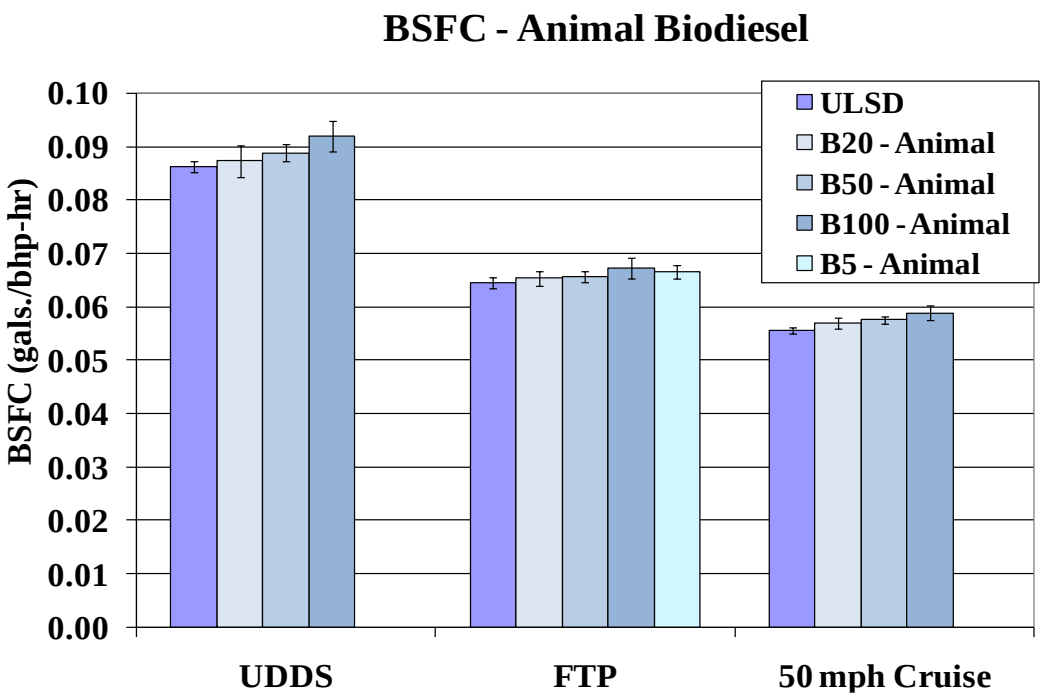


Figure 5-62. Average Brake Specific Fuel Consumption Results for the Animal-Based Biodiesel Feedstock 2006 Cummins ISM

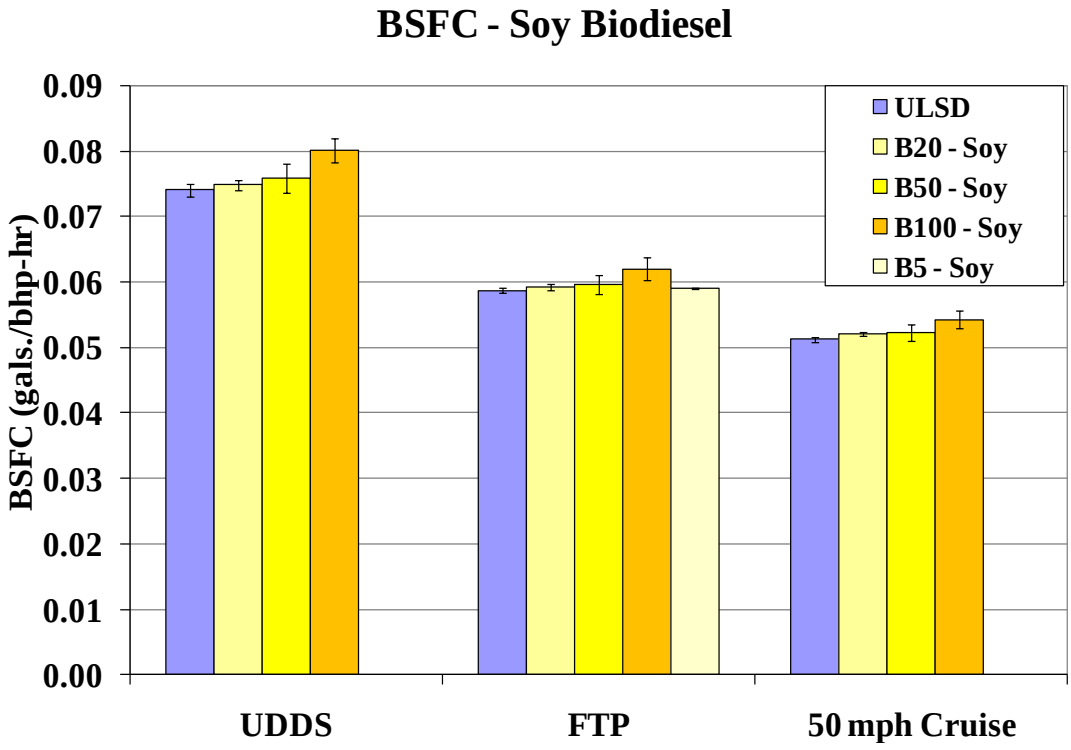


Figure 5-63. Average Brake Specific Fuel Consumption Results for the Soy-Based Biodiesel Feedstock 2007 MBE4000

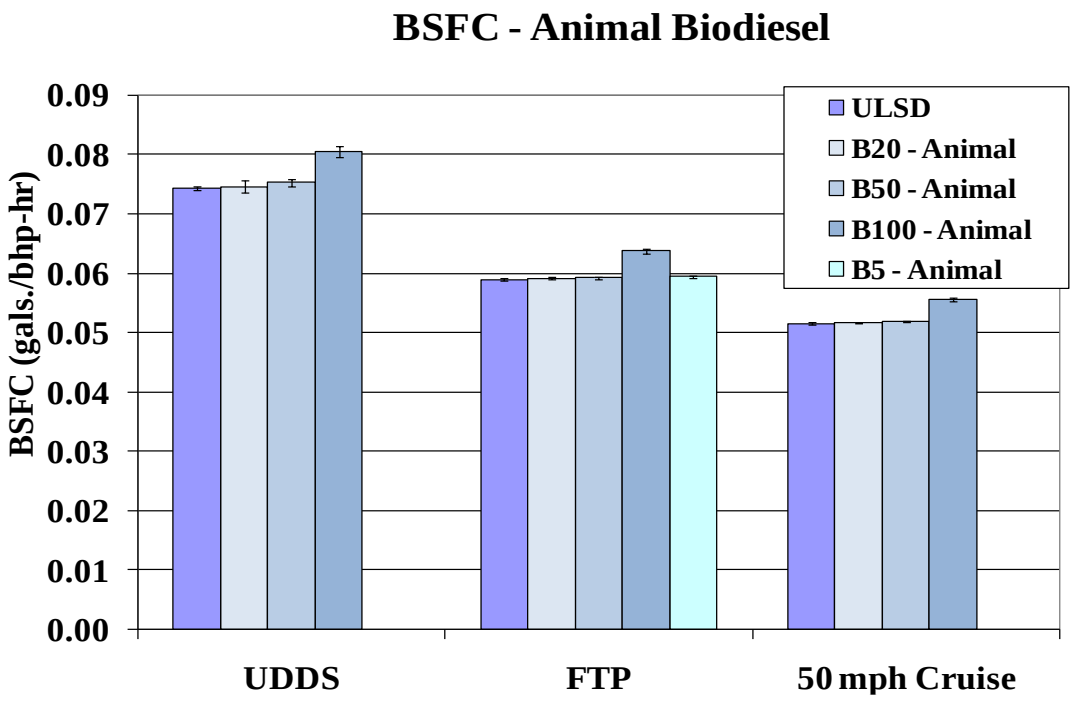


Figure 5-64. Average Brake Specific Fuel Consumption Results for the Animal-Based Biodiesel Feedstock 2007 MBE4000

The biodiesel blends showed an increase in fuel consumption with increasing levels of biodiesel. This is consistent with expectations based on the lower energy density of the biodiesel. The fuel consumption differences were generally greater for the soy-based biodiesel in comparison with the animal-based biodiesel for the 2006 Cummins engine, but not for the 2007 MBE4000 engine. The changes in fuel consumption for the soy-based biodiesel blends for the 2006 Cummins engine range from 1.4 to 1.8% for the B20 to 6.8 to 9.8% for the B100. The changes in fuel consumption for the animal-based biodiesel blends for the 2006 Cummins engine range from no statistical difference to 2.6% for the B20 to 4.4 to 6.7% for the B100. For the 2007 MBE4000 engine, the differences in fuel consumption ranged from 2.5% to no change for the B50 and lower blends, while the increases for the B100 blends ranged from 5.6 to 8.3%.

Table 5-6. Brake Specific Fuel Consumption Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Soy-based		Animal-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	1.8%	0.093	1.2%	0.404	1.0%	0.121	0.2%	0.000
	B50	5.1%	0.001	3.1%	0.005	2.5%	0.083	1.2%	0.008
	B100	9.8%	0.000	6.7%	0.000	8.3%	0.000	8.1%	0.000
FTP	B5	0.3% (Mit)	0.228	2.9%	0.031	0.3%	0.031	0.5%	0.015
	B10	0.3% (Mit)	0.167						
	B20	1.4%	0.001	1.4%	0.145	1.0%	0.016	0.3%	0.182
	B50	3.1%	0.000	1.8%	0.038	1.7%	0.034	0.4%	0.069
	B100	6.8%	0.000	4.4%	0.001	5.6%	0.000	8%	0.000
40 mph Cruise	B5	1.9%	0.065						
	B20	1.8%	0.001						
	B50	3.8%	0.000						
	B100	8.4%	0.000						
50 mph Cruise	B5	0.3%	0.690						
	B20	1.6%	0.002	2.6%	0.010	1.5%	0.002	0.2%	0.301
	B50	3.8%	0.000	3.5%	0.000	1.9%	0.081	0.6%	0.036
	B100	8.0%	0.000	5.9%	0.000	5.9%	0.000	7.8%	0.000

6.0 Renewable Diesel and GTL Results

6.1 NO_x Emissions

Renewable and GTL diesel fuels are considered to be one potential strategy for meeting the low carbon fuel standard requirements as well as mitigating any NO_x increases seen with increasing levels of biodiesel. NO_x emissions for the different blends and different test cycles for the renewable diesel fuel and the GTL diesel fuel are shown in Figure 6-1 and Figure 6-2, respectively, on a g/bhp-hr basis. These fuels were only characterized for 2006 Cummins ISM engine. The GTL diesel fuel was tested primarily for inclusion in the NO_x mitigation testing discussed below and, as such, it was only characterized over the FTP, and not the full range of cycles. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination. The error bars represent one standard deviation on the average value.

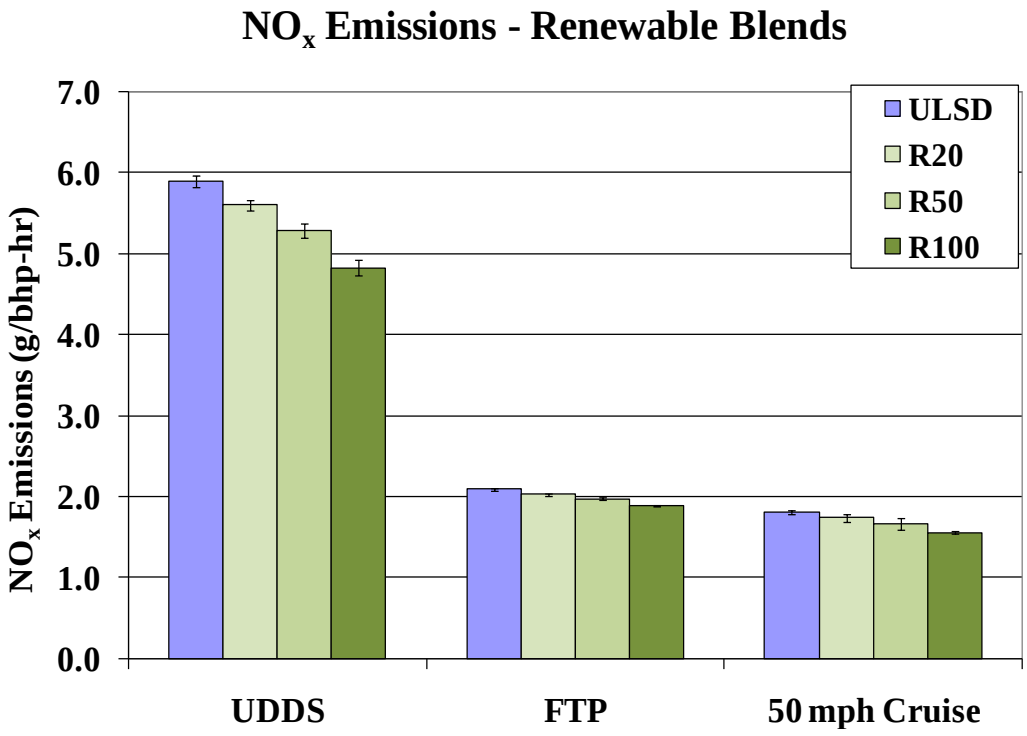


Figure 6-1. Average NO_x Emission Results for the Renewable Blends for 2006 Cummins ISM engine

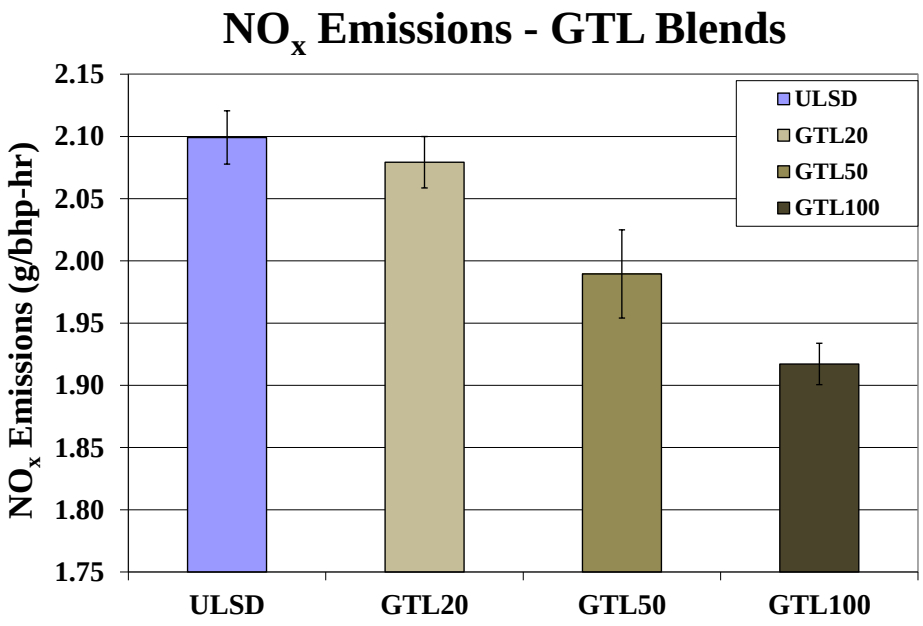


Figure 6-2. Average NO_x Emission Results for the GTL Blends for 2006 Cummins ISM engine

NO_x emissions showed a trend of decreasing emissions with increasing levels of the renewable and GTL diesel fuels. Table 6-1 shows the percentage differences for the different renewable blends for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

Table 6-1. NO_x Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	Renewable		GTL	
		% Difference	P-values	% Difference	P-values
UDDS	20% blend	-4.9%	0.000		
	50% blend	-10.2%	0.000		
	100% blend	-18.1%	0.000		
FTP	20% blend	-2.9%	0.000	-0.9%	0.053
	50% blend	-5.4%	0.000	-5.2%	0.000
	100% blend	-9.9%	0.000	-8.7%	0.000
50 mph Cruise	20% blend	-3.8%	0.007		
	50% blend	-7.8%	0.000		
	100% blend	-14.2%	0.000		

For the renewable and GTL diesel fuels, the results show a steady decrease in NO_x emissions with increasingly higher levels of renewable diesel fuel. Over the FTP cycle, the NO_x reductions for the renewable and GTL diesel were comparable. Larger emissions reductions were found over the UDDS and Cruise cycles, where only the renewable diesel fuel was tested. It should be noted that the magnitude of the impact NO_x reductions over the 50 mph cruise cycle was impacted by the differing engine operation condition discussed in Section 2.7.

The reductions in NO_x for the renewable diesel fuel are comparable to those found in previous studies of heavy-duty engines (Rothe et al. 2005; Kleinschek 2005; Aatola et al. 2008) and busses (Kuronen et al. 2007; Erikkila and Nylund) on a 100% renewable blend. The reduction of 5.4% for the R50 blend on the FTP is similar to the 5% reduction seen by Rothe et al. (2005) for a 50% blend on a heavy-duty engine. The NO_x reductions for the renewable diesel are also consistent with model predictions based on the EPA's Unified Model (Hodge, 2009). In previous studies, statistically significant NO_x reductions for the renewable diesel were not found for all testing configurations, however, including some lower blend levels (Aatola et al. 2008; Erkkila and Nylund) and for light-duty vehicles (Rantanen et al. 2005).

In comparison with the biodiesel feedstocks, the levels of reduction are less than the corresponding increases in NO_x seen for the soy-based biodiesel, but are more comparable to the increases seen for the animal-based biodiesel blends. With respect to NO_x mitigation, this suggests that the renewable and GTL diesel fuel levels will need to be slightly greater than the corresponding biodiesel level in order to mitigate the associated NO_x increase, as discussed in further detail below. This is especially true for the soy-based biodiesel blends.

Only the renewable diesel fuel was tested over cycles with different power levels, so trends of NO_x emissions as a function of power could only be examined for this fuel. NO_x emissions are plotted against cycle average power in Figure 6-3. These data show that NO_x emissions increase with average cycle power, as with the results in section 5.1. The NO_x differential between the CARB ULSD and the different blends was not a function of either average cycle power or fuel consumption, as shown in Figure 6-4 and in Figure 6-5, respectively. These Figures show that the lowest reductions in NO_x with the renewable fuel blend were found for the FTP certification cycle, which was in the middle of the power range examined.

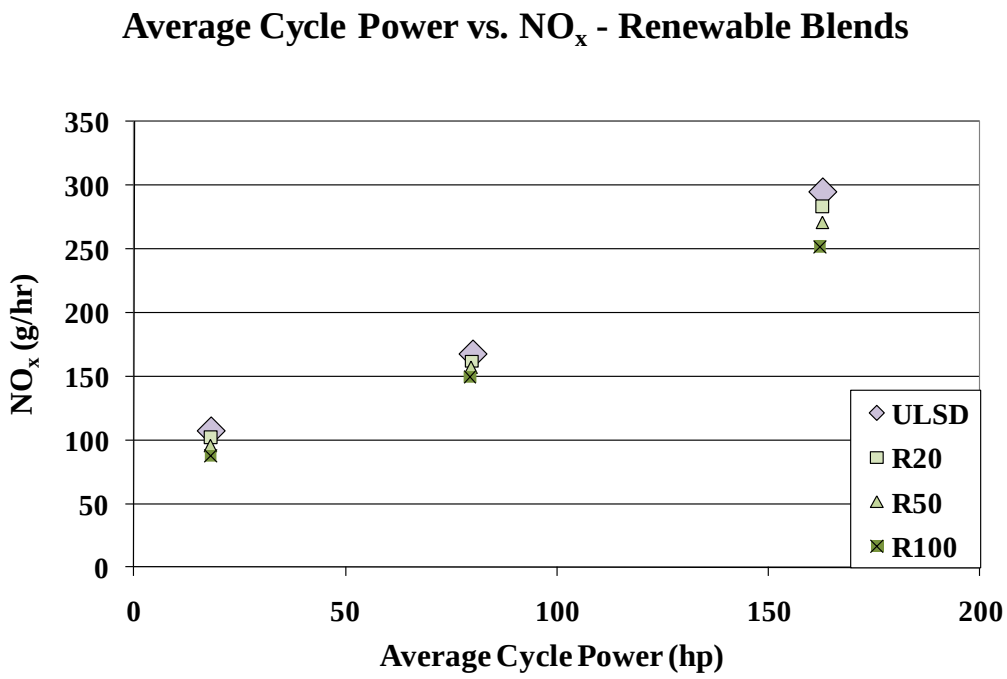


Figure 6-3. Average Cycle Power vs. NO_x Emissions for Testing on the Renewable Blends for 2006 Cummins ISM engine

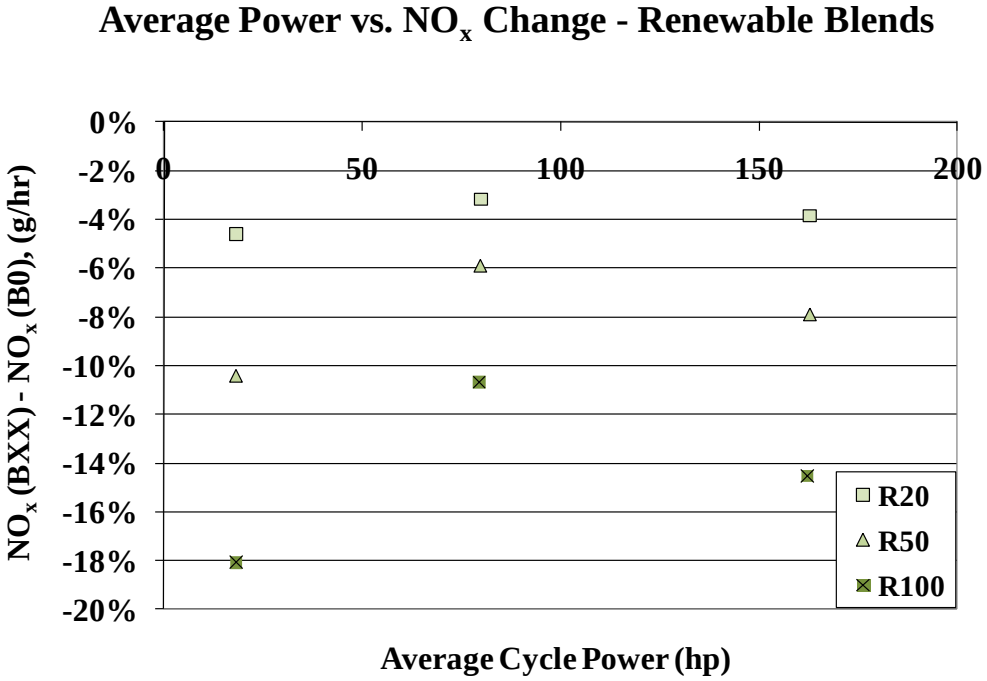


Figure 6-4. Average Cycle Power vs. NO_x Emissions Change for Testing on the Renewable Blends for 2006 Cummins ISM engine

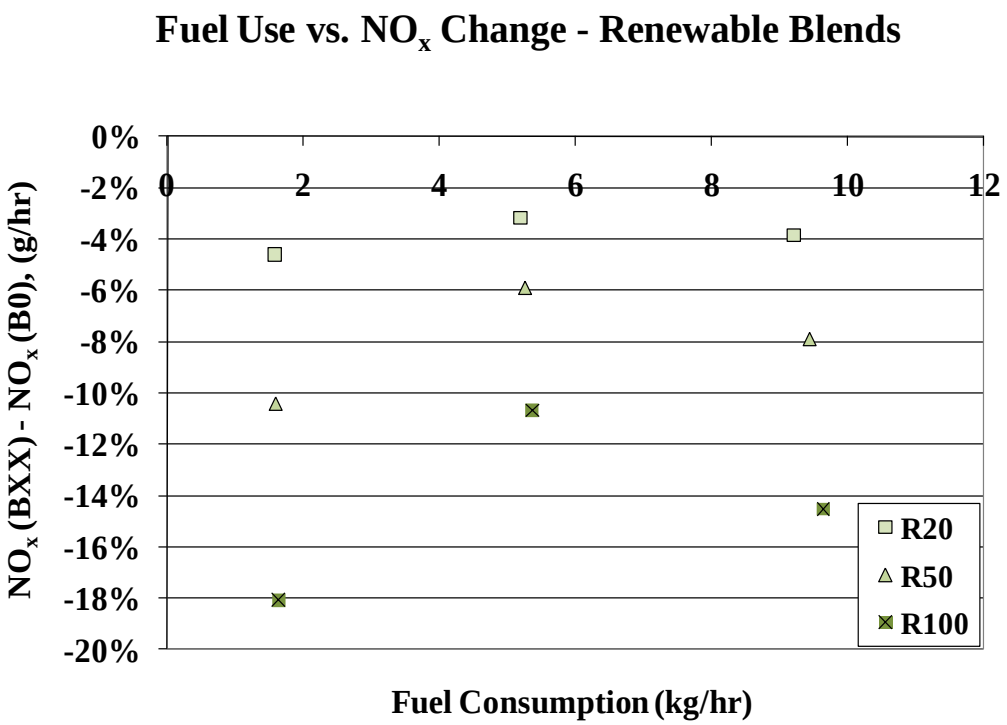


Figure 6-5. Fuel Consumption vs. NO_x Emissions Change for Testing on the Renewable Blends for 2006 Cummins ISM engine

6.2 PM Emissions

The PM emission results for the testing with the renewable and GTL diesel are presented in Figure 6-6 and Figure 6-7, respectively, on a g/bhp-hr basis. Table 6-2 shows the percentage differences for the renewable and GTL diesel for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

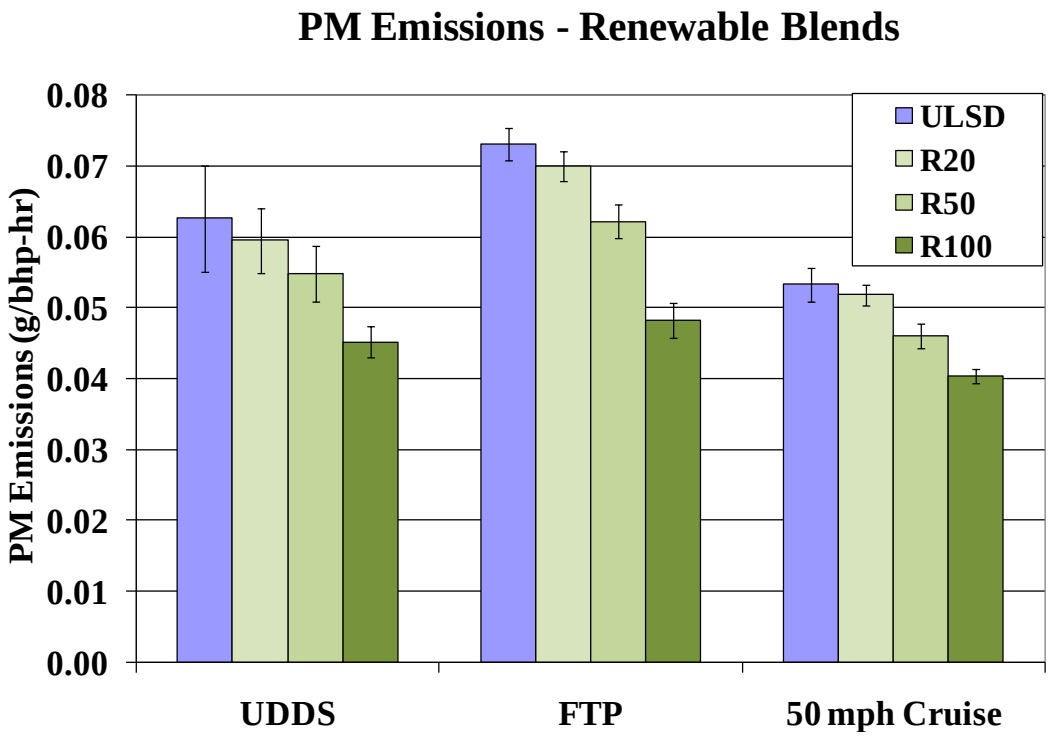


Figure 6-6. Average PM Emission Results for the Renewable Blends for 2006 Cummins ISM engine

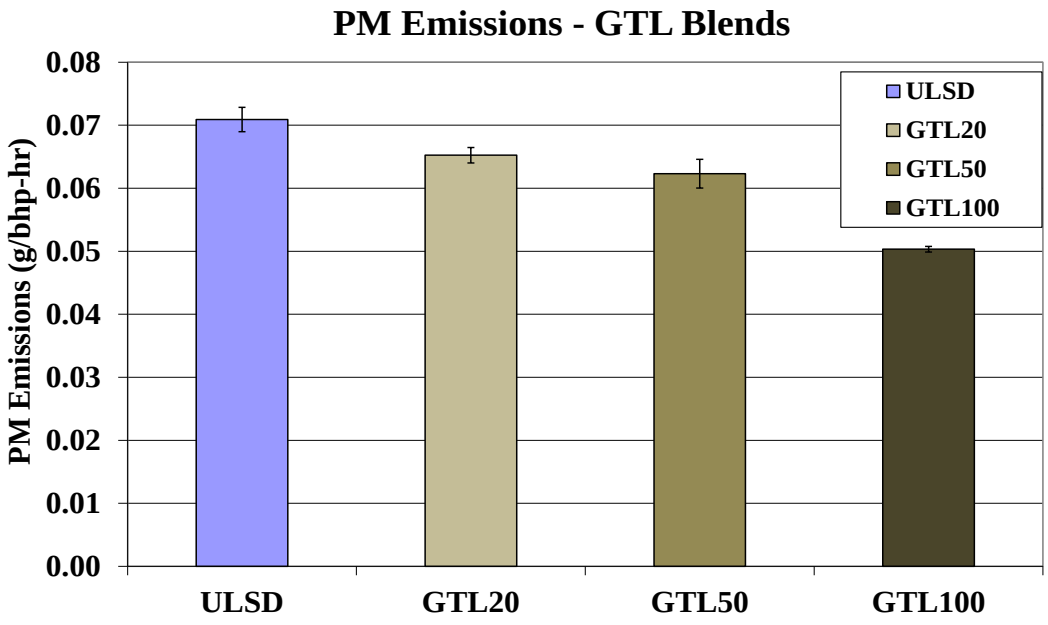


Figure 6-7. Average PM Emission Results for the GTL Blends for 2006 Cummins ISM engine

PM emissions showed consistent and significant reductions for the renewable and GTL blends, with the magnitude of the reductions increasing with blend level. The reductions for the renewable diesel were statistically significant for the higher blends and ranged from 12-15% for the R50 and from 24-34% for the R100. A statistically significant 4% reduction was also found for the R20 over the FTP. The GTL fuel showed a statistically significant reduction over the FTP, with reductions ranging from 8% for the 20% blend to 29% for the 100% blend. Similar reductions are found for the UDDS, FTP, and Cruise cycles for the renewable diesel indicating that cycle load does not have a significant impact on the PM reductions. The PM reductions for the renewable diesel are consistent with model predictions based on the EPA's Unified Model (Hodge, 2009).

Table 6-2. PM Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	Renewable		GTL	
		% Difference	P-values	% Difference	P-values
UDDS	20% blend	-5%	0.401		
	50% blend	-12%	0.044		
	100% blend	-28%	0.000		
FTP	20% blend	-4%	0.023	-8%	0.000
	50% blend	-15%	0.000	-12%	0.000
	100% blend	-34%	0.000	-29%	0.000
50 mph Cruise	20% blend	-3%	0.220		
	50% blend	-14%	0.000		
	100% blend	-24%	0.000		

PM emissions showed a trend of increasing emissions as a function of average cycle power for the various renewable blends, as presented in Figure 6-8. The PM differential between the CARB ULSD and the different blends was not a function of either average cycle power or fuel consumption, as shown in Figure 6-9 and in Figure 6-10, respectively. These Figures show that the largest reductions in PM with the renewable fuel blends were found for the FTP certification cycle, which was in the middle of the power range examined. Note that the corresponding NO_x reductions were the smallest for the FTP, as discussed above, consistent with a classical tradeoff between NO_x and PM emissions.

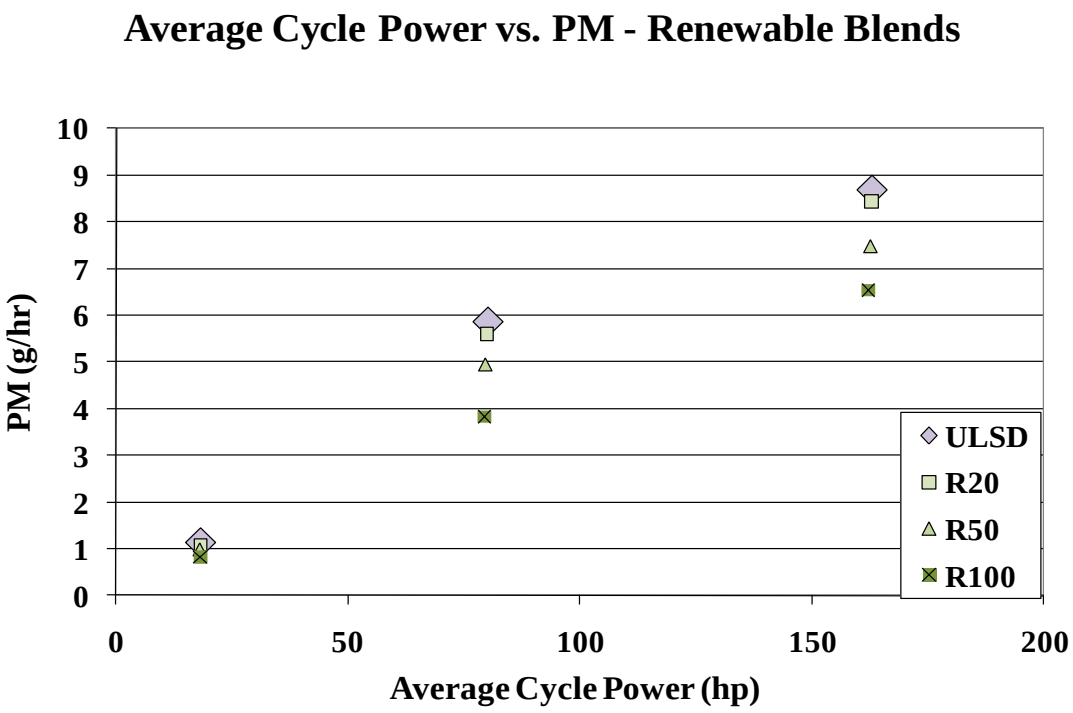


Figure 6-8. Average Cycle Power vs. PM Emissions for Testing on the Renewable Blends for 2006 Cummins ISM engine

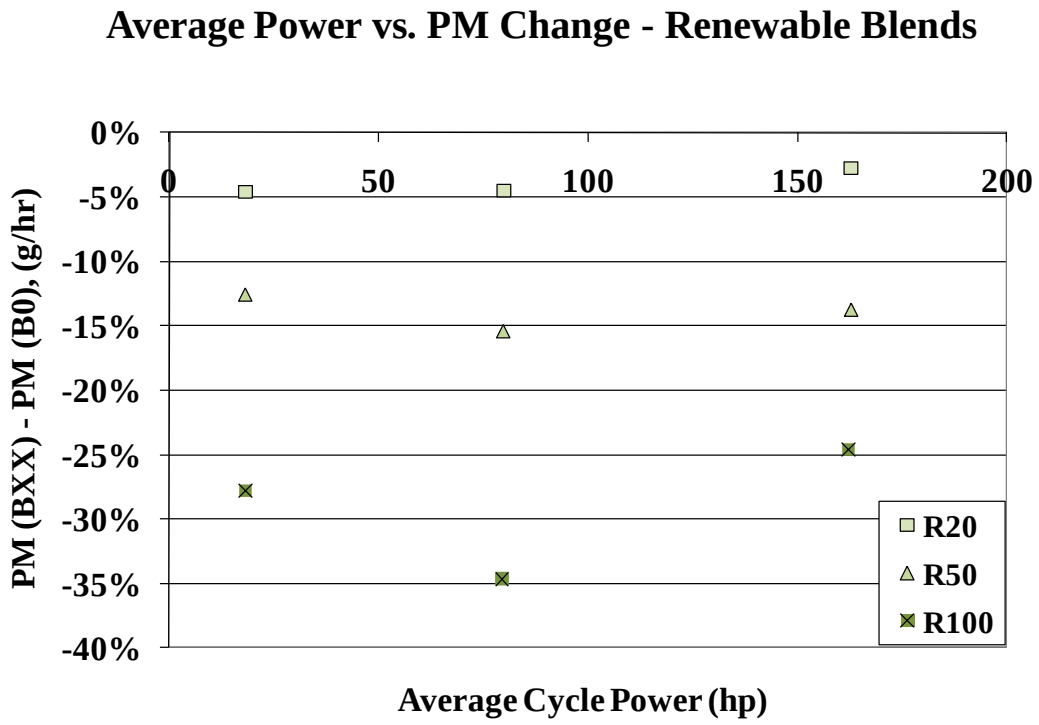


Figure 6-9. Average Cycle Power vs. PM Emissions Change for Testing on the Renewable Blends for 2006 Cummins ISM engine

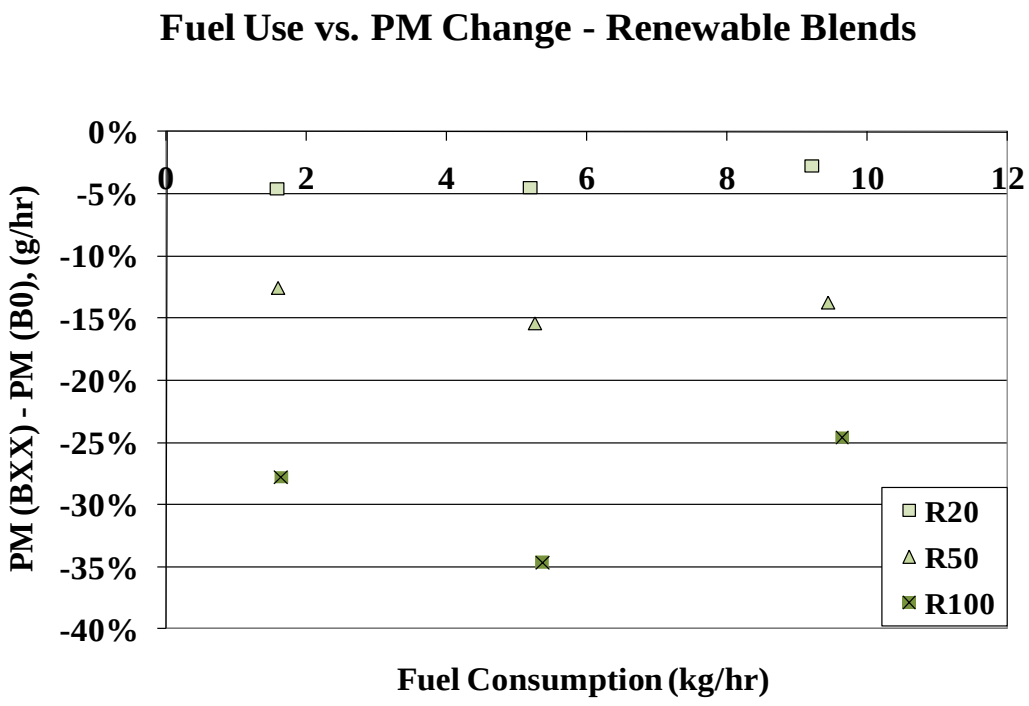


Figure 6-10. Fuel Consumption vs. PM Emissions Change for Testing on the Renewable Blends for 2006 Cummins ISM engine

6.3 THC Emissions

The THC emission results for the testing with the renewable and GTL diesels are presented in Figure 6-11 and Figure 6-12, respectively, on a g/bhp-hr basis. Table 6-3 shows the percentage differences for the renewable and GTL diesels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

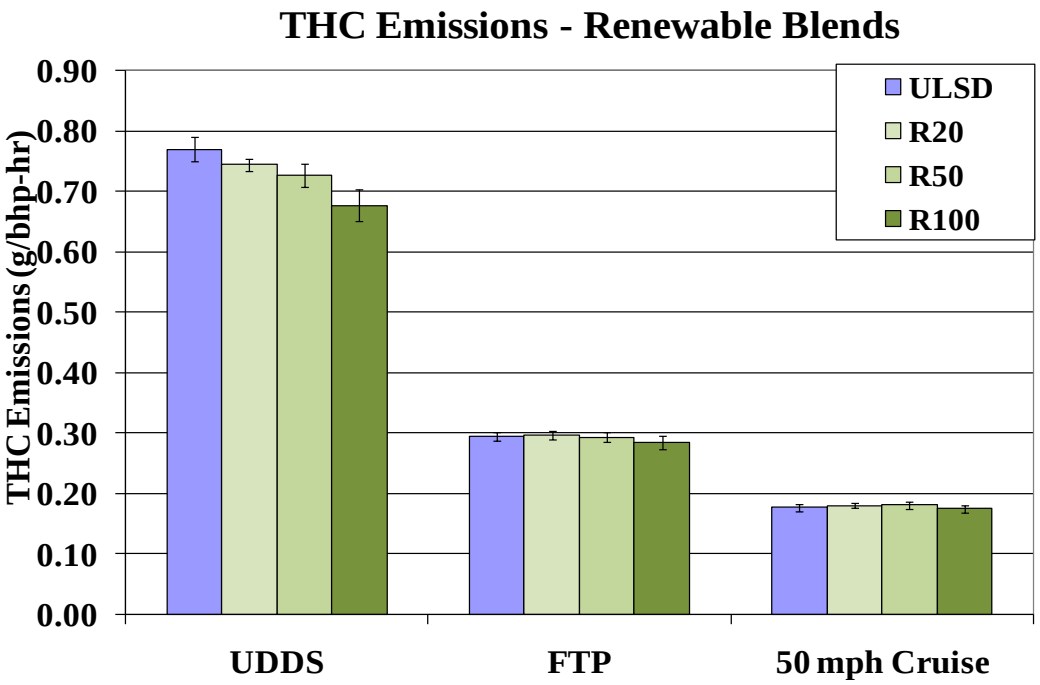


Figure 6-11. Average THC Emission Results for the Renewable Blends for 2006 Cummins ISM engine

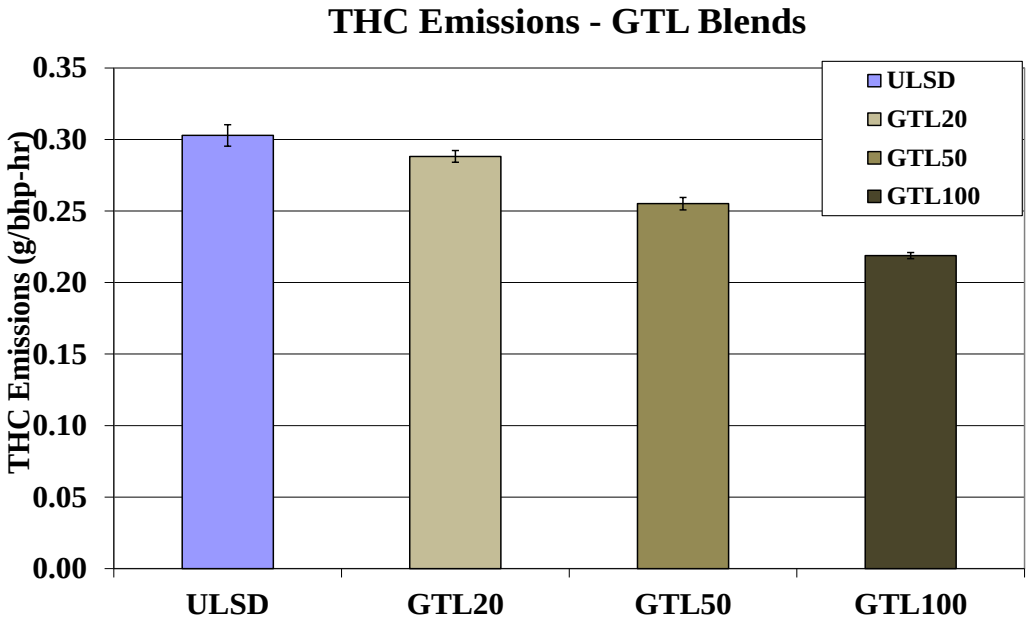


Figure 6-12. Average THC Emission Results for the GTL Blends for 2006 Cummins ISM engine

For the THC emissions, the GTL fuel showed statistically significant reductions over the FTP that increased with increasing blend level. These reductions ranged from 5% for the 20% blend to

28% for the 100% blend. The renewable diesel did not show consistent trends for THC emissions over the different test cycles. Statistically significant THC reductions were found for the renewable diesel fuel for the lowest load UDDS cycle, with the THC reductions increasing with increasing levels of the renewable diesel fuel. For the other cycles/blend levels, statistically significant reductions were only found for the R100 blend over the FTP. In several previous studies of the renewable diesel fuel, more consistent and robust reductions in THC as a function of increasing blend level have been found (Rothe et al. 2005; Kleinschek 2005; Aatola et al. 2008; Rantanen et al. 2008). These differences from the current study could be related to differences in the distillation properties of the fuels used in the different studies. In the European studies with the NExBTL fuel, a summer grade was used, while a winter grade NExBTL was used in the current study. 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. In fact, predictions with the EPA's Unified Model show that there should not be any significant differences between the THC emissions for the CARB fuel in comparison with the NExBTL winter blend used in the study, whereas the model predicts more significant and measureable reductions between the European base diesel fuel and the NExBTL summer blends used in the previous studies (Hodge, 2009). It should also be noted that in some cases in earlier studies, statistically significant reductions were not identified due to low THC emission levels from the engine or for lower blend levels (Kuronen et al. 2007; Erikkila and Nylund).

Table 6-3. THC Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	Renewable		GTL	
		% Difference	P-values	% Difference	P-values
UDDS	20% blend	-3%	0.018		
	50% blend	-6%	0.002		
	100% blend	-12%	0.000		
FTP	20% blend	0%	0.719	-5%	0.000
	50% blend	0%	0.777	-16%	0.000
	100% blend	-4%	0.057	-28%	0.000
50 mph Cruise	20% blend	2%	0.207		
	50% blend	2%	0.230		
	100% blend	-1%	0.510		

THC emissions showed a trend of increasing emissions as a function of average cycle power for the various renewable blends, as presented in Figure 6-13. The THC differential between the CARB ULSD and the different blends showed a trend of smaller reductions for cycles with higher average power levels and greater fuel consumption, as shown in Figure 6-14 and in Figure 6-15, respectively. It should be noted, however, that the reductions in THC emissions for the FTP and 50 mph Cruise were only statistically significant for the R100 fuel over the FTP. Thus, any trends are primarily driven by the larger emissions reductions for the lightly loaded UDDS cycle.

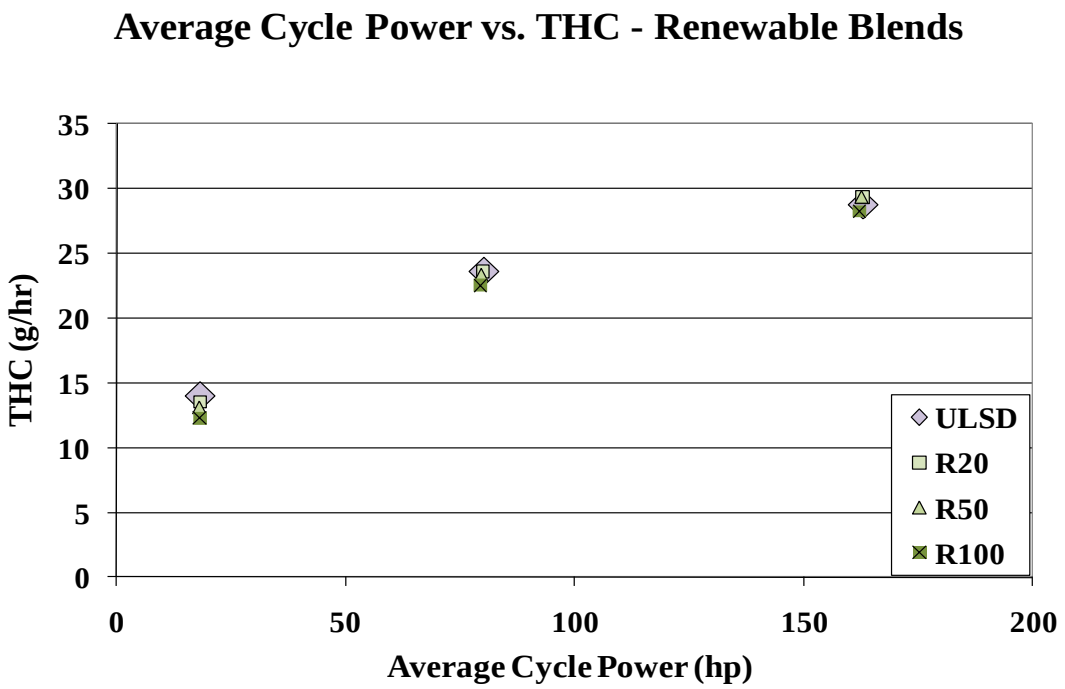


Figure 6-13. Average Cycle Power vs. THC Emissions for Testing on the Renewable Blends for 2006 Cummins ISM engine

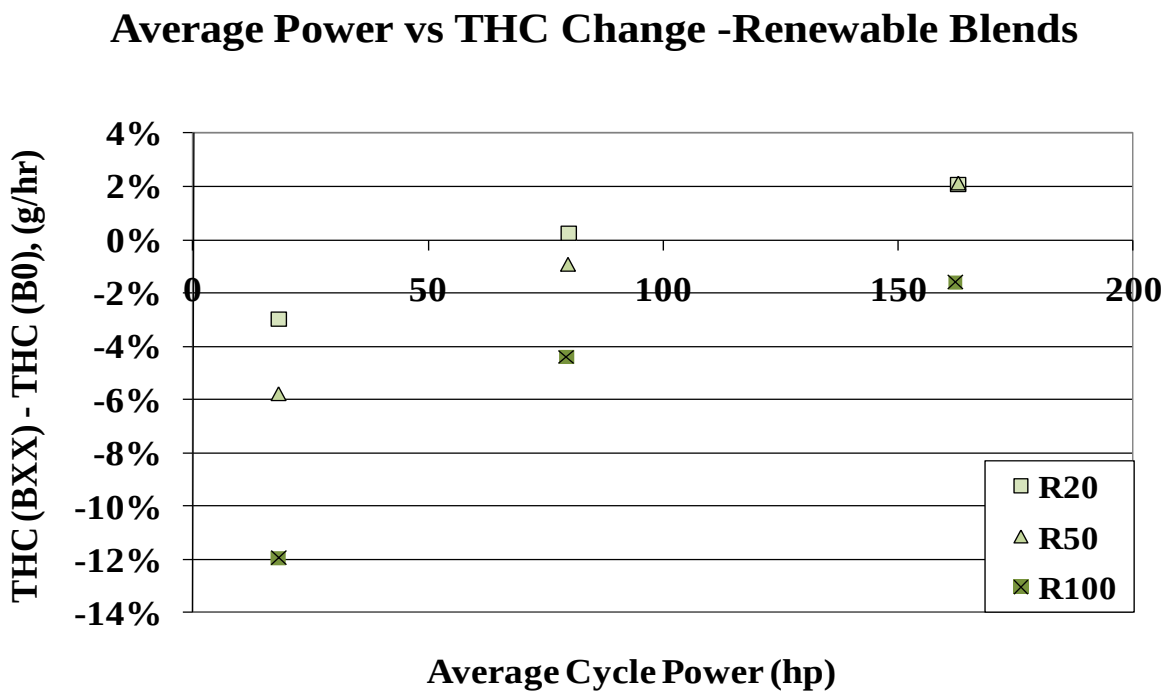


Figure 6-14. Average Cycle Power vs. THC Emissions Change for Testing on the Renewable Blends for 2006 Cummins ISM engine

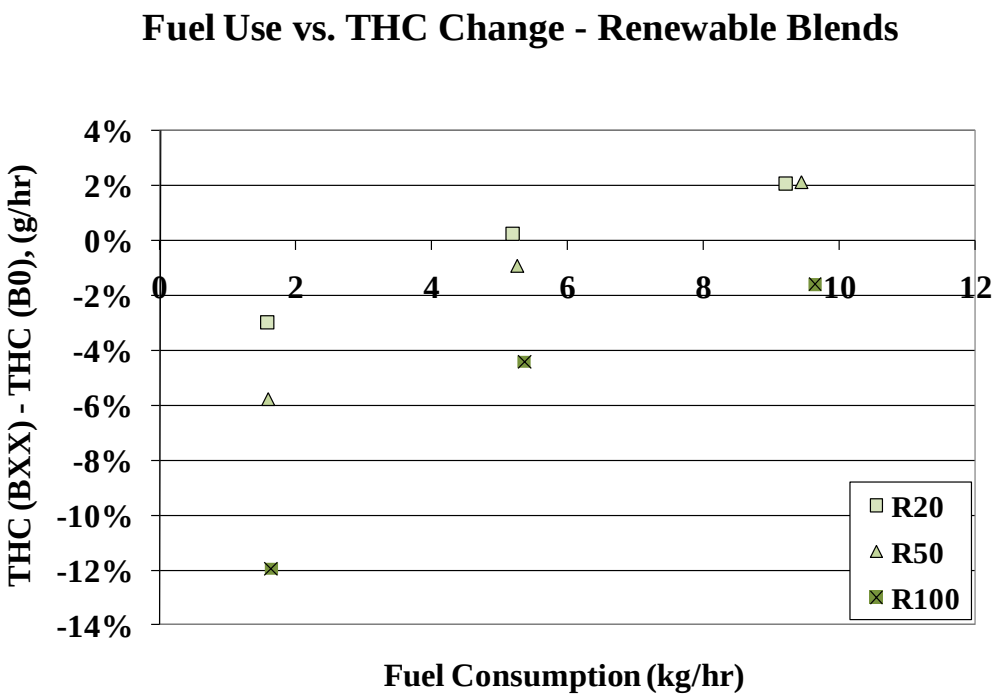


Figure 6-15. Fuel Consumption vs. THC Emissions Change for Testing on the Renewable Blends for 2006 Cummins ISM engine

6.4 CO Emissions

The CO emission results for the testing with the renewable and GTL diesels are presented in Figure 6-16 and Figure 6-17, respectively, on a g/bhp-hr basis. Table 6-4 shows the percentage differences for the renewable and GTL diesels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

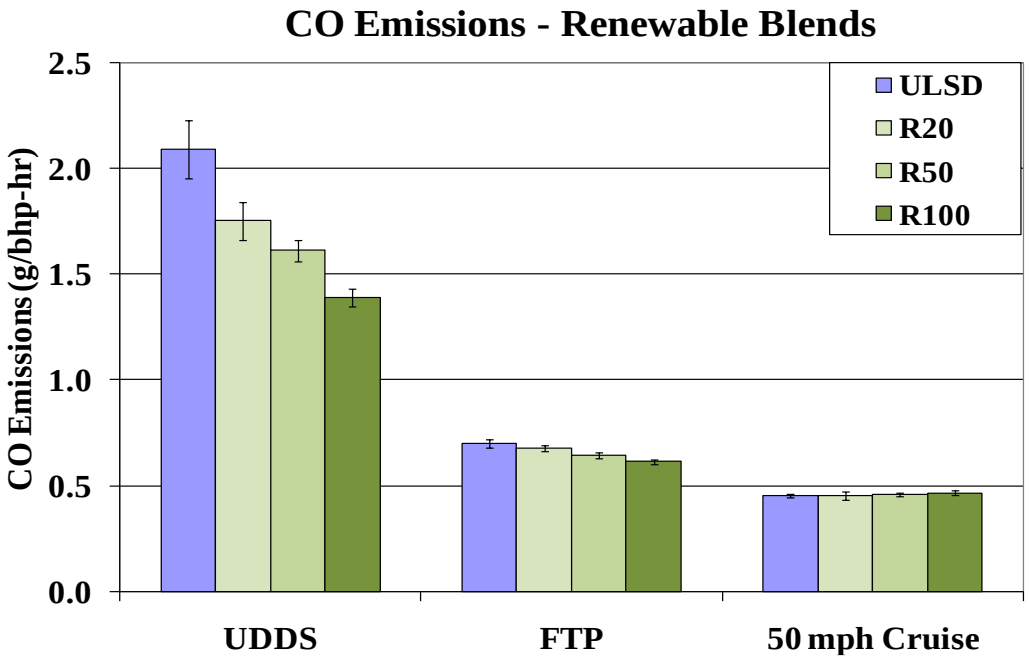


Figure 6-16. Average CO Emission Results for the Renewable Blends for 2006 Cummins ISM engine

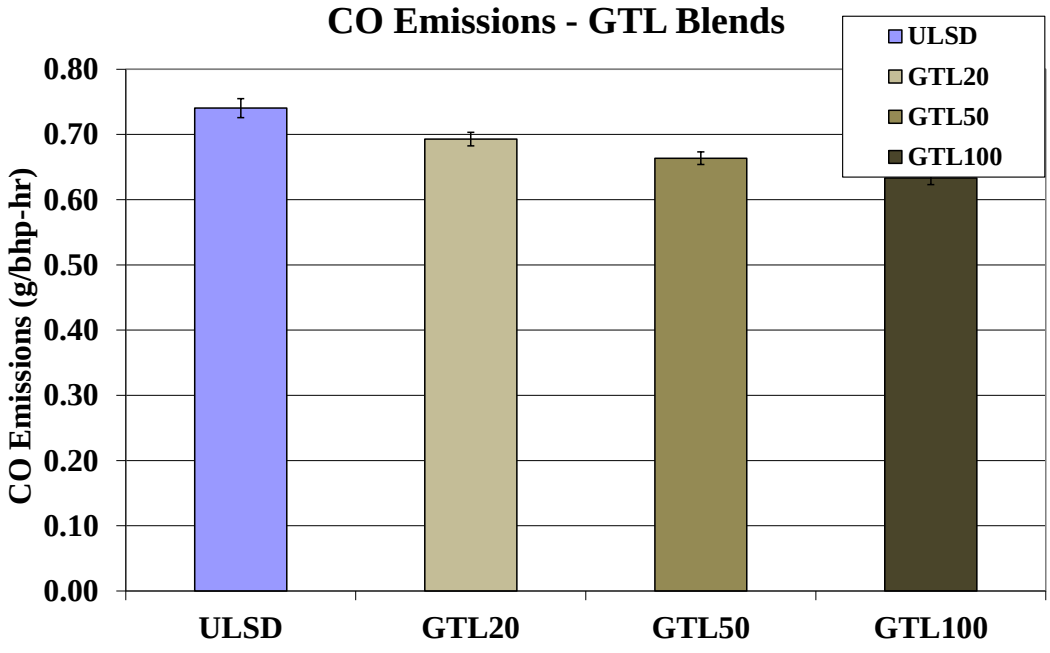


Figure 6-17. Average CO Emission Results for the GTL Blends for 2006 Cummins ISM engine

Reductions in CO emissions with the renewable diesel fuel were found for the UDDS and FTP cycles, but not for the cruise cycle, except for the R100 level. Over these cycles, the percentage reductions increased with increasing renewable diesel fuel blend. The GTL fuel also showed similar reductions over the FTP. The comparisons of CO emissions over the 50 mph cruise were obscured by the changes in engine operation that were seen for that cycle, as explained under section 2.7. The reductions in CO emissions as a function of renewable blend level for the UDDS and the FTP are within the range seen in previous studies of renewable blends in engine and chassis dynamometer tests (Rothe et al. 2005; Kleinschek 2005; Aatola et al. 2008; Rantanen et al. 2008; Kuronen et al. 2007; Erikkila and Nylund).

Table 6-4. CO Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	Renewable		GTL	
		% Difference	P-values	% Difference	P-values
UDDS	20% blend	-16%	0.000		
	50% blend	-23%	0.000		
	100% blend	-33%	0.000		
FTP	20% blend	-4%	0.022	-6%	0.000
	50% blend	-8%	0.000	-10%	0.000
	100% blend	-12%	0.000	-14%	0.000
50 mph Cruise	20% blend	0%	0.831		
	50% blend	1%	0.234		
	100% blend	3%	0.022		

CO emissions showed a trend of increasing emissions as a function of average cycle power for the various renewable blends, as presented in Figure 6-13. The CO differential between the CARB ULSD and the different blends showed a trend of smaller reductions for cycles with higher average power levels and greater fuel consumption, as shown in Figure 6-14 and in Figure 6-15, respectively. These trends are similar to those seen for the THC emissions for the renewable blends. The trend is slightly more robust for the CO emissions since the emissions reductions for both the UDDS and FTP are statistically significant, as well as the reductions for the R100 blend for the 50 mph cruise. Again, however, the comparisons for CO emissions over the 50 mph cruise were obscured by the changes in engine operation that were seen for that cycle.

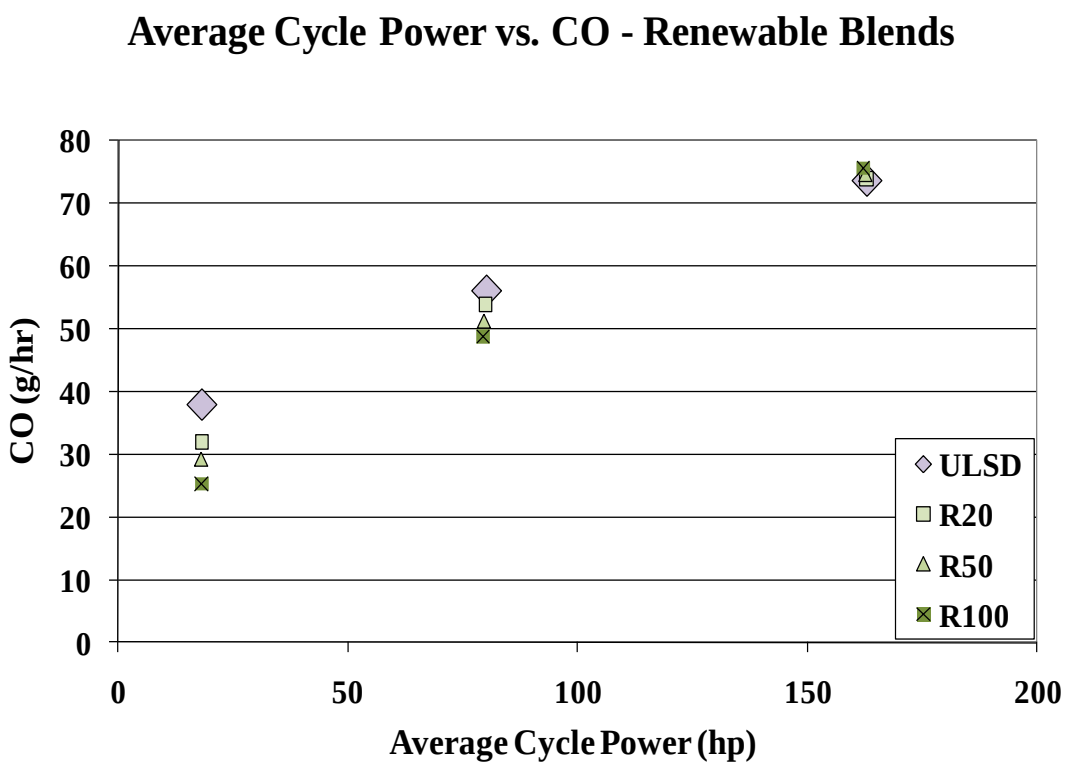


Figure 6-18. Average Cycle Power vs. CO Emissions for Testing on the Renewable Blends for 2006 Cummins ISM engine

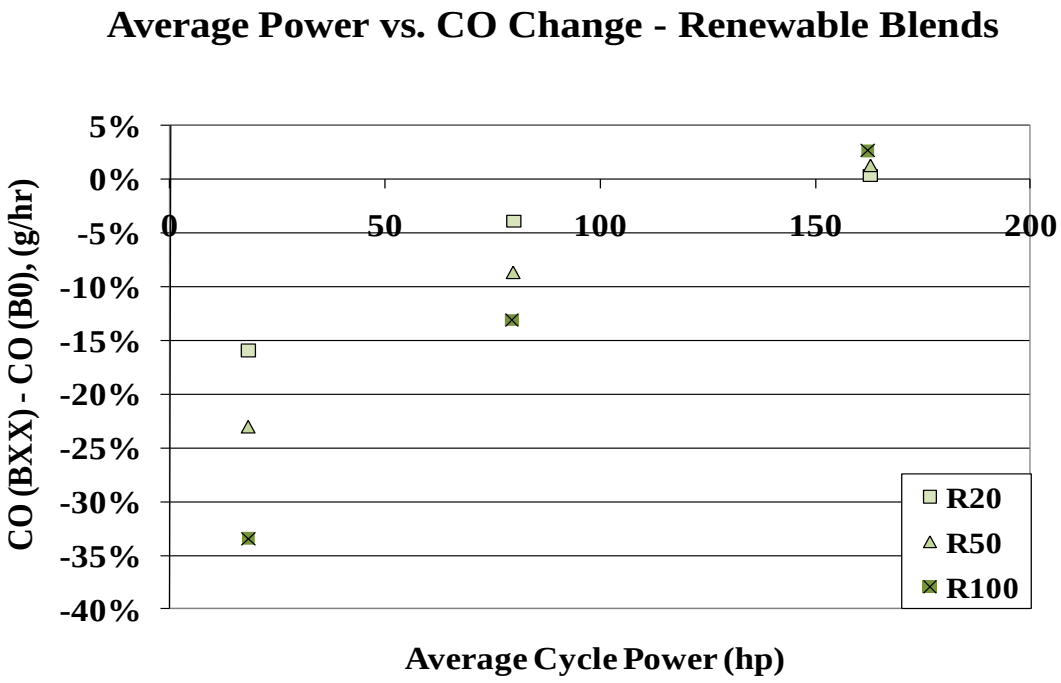


Figure 6-19. Average Cycle Power vs. CO Emissions Change for Testing on the Renewable Blends for 2006 Cummins ISM engine

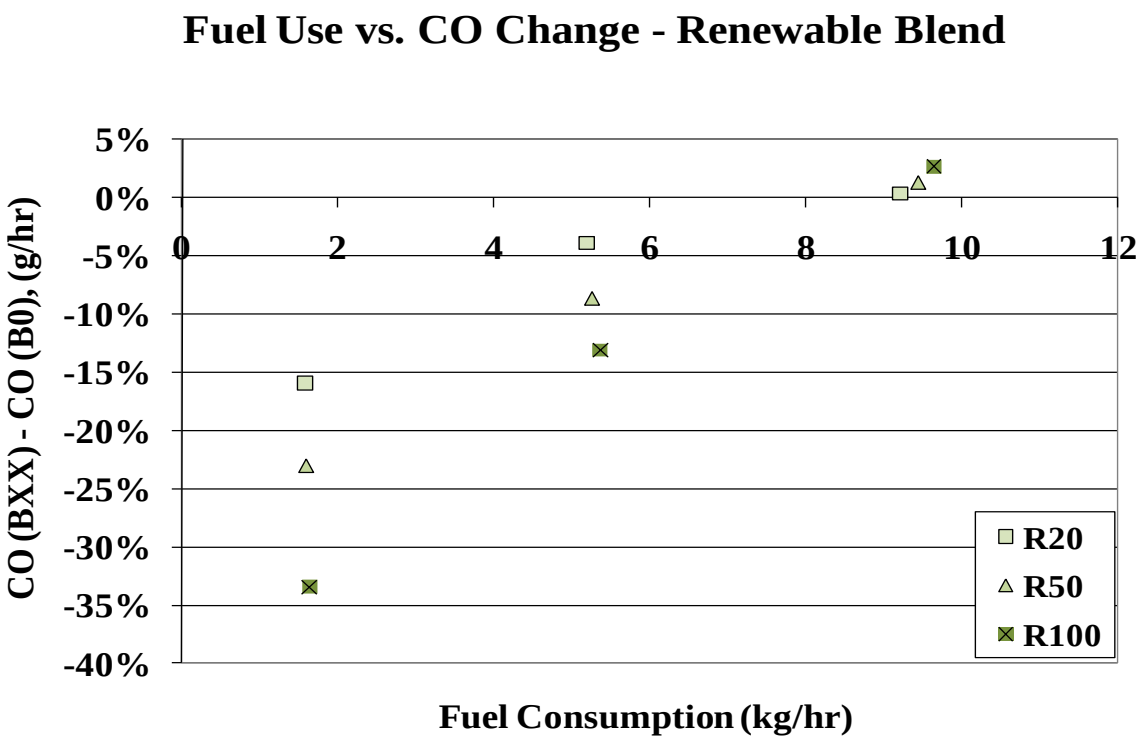


Figure 6-20. Fuel Consumption vs. CO Emissions Change for Testing on the Renewable Blends for 2006 Cummins ISM engine

6.5 CO_2 Emissions

The CO_2 emission results for the testing with the renewable and GTL diesels are presented in Figure 6-21 and Figure 6-22, respectively, on a g/bhp-hr basis. Table 6-5 shows the percentage differences for the renewable and GTL diesels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

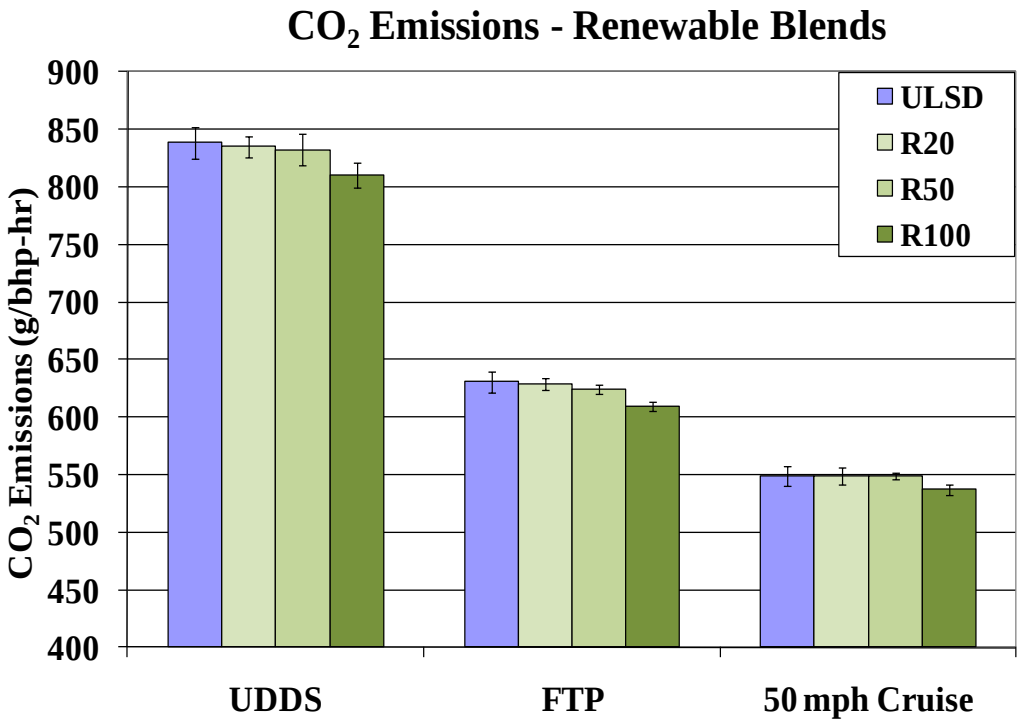


Figure 6-21. Average CO_2 Emission Results for the Renewable Blends for 2006 Cummins ISM engine

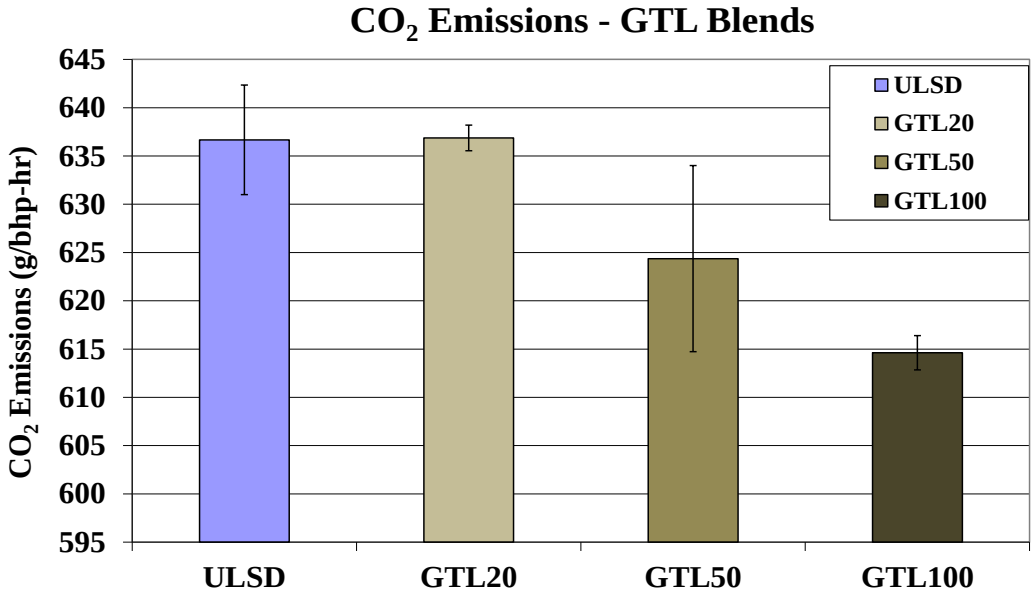


Figure 6-22. Average CO_2 Emission Results for the GTL Blends for 2006 Cummins ISM engine

The CO_2 emissions for the neat or 100% blend of renewable diesel and the 50% and 100% blends of the GTL fuels were lower than those for the CARB ULSD for each of the test cycles. This slight reduction in CO_2 emissions is consistent and comparable to previous studies of the renewable diesel fuel (Aatola et al., 2008; Kleinschek 2005; Kuronen et al. 2007; Rantanen et al. 2005). The reductions in CO_2 emissions for the renewable diesel can probably be attributed to the lower carbon weight fraction for the renewable diesel (84.8%), due to its paraffinic nature, compared to the CARB diesel (86.1%). There were no statistically significant CO_2 differences between the CARB ULSD and the 20% blend of the renewable or GTL fuels or the 50% blend of the renewable blend.

Table 6-5. CO_2 Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	Renewable		GTL	
		% Difference	P-values	% Difference	P-values
UDDS	20% blend	-0.4%	0.595		
	50% blend	-0.7%	0.448		
	100% blend	-3.3%	0.002		
FTP	20% blend	-0.3%	0.652	0.0%	0.933
	50% blend	-1.0%	0.124	-1.9%	0.001
	100% blend	-3.4%	0.000	-3.5%	0.000
50 mph Cruise	20% blend	0.0%	0.972		
	50% blend	0.0%	0.996		
	100% blend	-2.1%	0.011		

6.6 Brake Specific Fuel Consumption

The brake specific fuel consumption emission results for the testing with the renewable and GTL diesels are presented in Figure 6-23 and Figure 6-24 respectively, on a gal./bhp-hr basis. The brake specific fuel consumption was determined via carbon balance using the carbon weight fractions and densities of each fuel. Table 6-6 shows the percentage differences for the renewable and GTL diesels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

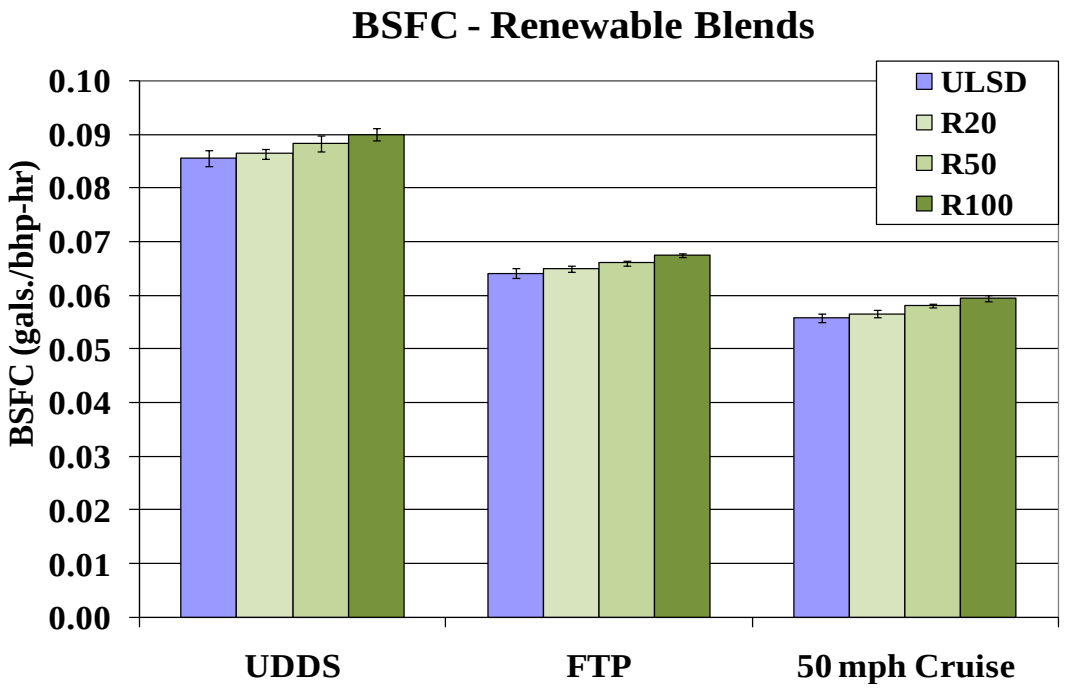


Figure 6-23. Average Brake Specific Fuel Consumption Results for the Renewable Blends for 2006 Cummins ISM engine

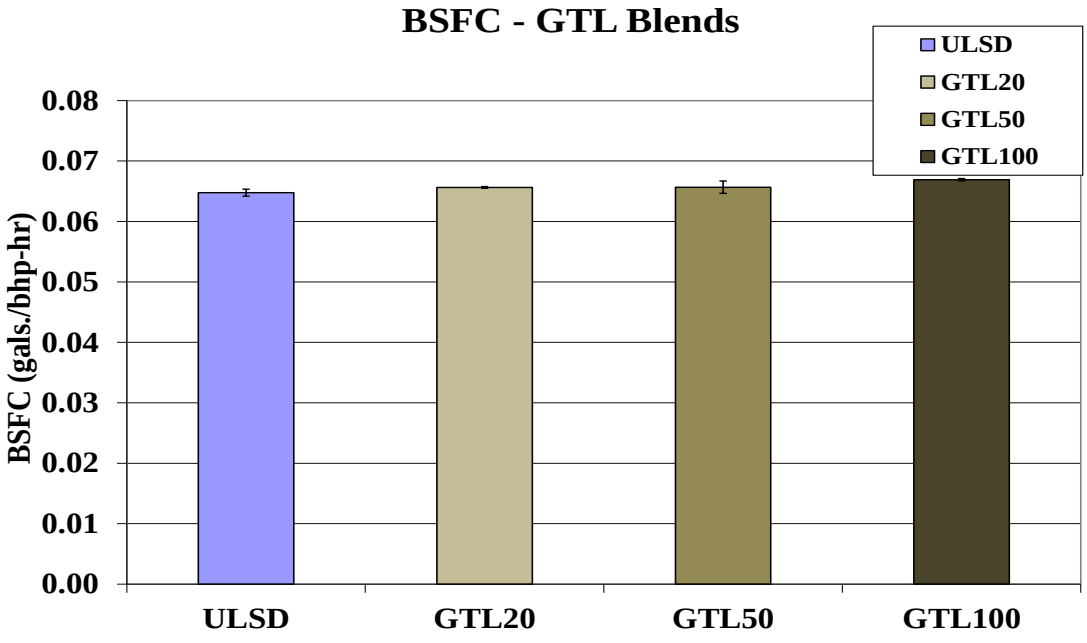


Figure 6-24. Average Brake Specific Fuel Consumption for the GTL Blends for 2006 Cummins ISM engine

The brake specific fuel consumption data showed increasing fuel consumption with increasing levels of renewable and GTL diesel fuel. The increases in fuel consumption range from 1.0-1.4% for the R20 and 5.1 to 6.6% for the R100. The increases in fuel consumption with blend level are slightly higher for the cruise cycle compared to the lower load UDDS and FTP, although this comparison is impacted the engine operational issues seen on the cruise cycle. The fuel consumption differences are consistent with the results from previous studies (Rothe et al. 2005; Kleinschek 2005; Aatola et al. 2008; Rantanen et al. 2008; Kuronen et al. 2007; Erikkila and Nylund), and can be attributed to the lower density or lower energy density of the renewable fuel compared to the CARB baseline fuel. The brake specific fuel consumption increases for the GTL ranged from 1.3% for the 20% blend to 3.3% for the 100% blend.

Table 6-6. Brake Specific Fuel Consumption Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	Renewable		GTL	
		% Difference	P-values	% Difference	P-values
UDDS	20% blend	1.0%	0.255		
	50% blend	3.1%	0.007		
	100% blend	5.1%	0.000		
FTP	20% blend	1.1%	0.117	1.3%	0.001
	50% blend	2.9%	0.001	1.4%	0.008
	100% blend	5.2%	0.000	3.3%	0.000
50 mph Cruise	20% blend	1.4%	0.107		
	50% blend	4.0%	0.000		
	100% blend	6.6%	0.000		

7.0 NO_x Mitigation Results

The mitigation of the NO_x emissions is one of the most critical elements of this program. For this program, various strategies were examined. These included formulations with additives and renewable and diesel fuels. For the NO_x mitigation formulations, a subset of fuel analyses were conducted, including density/API gravity and cetane number. These analyses are provided in Table 7-1. The results show elevated cetane numbers for the NO_x mitigation formulations with DTBP and 2-EHN cetane improver and for higher blends with the renewable diesel. The densities are consistent with roughly linear blending between the different fuel components that were blended.

Table 7-1. Selected Fuel Properties for NO_x Mitigation Formulations.

Blend	API at 60^0F	Sp.Gr at 60^0F	Cetane Number
	ASTM D4052		D613
CARB	39.3		55.8
B5-soy			56
B10-soy	38.4	0.833	54.7
B20-soy			56
B20-S 1% DTBP	37.3	0.838	71.4
B10-S 1% DTBP	38.5	0.832	74.2
B20-S 1% 2-EHN	37	0.840	73.0
B5-S 1% 2-EHN	38.8	0.831	71.5
R80/B20-soy	46.1	0.797	64.8
CARB25/R55/B20-S	43.2	0.810	62.9
CARB70/R20/B10-S	40.5	0.823	58.3
CARB75/R20/B5-S	41	0.820	60.2
CARB80/B10-S/B10-A	37.5	0.837	55.3
CARB80/R15/B5-S	40.6	0.822	57.1
CARB80/R13/B3-S/B4-A	40.2	0.824	57.5
CARB80/R10/B10-S 0.25% DTBP	39.6	0.827	63.9
CARB80/R15/B5-S --- B5-S 0.25% DTBP	40.6	0.822	58.6

7.1 NO_x Emissions

The NO_x emission results for the various mitigation strategies are presented in Figure 7-1 for the 2006 Cummins and Figure 7-2 for the 2007 MBE4000 on a gram per brake horsepower hour basis. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination within a particular test period. The NO_x mitigation testing for the 2006 Cummins was conducted over three separate test periods, the results of which are

separated by the vertical lines in the Figure 7-1. Only a single test period was used for the 2007 MBE4000. All comparisons with the CARB diesel are based on the CARB diesel results from that specific test period, so that the impacts of drift between different test periods were minimized. The error bars represent one standard deviation on the average value.

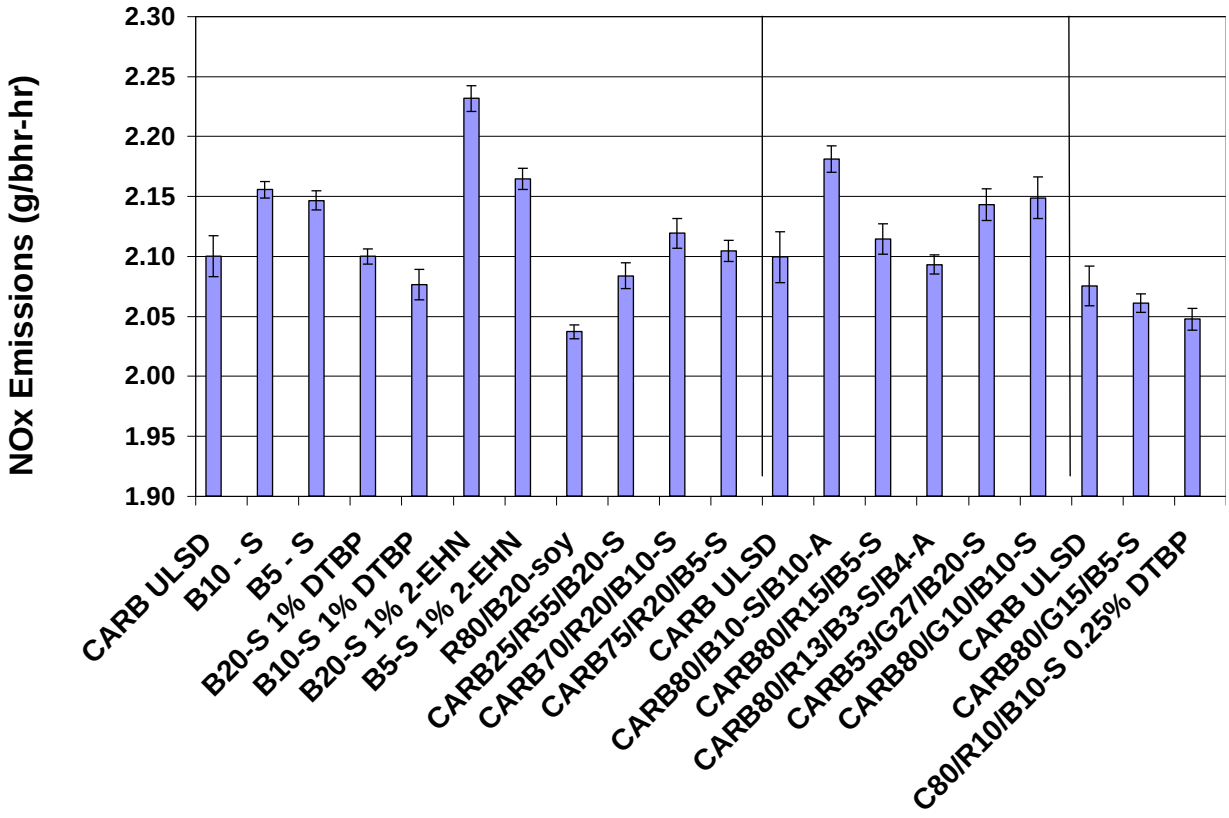


Figure 7-1. Average NO_x Emission Results for the NO_x Mitigation Formulations 2006 Cummins ISM

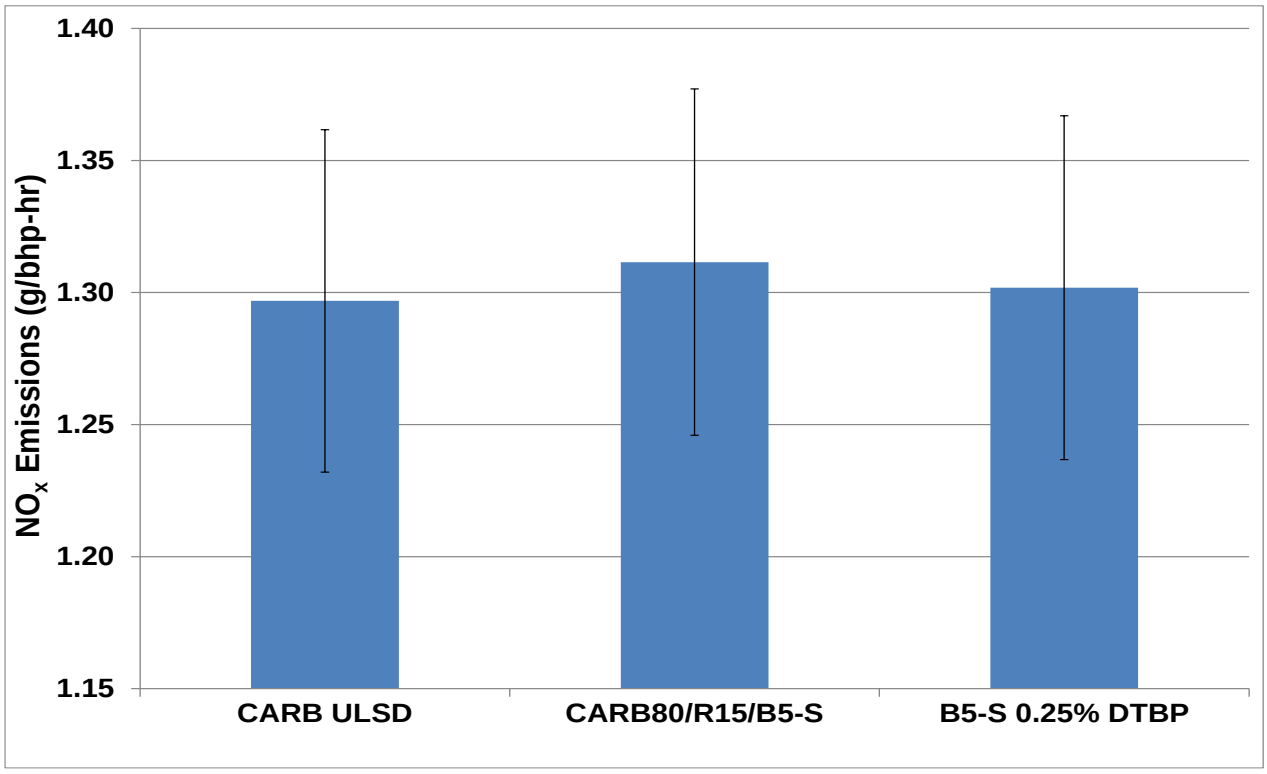


Figure 7-2. Average NO_x Emission Results for the NO_x Mitigation Formulations 2007 MBE4000

Table 7-2 shows the percentage differences for the different mitigation formulations along with the associated p-values for statistical comparisons using a t-test. Again note that all comparisons with the CARB diesel are based on the CARB diesel results from that specific test period for the 2006 Cummins engine. The results show that several of the formulations were either NO_x neutral or showed reductions in NO_x in comparison with the base CARB fuel. These formulations are shaded in the Table.

The NO_x mitigation testing was more extensive for the 2006 Cummins, with tests including lower level biodiesel blends (i.e., B5 and B10) for comparison purposes, renewable blends with various blend levels, and blends with different levels and types of additives. The results from the B20-soy from the primary testing on the soy-based biodiesel feedstock are also included in the table for comparison. These B5-soy and B10-soy blends both also showed increases in NO_x in comparison with the CARB fuel, although the increases were approximately 1/3 of the increases seen for the B20-soy blend. Additionally, a blend composed of 10% soy-biodiesel and 10% animal-based biodiesel with 80% CARB ULSD was tested. This blend showed an increase of approximately 3.9%, which is approximately the same value as the average of the increases for the B20-soy (+6.6%) and the B20-animal (+1.5%). This indicates that the NO_x impact for a particular biodiesel feedstock can be mitigated in part by blending with another biodiesel feedstock with a lower tendency for increasing NO_x.

Table 7-2. NO_x Percentage Differences Between the Blends used for the NO_x Mitigation and the CARB ULSD base fuel.

CARB vs.	2006 Cummins ISM		2007 MBE4000	
	% Difference	P-values	% Difference	P-values
B5 – S	2.2%	0.000		
B10 – S	2.6%	0.000		
B20 – S*	6.6%	0.000		
B20-S 1% DTBP	0.0%	0.959		
B10-S 1% DTBP	-1.1%	0.002		
B20-S 1% 2-EHN	6.3%	0.000		
B5-S 1% 2-EHN	3.1%	0.000		
R80/B20-soy	-3.0%	0.000		
CARB25/R55/B20-S	-0.8%	0.029		
CARB70/R20/B10-S	0.9%	0.014		
CARB75/R20/B5-S	0.2%	0.674		
CARB80/B10-S/B10-A	3.9%	0.000		
CARB80/R15/B5-S	0.7%	0.117	1.1%	0.029
CARB80/R13/B3-S/B4-A	-0.3%	0.501		
CARB53/G27/B20-S	2.1%	0.000		
CARB80/G10/B10-S	2.4%	0.000		
CARB80/G15/B5-S	-0.7%	0.068		
CARB80/R10/B10-S 0.25% DTBP	-1.3%	0.002		
B5-S 0.25% DTBP			0.4%	0.175

* From testing with soy-biodiesel feedstock

Two additives were used in this test phase, 2-ethylhexyl nitrate (2-EHN) and di tertiary butyl peroxide (DTBP). Of these two additives, the DTBP was effective in testing on the 2006 Cummins engine. A 1% DTBP additive blend was found to fully mitigate the NO_x impacts for a B20 soy biodiesel. Tests at a lower B10-soy biodiesel level with a 1% DTBP additive were additionally found to reduce NO_x emissions below those of the CARB fuel. The 2-EHN was tested at 1% level in both a B20-soy and B5-soy blend for the 2006 Cummins engine. This additive did not show any significant NO_x reductions from the pure blends for this engine.

A number of renewable and GTL blends with biodiesel were also tested in the 2006 Cummins engine. At higher levels of the renewable diesel fuel, the blends showed NO_x emissions below those of the baseline CARB ULSD. This included a R80/B20-soy and a CARB25/R55/B20-soy blend. At lower levels, more comparable to those that could potentially be used to meet the low carbon fuel standard, several blends showed NO_x neutrality, including a CARB75/R20/B5-soy, a CARB80/R13/B3-soy/B4-animal, and a CARB80/R15/B5-soy. A CARB80/GTL15/B5-soy blend was also found to achieve NO_x neutrality. Overall, the renewable and GTL diesels provide comparable levels of reductions for NO_x neutrality at the 15% blend level with a B5-soy. As discussed above, the level of renewable or GTL diesel fuels can be reduced if a biodiesel fuel with more favorable NO_x characteristics is used. This is demonstrated by the success of the CARB80/R13/B3-S/B4-A blend that combined both the soy and animal-based biodiesel. The use

of an additive in conjunction with lower levels of renewable diesel and GTL can also be used to provide NO_x neutrality, as shown by the CARB80/R10/B10-S 0.25% DTBP blend.

For the 2007 MBE4000 engine, only two blends were tested. The blends included a CARB80/R15/B5-soy, since this blend showed the potential for NO_x neutrality in the 2006 Cummins testing. The second blend was a B-5 soy with a 0.25% DTBP additive, which could represent a more commercially viable additive/biodiesel combination. Of these two blends, only the CARB95/ B5-S 0.25% DTBP blend was found to provide NO_x neutrality. Overall, it appears that different strategies will provide mitigation for different engines, but that the specific response will vary somewhat from engine to engine.

7.2 PM Emissions

The PM emission results for the various mitigation strategies are presented in Figure 7-3 and Figure 7-4 on a g/bhp-hr basis. Table 7-3 shows the percentage differences for the various mitigation strategies for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

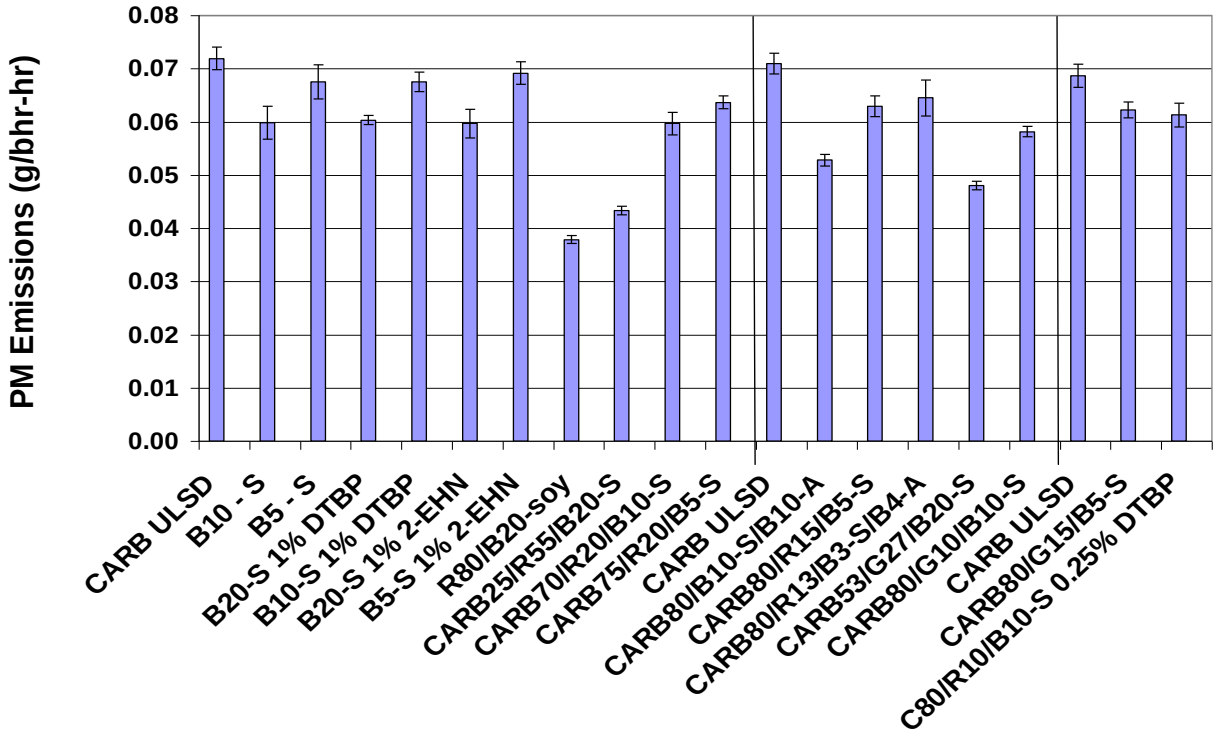


Figure 7-3. Average PM Emission Results for the NO_x Mitigation Formulations 2006 Cummins ISM

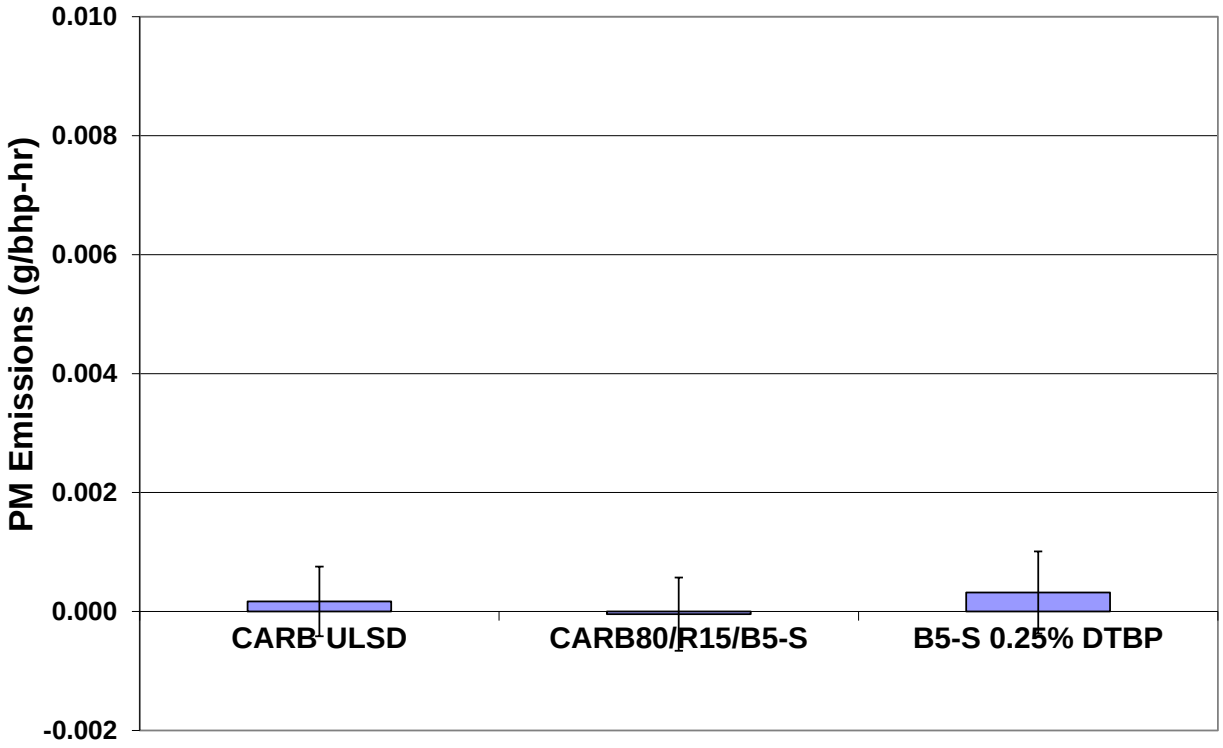


Figure 7-4. Average PM Emission Results for the NO_x Mitigation Formulations 2007 MBE4000

For the 2006 Cummins engine, the PM emissions showed reductions for all of the NO_x mitigation formulations for both the additive blends and the renewable blends. The largest reductions were found for the formulations with higher percentages of both biodiesel (B20) and the renewable diesel (55%-80%). Most of the other blends provided PM reductions that are slightly greater than those found for the corresponding B20 or lower soy biodiesel blends.

The PM emissions for the 2007 MBE4000 were all well below the certification standard of 0.01 g/bhp-hr and near the limits of detection, similar to the results from the main testing of the biodiesel blends on this engine. At these low levels, and with the associated testing variability, neither of the NO_x mitigation blends showed any statistically differences from the CARB diesel fuel.

Table 7-3. PM Percentage Differences Between the Blends used for the NO_x Mitigation and the CARB ULSD base fuel.

CARB vs.	2006 Cummins ISM		2007 MBE4000	
	% Difference	P-values	% Difference	P-values
B5 – S	-6%	0.000		
B10 – S	-17%	0.000		
B20 – S*	-25%	0.000		
B20-S 1% DTBP	-16%	0.000		
B10-S 1% DTBP	-6%	0.000		
B20-S 1% 2-EHN	-17%	0.000		
B5-S 1% 2-EHN	-4%	0.007		
R80/B20-S	-47%	0.000		
CARB25/R55/B20-S	-40%	0.000		
CARB70/R20/B10-S	-17%	0.000		
CARB75/R20/B5-S	-11%	0.000		
CARB80/B10-S/B10-A	-26%	0.000		
CARB80/R15/B5-S	-11%	0.000	-126%	0.551
CARB80/R13/B3-S/B4-A	-9%	0.000		
CARB53/G27/B20-S	-32%	0.000		
CARB80/G10/B10-S	-18%	0.000		
CARB80/G15/B5-S	-9%	0.000		
C80/R10/B10-S 0.25% DTBP	-11%	0.000		
B5-S 0.25% DTBP			88%	0.694

* From testing with soy-biodiesel feedstock

7.3 THC Emissions

The THC emission results for the various mitigation strategies are presented in Figure 7-5 and Figure 7-6 on a g/bhp-hr basis. Table 7-4 shows the percentage differences for the various mitigation strategies for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

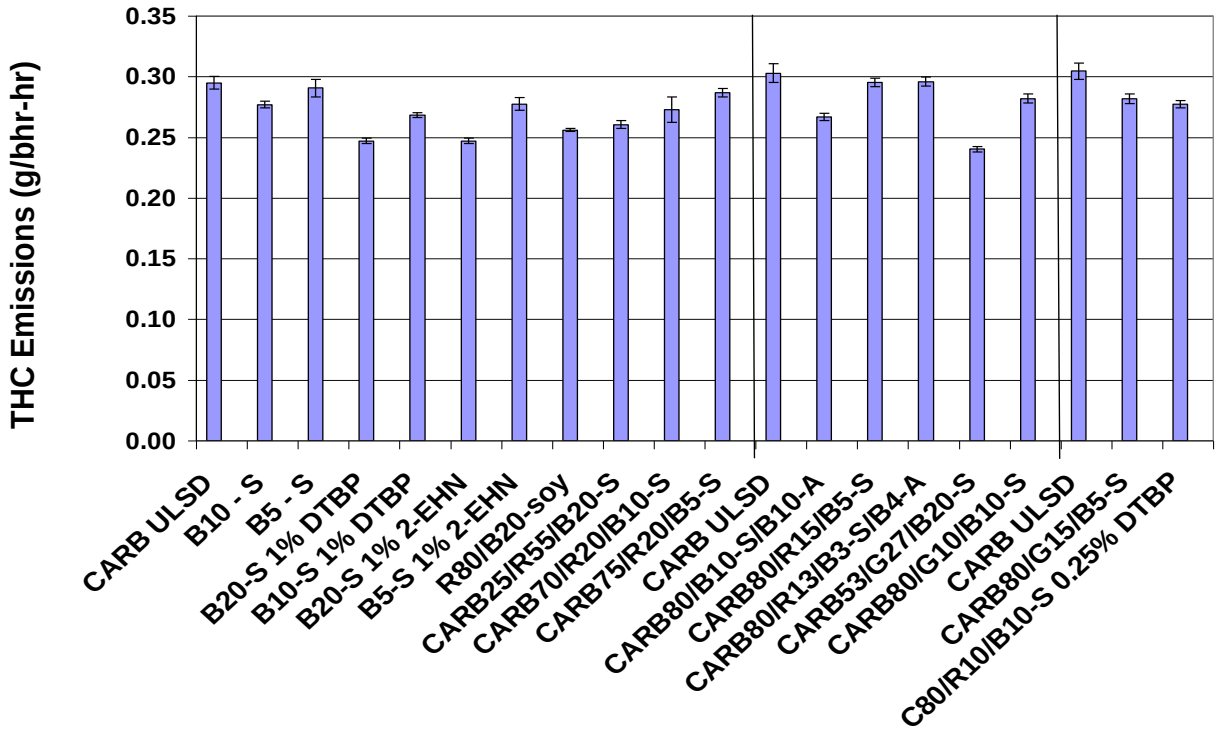


Figure 7-5. Average THC Emission Results for the NO_x Mitigation Formulations 2006 Cummins ISM

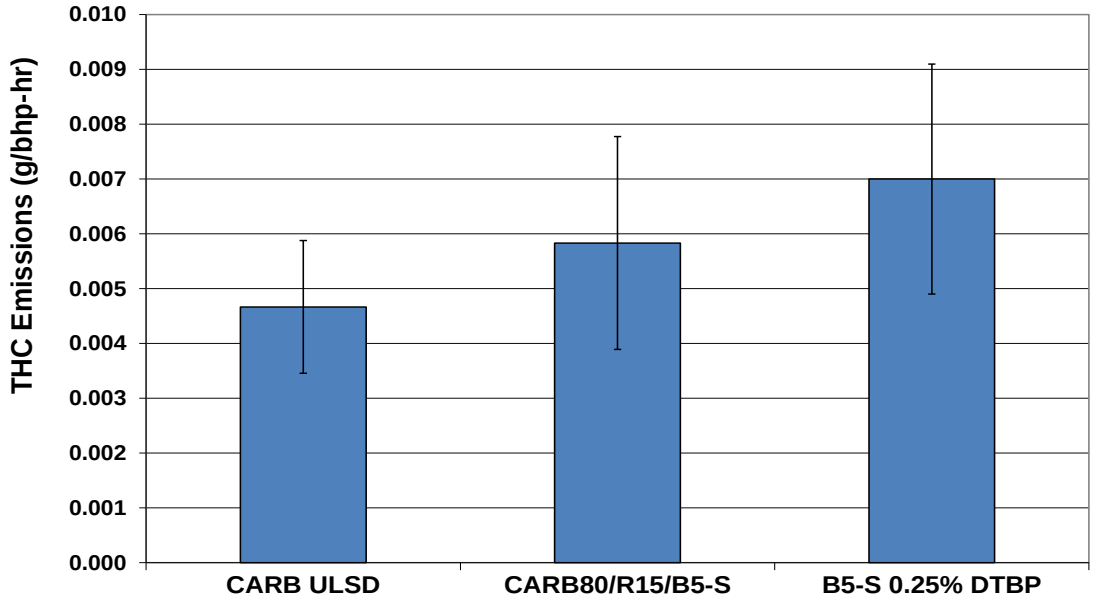


Figure 7-6. Average THC Emission Results for the NO_x Mitigation Formulations 2007 MBE4000

THC emissions for the 2006 Cummins engine showed consistent reductions for the NO_x mitigation blends ranging from 3 to 21%. These reductions were highest for the blends with the B20 blend level. Generally, the blends of biodiesel with either a renewable diesel, a GTL diesel, or an additive showed THC reductions that were either higher than or equivalent to the levels found for the biodiesel by itself at a particular blend level.

The THC emissions for the 2007 MBE4000 engine were about 2 orders of magnitude lower than the levels seen for the 2006 Cummins engine and near the limits of detection. The test results did show a statistically significant increase in THC emissions for the CARB95/B5-S/0.25% DTBP blend. This result is consistent with the trends for the soy-based biodiesel over the FTP discussed in section 3.3, but additional testing would be needed to further verify any such trends.

Table 7-4. THC Percentage Differences Between the Blends used for the NO_x Mitigation and the CARB ULSD base fuel.

CARB vs.	2006 Cummins ISM		2007 MBE4000	
	% Difference	P-values	% Difference	P-values
B5 – S	-1%	0.087		
B10 - S	-6%	0.000		
B20 – S*	-11%	0.000		
B20-S 1% DTBP	-16%	0.000		
B10-S 1% DTBP	-9%	0.000		
B20-S 1% 2-EHN	-16%	0.000		
B5-S 1% 2-EHN	-6%	0.000		
R80/B20-soy	-13%	0.000		
CARB25/R55/B20-S	-12%	0.000		
CARB70/R20/B10-S	-8%	0.000		
CARB75/R20/B5-S	-3%	0.014		
CARB80/B10-S/B10-A	-12%	0.000		
CARB80/R15/B5-S	-3%	0.024	25%	0.240
CARB80/R13/B3-S/B4-A	-2%	0.039		
CARB53/G27/B20-S	-21%	0.000		
CARB80/G10/B10-S	-7%	0.000		
CARB80/G15/B5-S	-7%	0.000		
CARB80/R10/B10-S 0.25% DTBP	-9%	0.000		
B5-S 0.25% DTBP			50%	0.040

* From testing with soy-biodiesel feedstock

7.4 CO Emissions

The CO emission results for the various mitigation strategies are presented in Figure 7-7 and Figure 7-8 on a g/bhp-hr basis. Table 7-5 shows the percentage differences for the various mitigation strategies for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

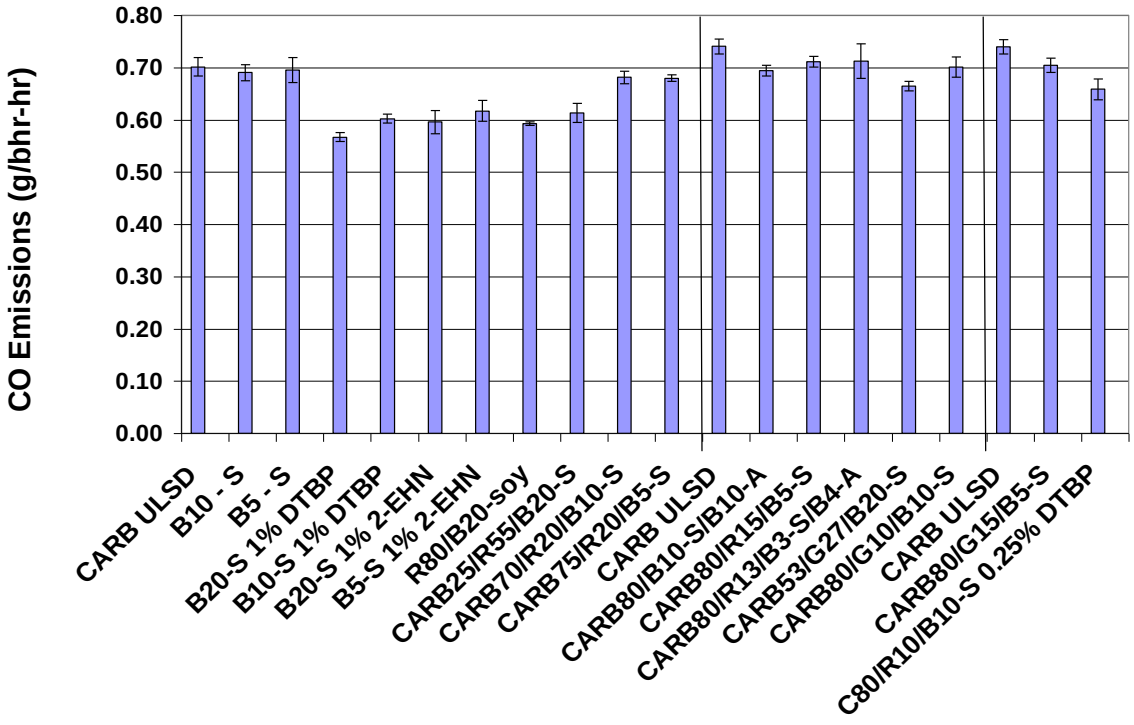


Figure 7-7. Average CO Emission Results for the NO_x Mitigation Formulations 2006 Cummins ISM

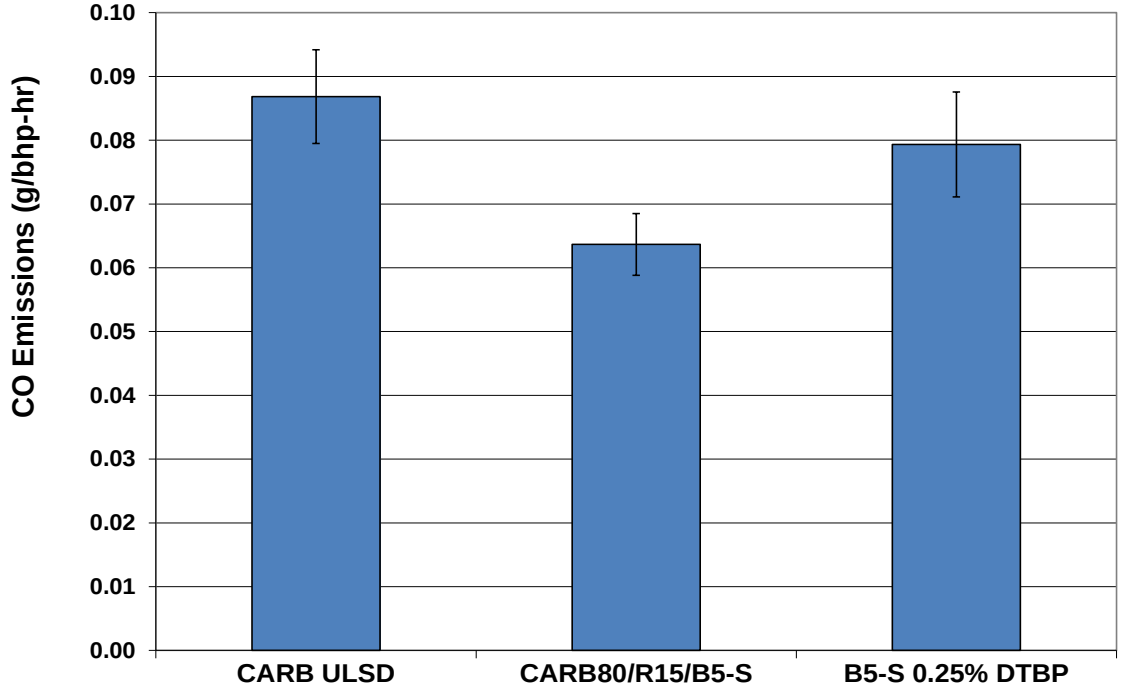


Figure 7-8. Average CO Emission Results for the NO_x Mitigation Formulations 2007 MBE4000

All formulations used for the NO_x mitigation showed reductions in CO for the 2006 Cummins engine compared to the CARB fuel ranging from 3 to 19%. The formulations with higher percentages of renewable/GTL diesel fuel (R80, R55, and GTL27) with B20 and those with additives all showed statistically significant reductions in CO emissions of 10% or greater for the 2006 Cummins engine. For comparison, the baseline soy-based biodiesel did not show significant CO reductions for either the main testing phase, discussed in section 5.4, or for the low levels used during the NO_x mitigation testing.

The CO emissions for the 2007 MBE4000 engine were approximately an order of magnitude lower than those for the 2006 Cummins engine due to the DPF. The test results did show a statistically significant difference for the CARB80/R15/B5-S blend. In comparison with the primary testing done on the biodiesel blends, only a limited number of higher level biodiesel blends (i.e., B50 and B100) showed CO reductions over the FTP, as discussed in section 5.4. Thus, further testing would be needed to verify this trend for the CARB80/R15/B5-S blend.

Table 7-5. CO Percentage Differences Between the Blends used for the NO_x Mitigation and the CARB ULSD base fuel.

CARB vs.	2006 Cummins ISM		2007 MBE4000	
	% Difference	P-values	% Difference	P-values
B5 – S	-1%	0.471		
B10 – S	-2%	0.171		
B20 – S*	-3%	0.078		
B20-S 1% DTBP	-19%	0.000		
B10-S 1% DTBP	-14%	0.000		
B20-S 1% 2-EHN	-15%	0.000		
B5-S 1% 2-EHN	-12%	0.000		
R80/B20-soy	-16%	0.000		
CARB25/R55/B20-S	-13%	0.000		
CARB70/R20/B10-S	-3%	0.013		
CARB75/R20/B5-S	-3%	0.048		
CARB80/B10-S/B10-A	-6%	0.000		
CARB80/R15/B5-S	-4%	0.000	-27%	0.000
CARB80/R13/B3-S/B4-A	-4%	0.005		
CARB53/G27/B20-S	-10%	0.000		
CARB80/G10/B10-S	-5%	0.000		
CARB80/G15/B5-S	-5%	0.000		
CARB80/R10/B10-S 0.25% DTBP	-11%	0.000		
B5-S 0.25% DTBP			-9%	0.127

* From testing with soy-biodiesel feedstock

7.5 CO_2 Emissions

The CO_2 emission results for the various mitigation strategies are presented in Figure 7-9 and Figure 7-10 on a gram per brake horsepower hour basis. Table 7-6 shows the percentage differences for the various mitigation strategies for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

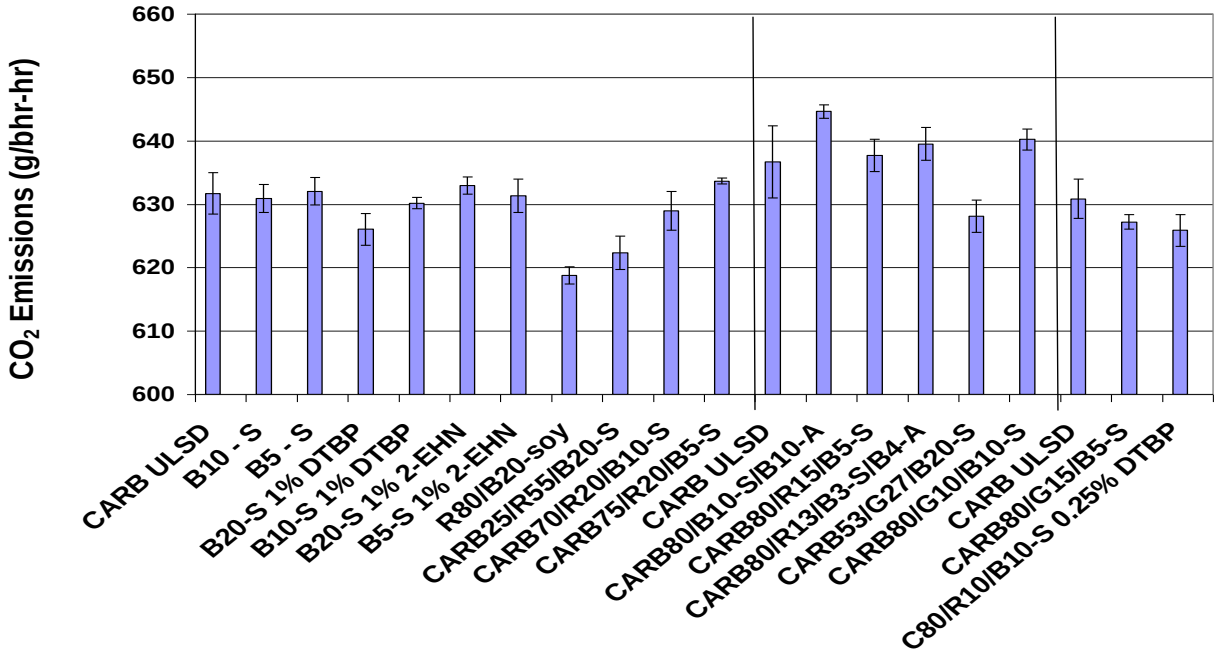


Figure 7-9. Average CO_2 Emission Results for the NO_x Mitigation Formulations 2006 Cummins ISM

For the 2006 Cummins engine, CO_2 emissions showed statistically significant changes for about half of the NO_x mitigation formulations tested. The statistically significant changes were all reductions in CO_2 that were 2% or less for the 2006 Cummins engine. This included some for the formulations with higher blends (55 and 80%) of renewable diesel. This is consistent with the CO_2 reductions seem for the higher blends of the renewable diesel and GTL fuels discussed above. Both mitigation formulations for the 2007 MBE4000 engine showed slight increases of in CO_2 emissions that were either statistically significant at the 95% or 90% level, but the increases were 0.5% or less.

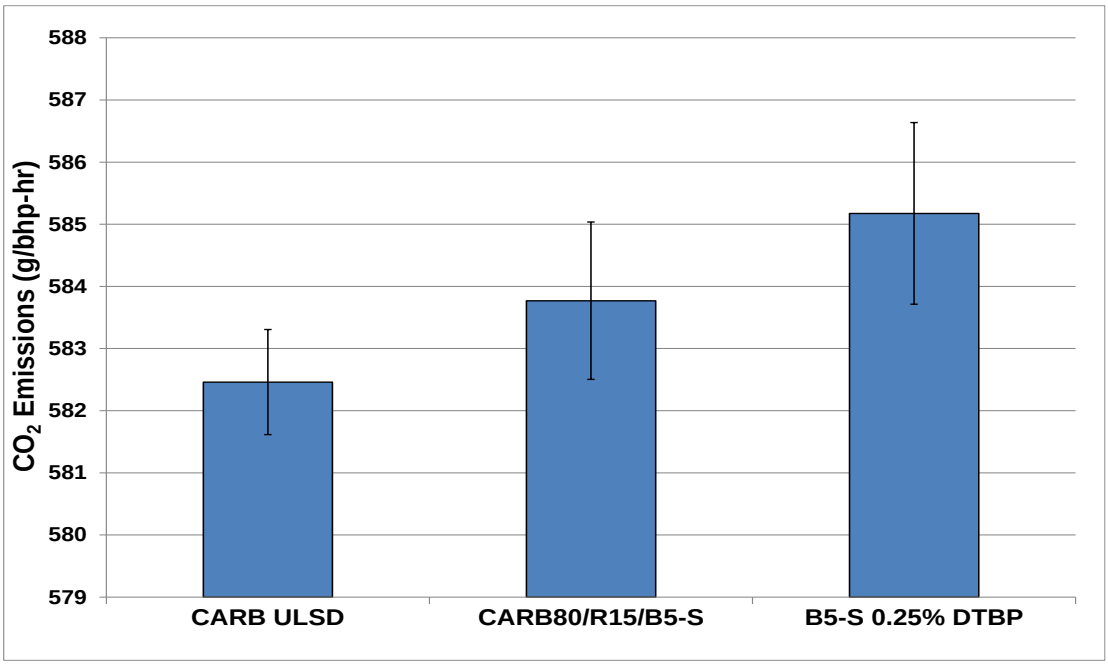


Figure 7-10. Average CO_2 Emission Results for the NO_x Mitigation Formulations 2007 MBE4000

Table 7-6. CO_2 Percentage Differences Between the Blends used for the NO_x Mitigation and the CARB ULSD fuel.

CARB vs.	2006 Cummins ISM		2007 MBE4000	
	% Difference	P-values	% Difference	P-values
B5 - S	0.1%	0.816		
B10 - S	-0.1%	0.569		
B20 – S*	0.4%	0.309		
B20-S 1% DTBP	-0.9%	0.000		
B10-S 1% DTBP	-0.2%	0.258		
B20-S 1% 2-EHN	0.2%	0.362		
B5-S 1% 2-EHN	-0.1%	0.782		
R80/B20-soy	-2.0%	0.000		
CARB25/R55/B20-S	-1.5%	0.000		
CARB70/R20/B10-S	-0.4%	0.059		
CARB75/R20/B5-S	0.3%	0.309		
CARB80/B10-S/B10-A	1.2%	0.003		
CARB80/R15/B5-S	0.2%	0.686	0.2%	0.061
CARB80/R13/B3-S/B4-A	0.4%	0.251		
CARB53/G27/B20-S	-1.4%	0.001		
CARB80/G10/B10-S	0.6%	0.150		
CARB80/G15/B5-S	-0.6%	0.018		
CARB80/R10/B10-S 0.25% DTBP	-0.8%	0.006		
B5-S 0.25% DTBP			0.5%	0.003

* From testing with soy-biodiesel feedstock

7.6 Brake Specific Fuel Consumption

The brake specific fuel consumption results for the various mitigation strategies are presented in Figure 7-11 and Figure 7-12 on a gal./bhp-hr basis. Table 7-7 shows the percentage differences for the various mitigation strategies for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

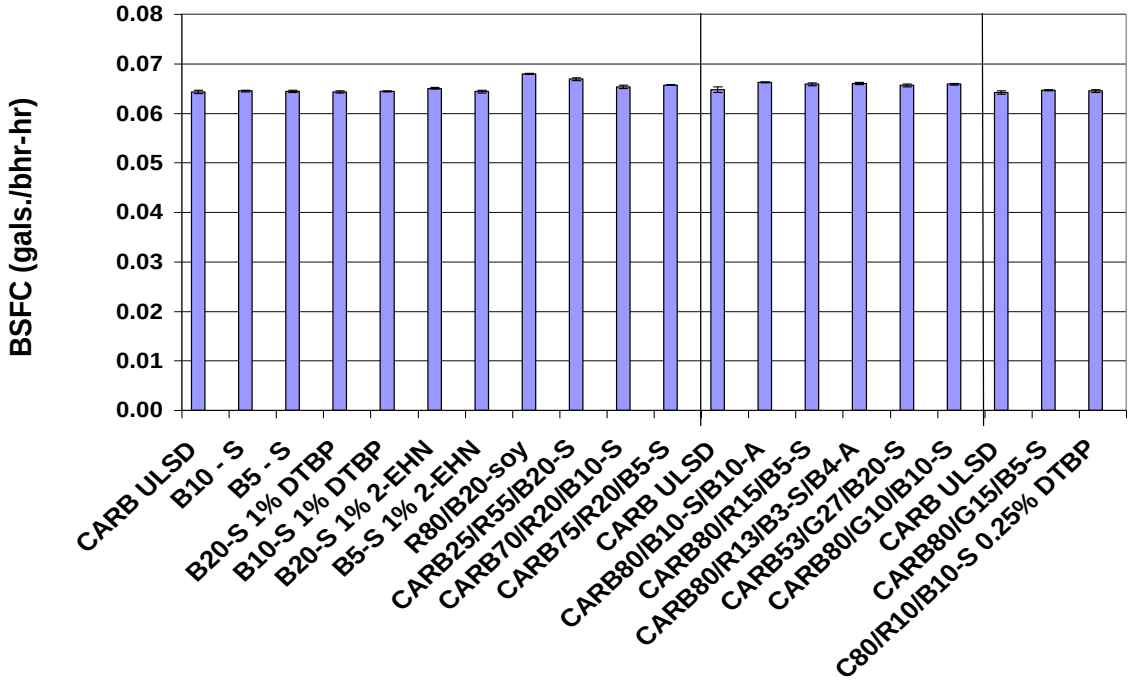


Figure 7-11. Average Brake Specific Fuel Consumption Results for the NO_x Mitigation Formulations 2006 Cummins ISM

The fuel consumption for the NO_x mitigation formulations was generally higher than for the CARB fuel for both engines. This is not surprising given that the fuel consumption increased with higher blend levels of biodiesel, renewable diesel, and GTL. The increase in fuel consumption was highest for the fuels with the highest combined percentages of the renewable/GTL diesel and biodiesel. The B5 and B10 biodiesel blends, and the formulations with the DTBP additive did not show statistically significant increases in fuel consumption for the 2006 Cummins engine. Both NO_x mitigation formulations showed statistically significant increases in BSFC for 2007 MBE4000 engine.

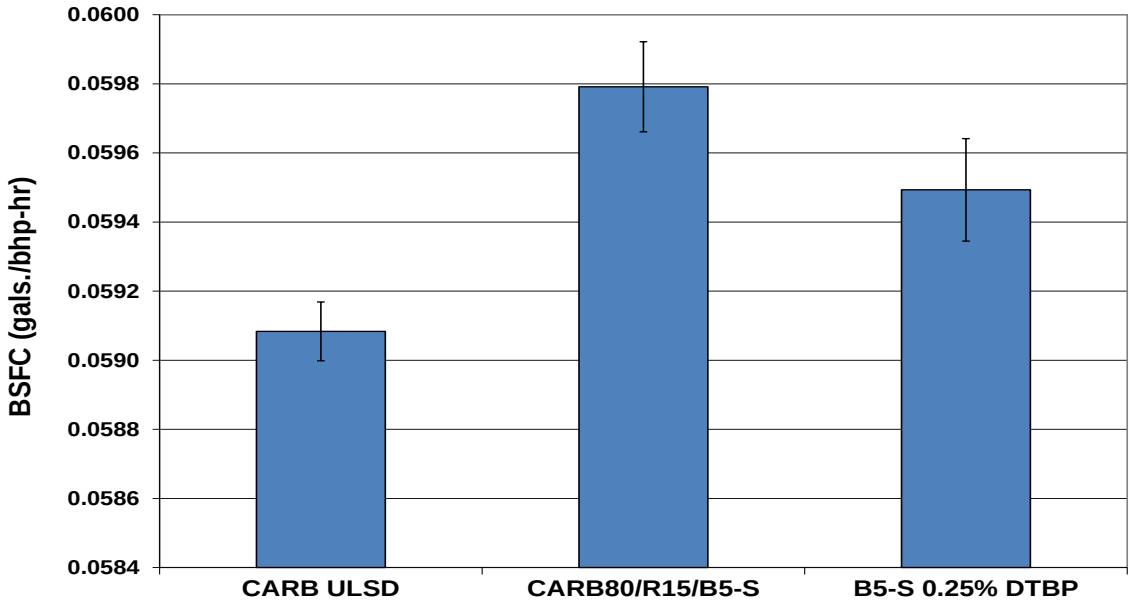


Figure 7-12. Average Brake Specific Fuel Consumption Results for the NO_x Mitigation Formulations 2007 MBE4000

Table 7-7. Brake Specific Fuel Consumption Percentage Differences Between the Blends used for the NO_x Mitigation and the CARB ULSD base fuel.

CARB vs.	2006 Cummins ISM		2007 MBE4000	
	% Difference	P-values	% Difference	P-values
B5 - S	0.3%	0.228		
B10 - S	0.3%	0.167		
B20 – S*	1.4%	0.001		
B20-S 1% DTBP	0.1%	0.748		
B10-S 1% DTBP	0.2%	0.445		
B20-S 1% 2-EHN	1.2%	0.000		
B5-S 1% 2-EHN	0.1%	0.564		
R80/B20-soy	5.7%	0.000		
CARB25/R55/B20-S	4.1%	0.000		
CARB70/R20/B10-S	1.7%	0.000		
CARB75/R20/B5-S	2.2%	0.000		
CARB80/B10-S/B10-A	2.2%	0.000		
CARB80/R15/B5-S	1.6%	0.000	1.2%	0.000
CARB80/R13/B3-S/B4-A	1.9%	0.000		
CARB53/G27/B20-S	1.3%	0.002		
CARB80/G10/B10-S	1.7%	0.000		
CARB80/G15/B5-S	0.6%	0.010		
CARB80/R10/B10-S 0.25% DTBP	0.5%	0.081		
B5-S 0.25% DTBP			0.7%	0.000

* From testing with soy-biodiesel feedstock

8.0 Non-Road Engine Testing Results

8.1 NO_x Emissions

Studies of biodiesel with CARB-like diesel fuels in non-road engines are particularly important, as extremely few such studies are available in the literature. The NO_x emission results for the John Deere and TRU engines are presented in Figure 8-1 and Figure 8-2, respectively on a gram per brake horsepower hour basis. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination within a particular test period. The testing for the TRU engine was conducted in two series that were separated by the white and black bars in Figure 8-2. The error bars represent one standard deviation on the average value. Table 8-1 shows the percentage differences for the different biodiesel blends relative to the CARB diesel for all testing combinations along with the associated p-values for statistical comparisons using a t-test. For the off-road engine testing, the results are considered to be statistically significant for p-values less than 0.05, which represents a 95% confidence level.

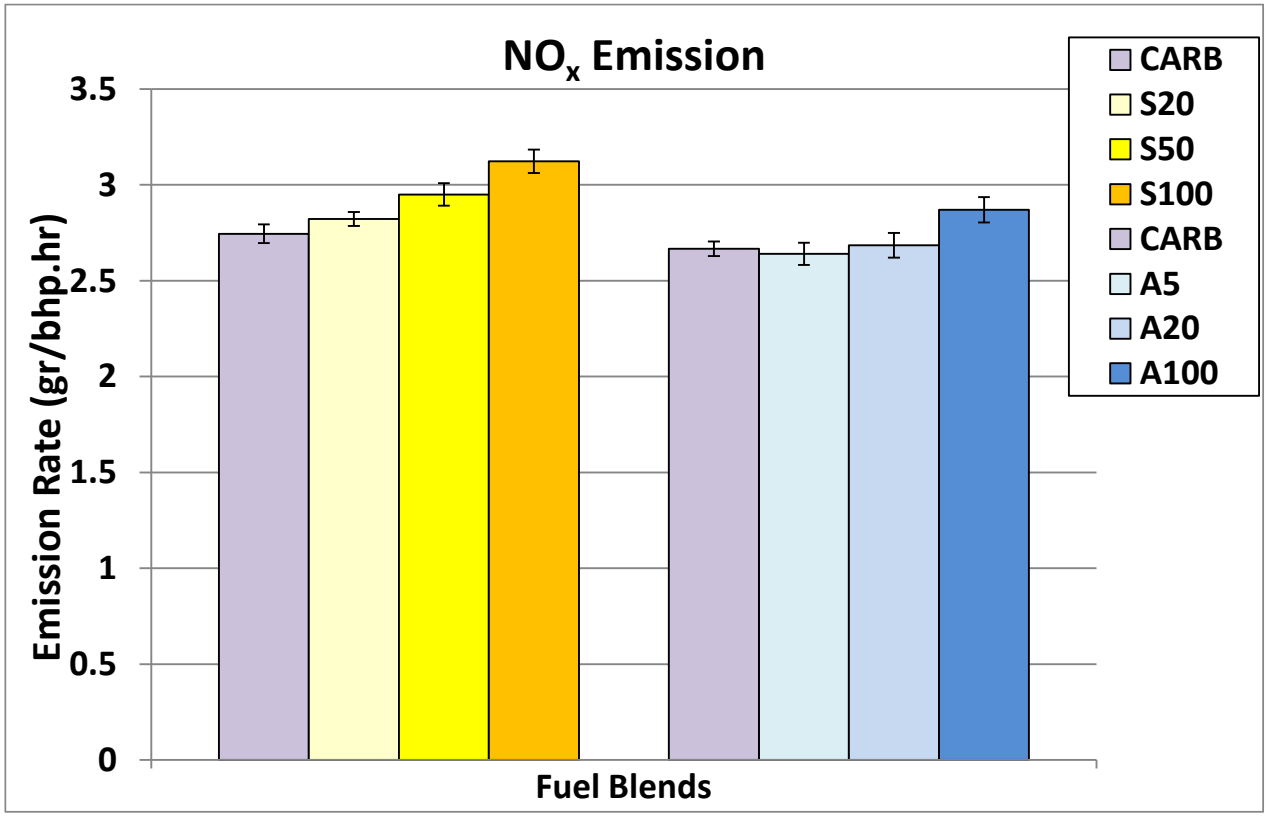


Figure 8-1. Average NO_x Emission Results for the John Deere Engine

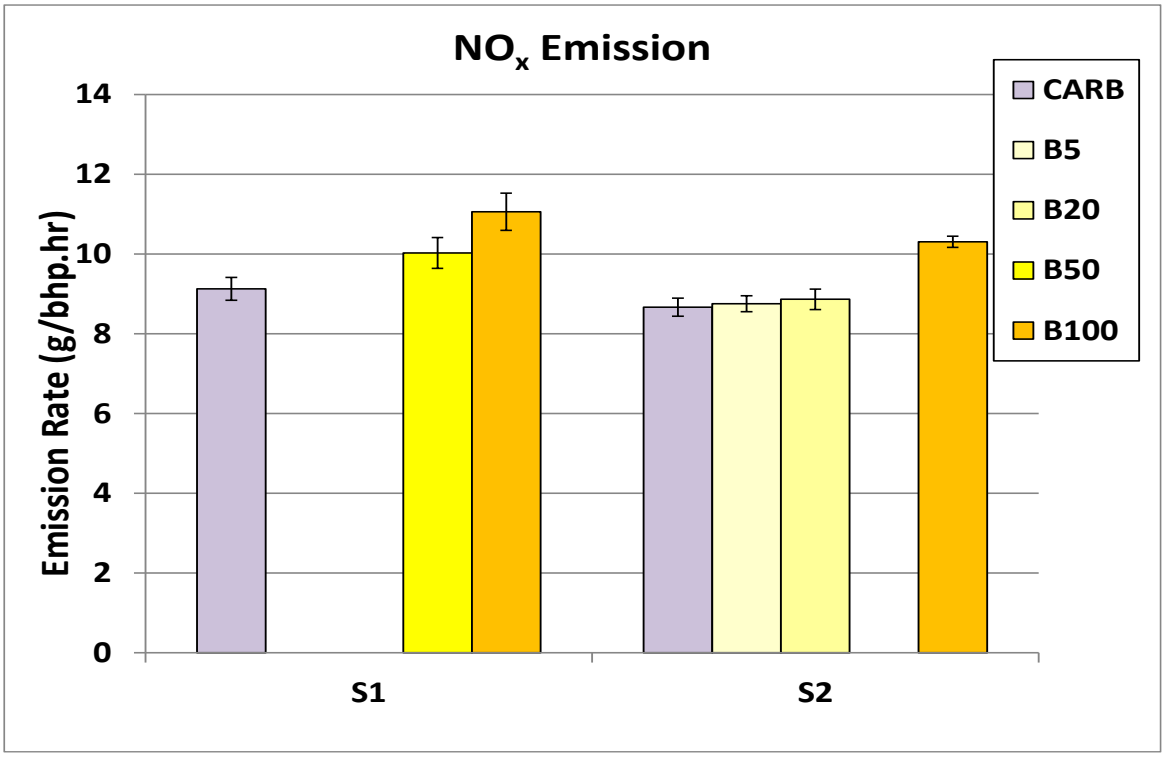


Figure 8-2. Average NO_x Emission Results for the TRU Engine
Note : S1 : Series 1; S2: Series 2

The NO_x emissions show general increases in NO_x emissions with increasing biodiesel blend level for both off-road engines. The NO_x increases were statistically significant for the B50 and B100 soy-based blends for both engines. The soy-based B20 blends also showed increases that were statistically significant for the John Deere engine and statistically significant at the lesser 90% confidence level for the TRU engine. The NO_x increases for the TRU engine were comparable the ones obtained for 2006 Cummins engine (9.8-13.2% for B50 & 17.4-26.6% for B100), but were lower than the ones obtained for 2007 MBE4000 (15.3-18.2% for B50 & 36.6-47.1% for B100). The magnitude of the increases in NO_x emissions for the John Deere engine were less than those for either the TRU or the on-road heavy-duty engines. The animal-based biodiesel also did not show as great a tendency to increase NO_x emissions compared to the soy-based biodiesel for the John Deere engine, with only the B100 animal-based biodiesel showing statistically significant increases in NO_x emissions.

Table 8-1. NO_x Percentage Differences and Statistical Analysis Results for the Off-Road Engines.

CARB vs.	John Deere Engine				TRU Engine			
	Soy-based		Animal-based		Soy-based Series 1		Soy-based Series 2	
	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
B5			-1.00%	0.314			0.97%	0.412
B20	2.82%	0.021	0.66%	0.528			2.25%	0.086
B50	7.63%	0.000			9.85%	0.000		
B100	13.76%	0.000	7.63%	0.000	21.20%	0.000	18.89%	0.000

8.2 PM Emissions

The PM emission results for the off-road engine testing are presented in Figure 8-3 and Figure 8-4 for the John Deere and the TRU engines, respectively. Table 8-2 shows the percentage differences for the different biodiesel blends relative to the CARB diesel for all testing combinations, along with the associated p-values for statistical comparisons using a t-test.

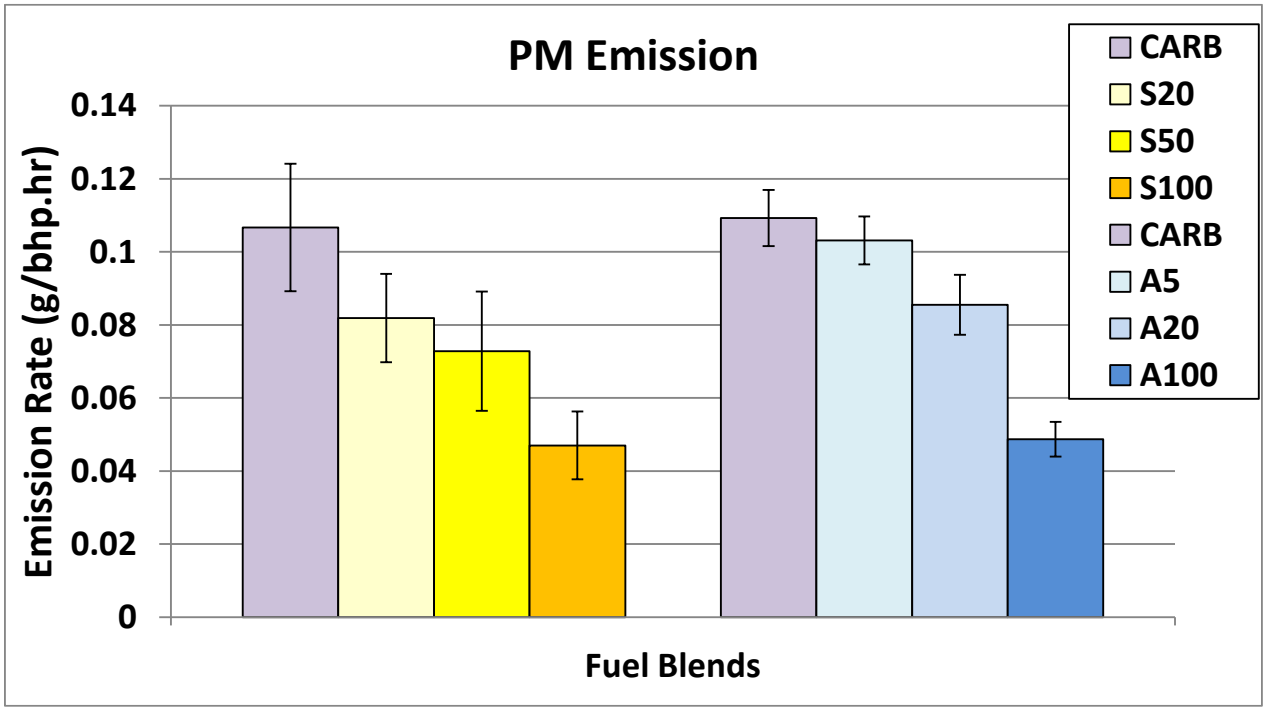


Figure 8-3. Average PM Emission Results for the John Deere engine

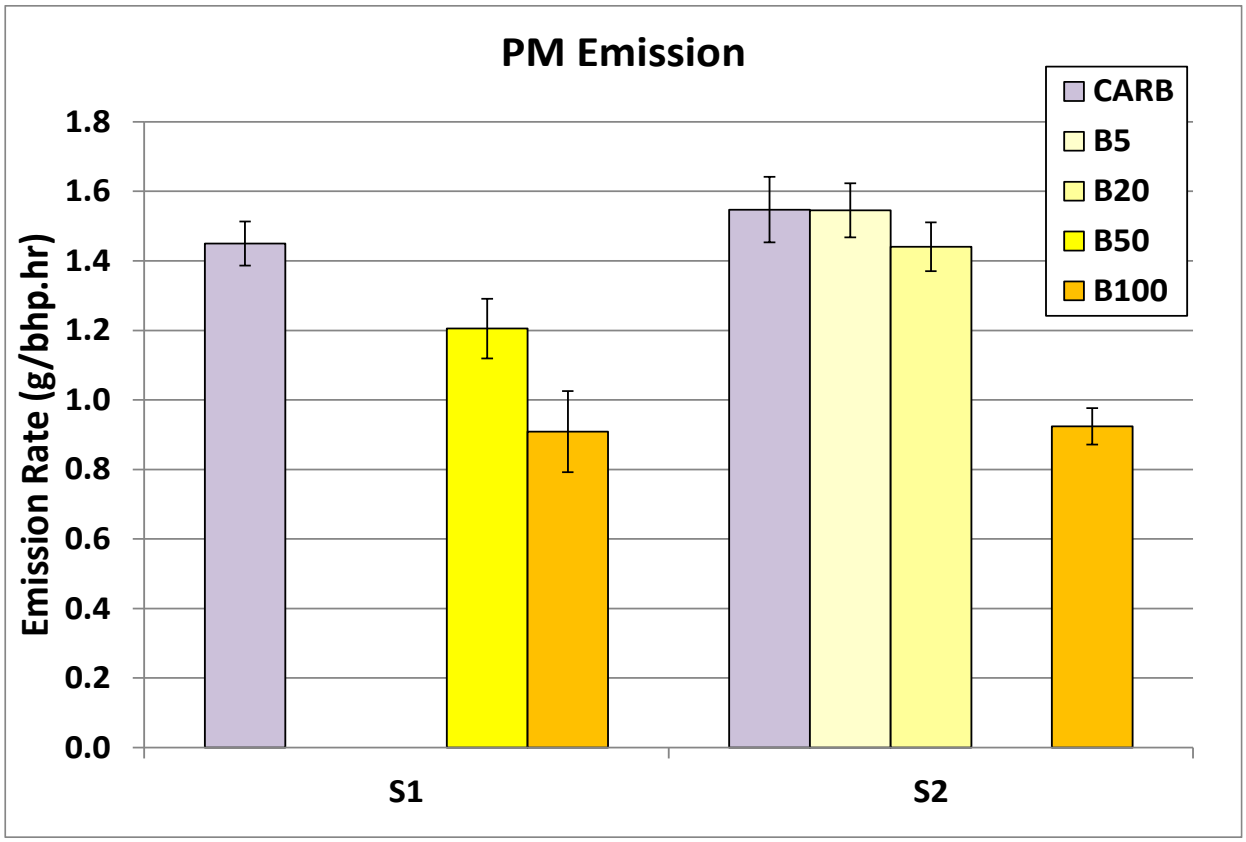


Figure 8-4. Average PM Emission Results for the TRU Engine.

Note : S1 : Series 1; S2: Series 2

PM emissions showed consistent reductions with increasing biodiesel blend level for both engines. The magnitude of the reductions in the PM emissions for the John Deere engine were comparable to those of the 2006 Cummins ISM engine dynamometer tests, while the reductions seen for the TRU engine were on the lower end or were less than those seen for the 2006 Cummins. The PM reductions for the 2006 Cummins engine ranged from 30-46% for the B50 blend and from 33-58% for the B100 blend.

Table 8-2. PM Percentage Differences and Statistical Analysis Results for the Off-Road Engines

CARB vs.	John Deere Engine				TRU Engine			
	Soy-based		Animal-based		Soy-based Series 1		Soy-based Series 2	
	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
B5			-5.63%	0.151			-0.13%	0.594
B20	-23.25%	0.028	-21.77%	0.000			-6.91%	0.011
B50	-31.75%	0.013			-16.86%	0.000		
B100	-55.93%	0.000	-55.42%	0.000	-37.31%	0.000	-40.30%	0.000

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8.3 THC Emissions

The THC emission results for the off-road engine testing are presented in Figure 8-5 and Figure 8-6 on a g/bhp-hr basis. Table 8-3 shows the percentage differences for the different biodiesel blends relative to the CARB diesel for all testing combinations along with the associated p-values for statistical comparisons using a t-test.

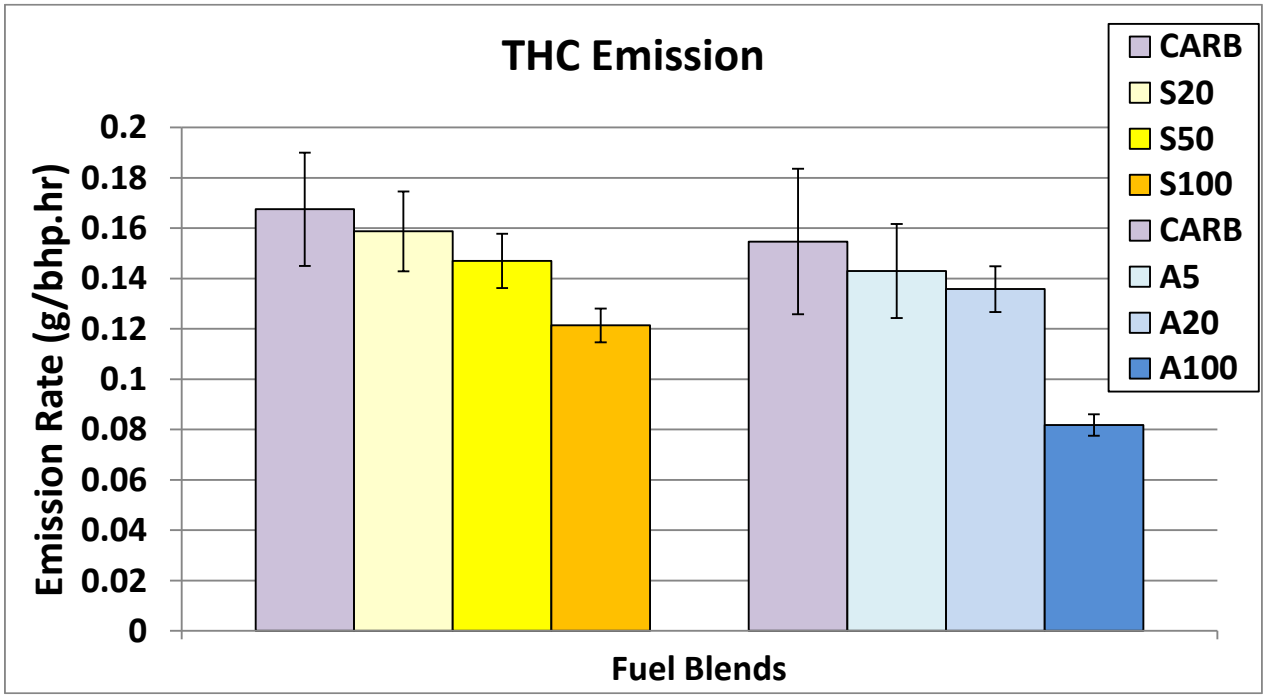


Figure 8-5. Average THC Emission Results for the John Deere Engine

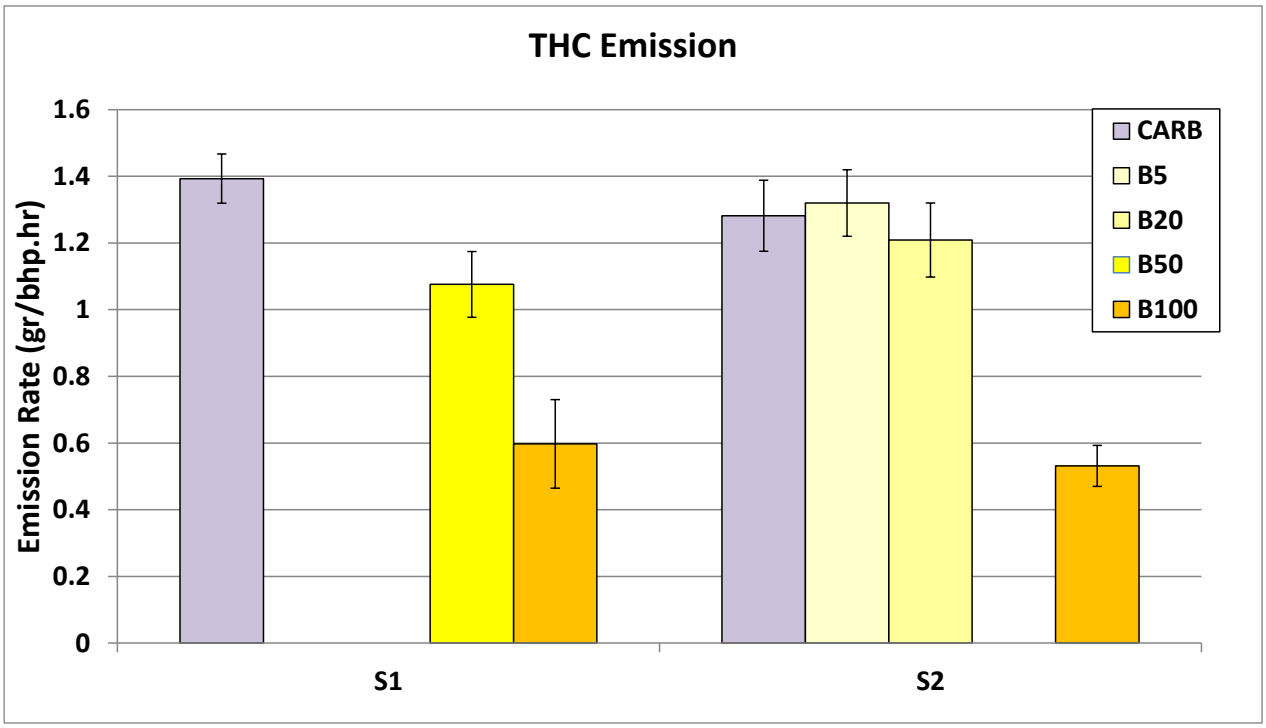


Figure 8-6. Average THC Emission Results for the TRU Engine

Note : S1 : Series 1; S2: Series 2

THC emissions showed consistent reductions with increasing biodiesel blend level for both engines. The magnitude of the reductions in the PM emissions depended on the specific engine/fuel/blend level combination. The THC reductions for the off-road engines were generally either comparable to or were less than those seen for the 2006 Cummins ISM engine dynamometer testing. The PM reductions for the 2006 Cummins engine ranged from 11-16% for the B20 blend, from 28-38% for the B50 blend, and from 55-73% for the B100 blend.

Table 8-3. THC Percentage Differences and Statistical Analysis Results for the Off-Road Engines.

CARB vs.	John Deere Engine				TRU Engine			
	Soy-based		Animal-based		Soy-based Series 1		Soy-based Series 2	
	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
B5			-7.54%	0.442			3.01%	0.436
B20	-5.22%	0.498	-12.22%	0.189			-5.68%	0.153
B50	-15.12%	0.104			-22.77%	0.000		
B100	-27.54%	0.001	-47.13%	0.001	-57.12%	0.000	-58.53%	0.000

8.4 CO Emissions

The CO emission results for the off-road engine testing are presented in Figure 8-7 and Figure 8-8 for the John Deere and TRU engines, respectively. Table 8-4 shows the percentage differences for the different biodiesel blends relative to the CARB diesel for all testing combinations, along with the associated p-values for statistical comparisons using a t-test.

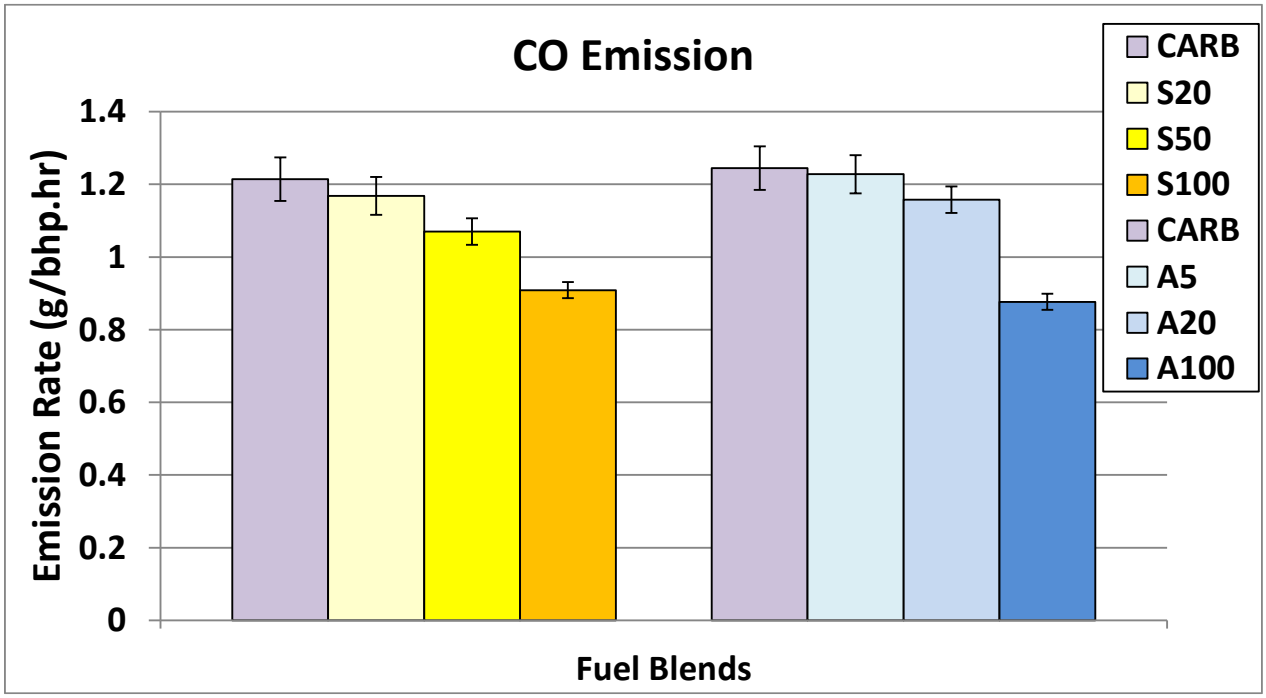


Figure 8-7. Average CO Emission Results for the John Deere Engine

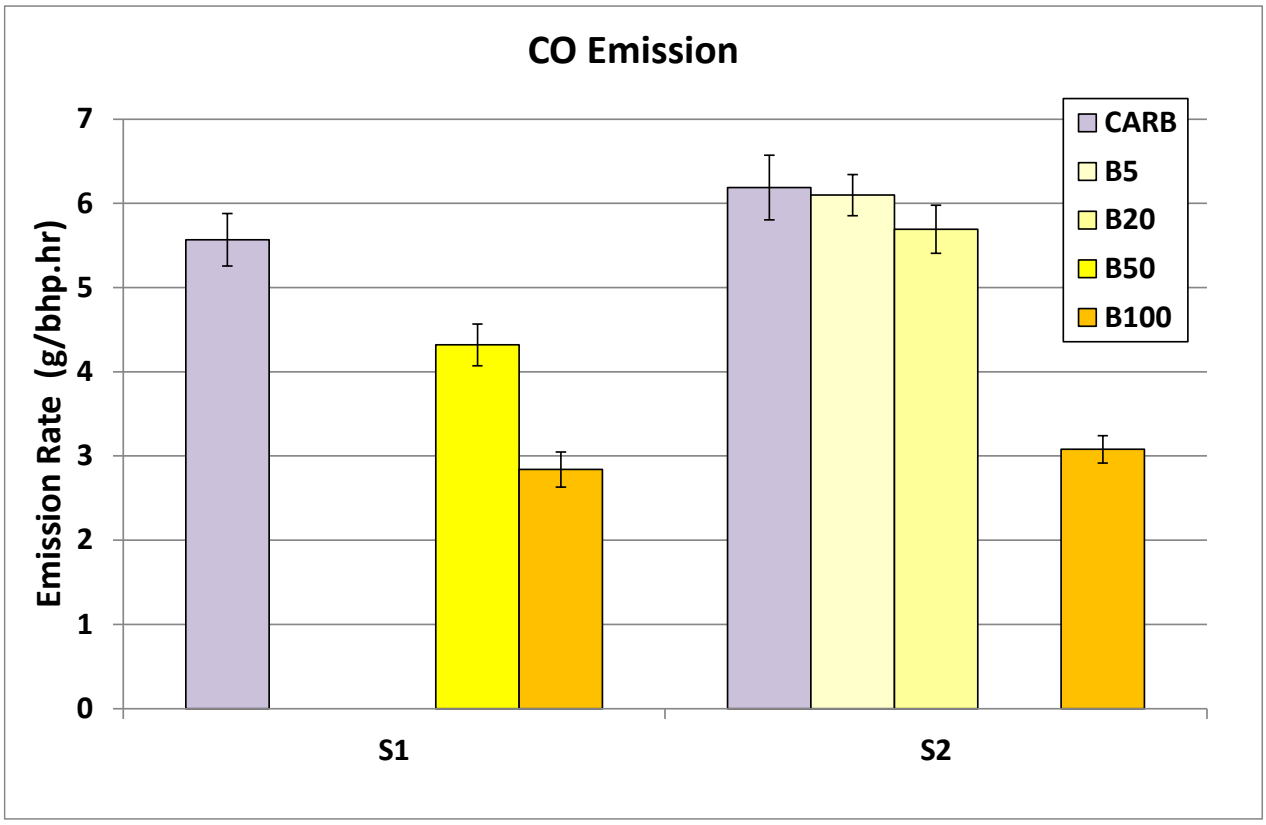


Figure 8-8. Average CO Emission Results for the TRU Engine

Note : S1 : Series 1; S2: Series 2

CO emissions showed consistent reductions with increasing biodiesel blend level for both engines. The CO reductions for the John Deere engine were comparable to those seen for the 2006 Cummins ISM engine for the engine dynamometer testing, while the CO reductions for the TRU engine were generally greater than those found for the 2006 Cummins for the animal-based blends. The CO reductions for the 2006 Cummins engine for the animal-based biodiesel ranged from 7-10% for the B20 blend, from 9-12% for the B50 blend, and from 20-27% for the B100 blend. Note that CO emissions did not show consistent reductions for the soy-based biodiesel for the Cummins engine over the full range of test cycles. For the John Deere engine, the CO reductions for B100 soy-based and animal-based biodiesel blends were similar.

Table 8-4. CO Percentage Differences and Statistical Analysis Results for the Off-Road Engines.

CARB vs.	John Deere Engine				TRU Engine			
	Soy-based		Animal-based		Soy-based Series 1		Soy-based Series 2	
	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
B5			1.32%	0.603			-1.46%	0.567
B20	-3.80%	0.142	-6.98%	0.009			-8.04%	0.005
B50	-12.43%	0.001			-22.42%	0.000		
B100	-25.14%	0.000	-29.54%	0.000	-49.01%	0.000	-50.25%	0.000

8.5 CO_2 Emissions

The CO_2 emission results for the off-road engine testing are presented in Figure 8-9 and Figure 8-10 for the John Deere and TRU engine, respectively. Table 8-5 shows the percentage differences for the different biodiesel blends relative to the CARB diesel for all testing combinations, along with the associated p-values for statistical comparisons using a t-test.

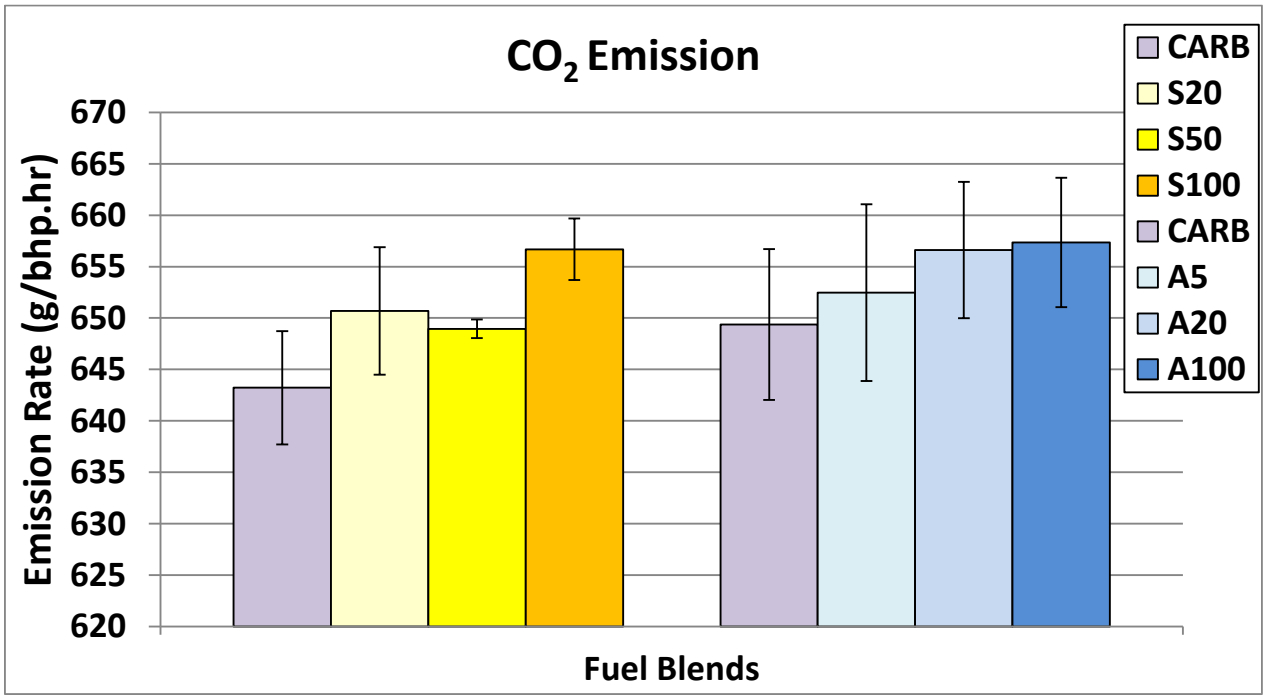


Figure 8-9. Average CO_2 Emission Results for the John Deere Engine

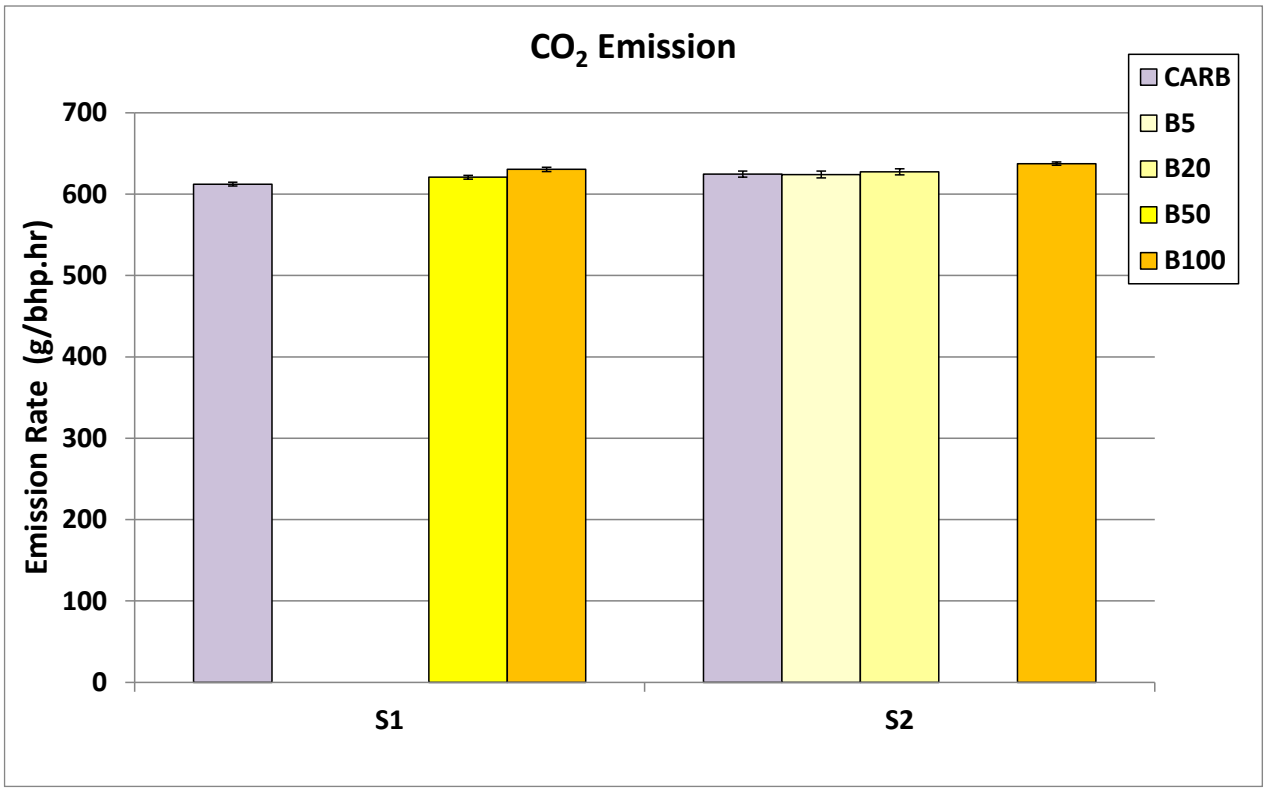


Figure 8-10. Average CO_2 Emission Results for the TRU Engine

Note : S1 : Series 1; S2: Series 2

CO_2 emissions showed some slight increases for the biodiesel blends for both engines. These increases were statistically significant for the TRU engine for both the B50 and B100 blends on the first series of tests and for the B100 blend on the second series of tests. Increases of 1-5% in CO_2 emissions were also seen for the 2006 Cummins and MBE4000 in the on-road engine dynamometer testing.

Table 8-5. CO_2 Percentage Differences and Statistical Analysis Results for the Off-Road Engines.

CARB vs.	John Deere Engine				TRU Engine			
	Soy-based		Animal-based		Soy-based Series 1		Soy-based Series 2	
	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
B5			0.48%	0.499			-0.10%	0.753
B20	1.16%	0.154	1.12%	0.081			0.45%	0.114
B50	0.87%	0.082			1.38%	0.000		
B100	2.09%	0.001	1.23%	0.069	2.96%	0.000	2.06%	0.000

8.6 Greenhouse Gas Emission Equivalents

For the TRU engine, N_2O emissions were measured in addition to the CH_4 and CO_2 emissions. This enabled the calculation of tailpipe greenhouse gas emission equivalents. The tailpipe greenhouse gas equivalent emissions results are presented in Figure 8-11 for the TRU engine. The

results show that the B50 and B100 blends produced some increases in tailpipe greenhouse gas equivalent emissions relative to the CARB diesel. It must be emphasized that these increases represent only the tailpipe contribution to the greenhouse gas emissions. The actual contribution of each fuel towards total greenhouse gas emissions would need to be assessed through a full lifecycle analysis, which would account for the emissions attributed to harvesting, extracting, and producing the various fuels.

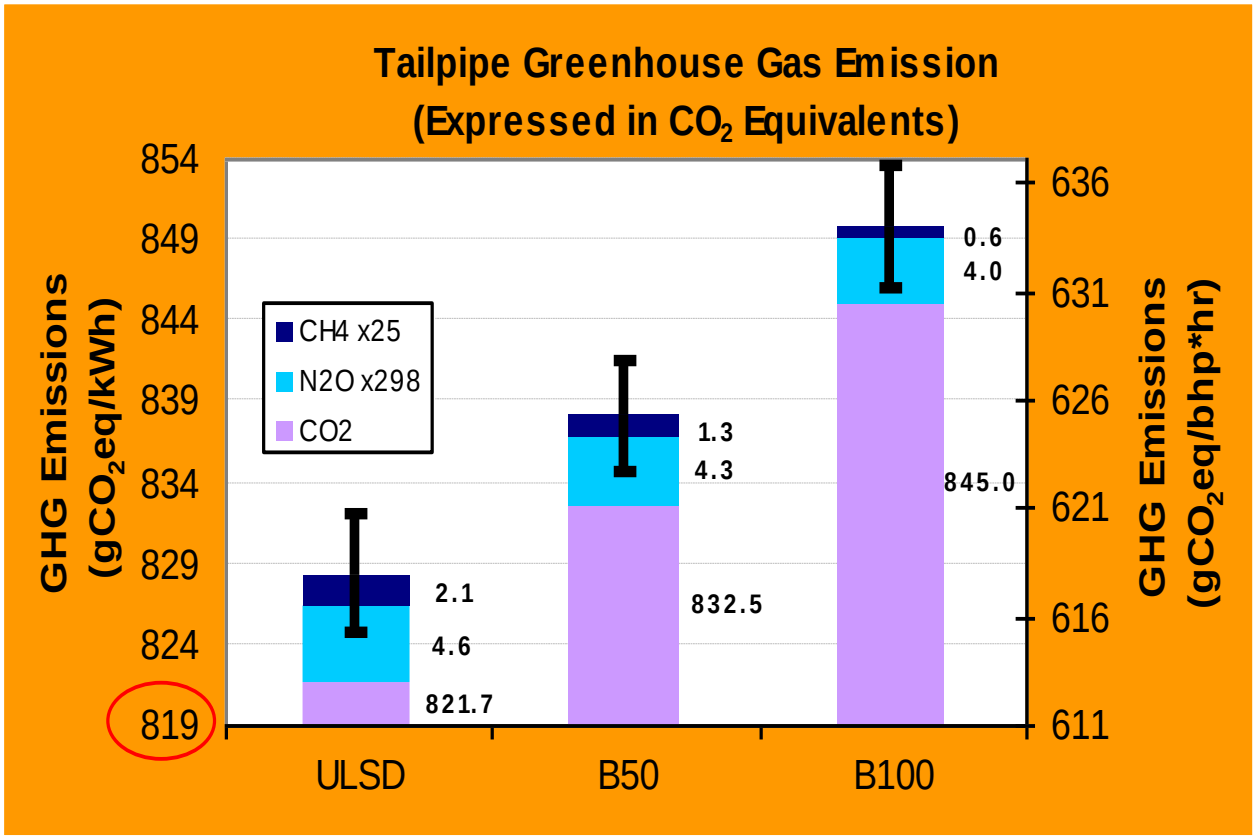


Figure 8-11. Tailpipe Greenhouse Gas Equivalent Emissions for the TRU Engine

9.0 Heavy-Duty Chassis Dynamometer Testing – Regulated Emissions

9.1 NO_x Emissions

The NO_x emission results for the testing with the soy-based biodiesel blends, the animal-based biodiesel blends, and renewable diesel blends for each of the test cycles for the heavy-duty chassis dynamometer testing are presented in Figure 9-1, Figure 9-2, and Figure 9-3 for the Caterpillar C-15, 2006 Cummins ISM, and 2007 MBE4000, respectively. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination. The error bars represent one standard deviation on the average value.

Table 9-1 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles relative to the CARB diesel, along with the associated p-values for statistical comparisons using a 2-tailed, 2 sample equal variance t-test. For the purposes of this discussion, we are considering p values of less that 0.05 to be statistically significant and p values of less than 0.10 to be marginally statistically significant. These limits are less stringent than for the engine testing due to the greater variability that is typically seen for chassis dynamometer vs. engine dynamometer testing.

It should be noted that for the 2000 Caterpillar C-15, the results are separated for the different feedstocks since there was a noticeable shift/drift in the NO_x emissions between the different test sequences that could not be attributed to fuel differences. This can be seen by comparing the emissions of the CARB-soy, CARB-animal, and CARB renewable for the UDDS cycle in Figure 9-1. The labeling of the CARB test results as CARB-soy, CARB-animal, and CARB renewable is meant to differentiate the test results for the CARB fuel for the different feedstock sequences, rather than a change in the CARB fuel that was used for each test sequence. The CARB fuel for all tests was the same as that used for the engine testing above. There is also a CARB fuel labeled CARB-2 that corresponds to the CARB results that were conducted in conjunction with the A20 and the A100 tests done at the end of the main test sequences. These tests were conducted as makeup for tests that were not considered to be valid in the main test sequence. These tests are also differentiated as "B20-2" and "B100-2" in Table 9-1. For the 2006 Cummins ISM and the 2007 MBE4000, there was no noticeable drift across the entire test sequence, so the average CARB values for these engines included the CARB test results over the entire sequence of testing.

For the heavy-duty chassis results, the NO_x emissions showed a consistent trend of increasing emissions with increasing biodiesel blend level. These differences were statistically significant or marginally statistically significant for nearly all of the test sequences for the B50 and B100 fuels, and for a subset of the tests on the B20 blends. The percentage increases for the NO_x emissions with biodiesel were generally greater for soy-based biodiesel compared with the animal-based biodiesel. The magnitude of the increases in NO_x emissions for the biodiesel blends for the 2006 Cummins ISM engine were either greater than or comparable to those found for the engine testing on this engine. For the 2007 MBE4000, the overall NO_x increases are in the same range for the chassis and engine dynamometer testing, with some differences seen for cycle/fuel/blend level combinations. The results for the renewable diesel fuel showed NO_x reductions for the UDDS cycle for the higher blends, but not statistically significant reductions over the 50-mph cruise

cycle. The magnitude of the reductions found for the renewable diesel was similar to those found in the engine testing.

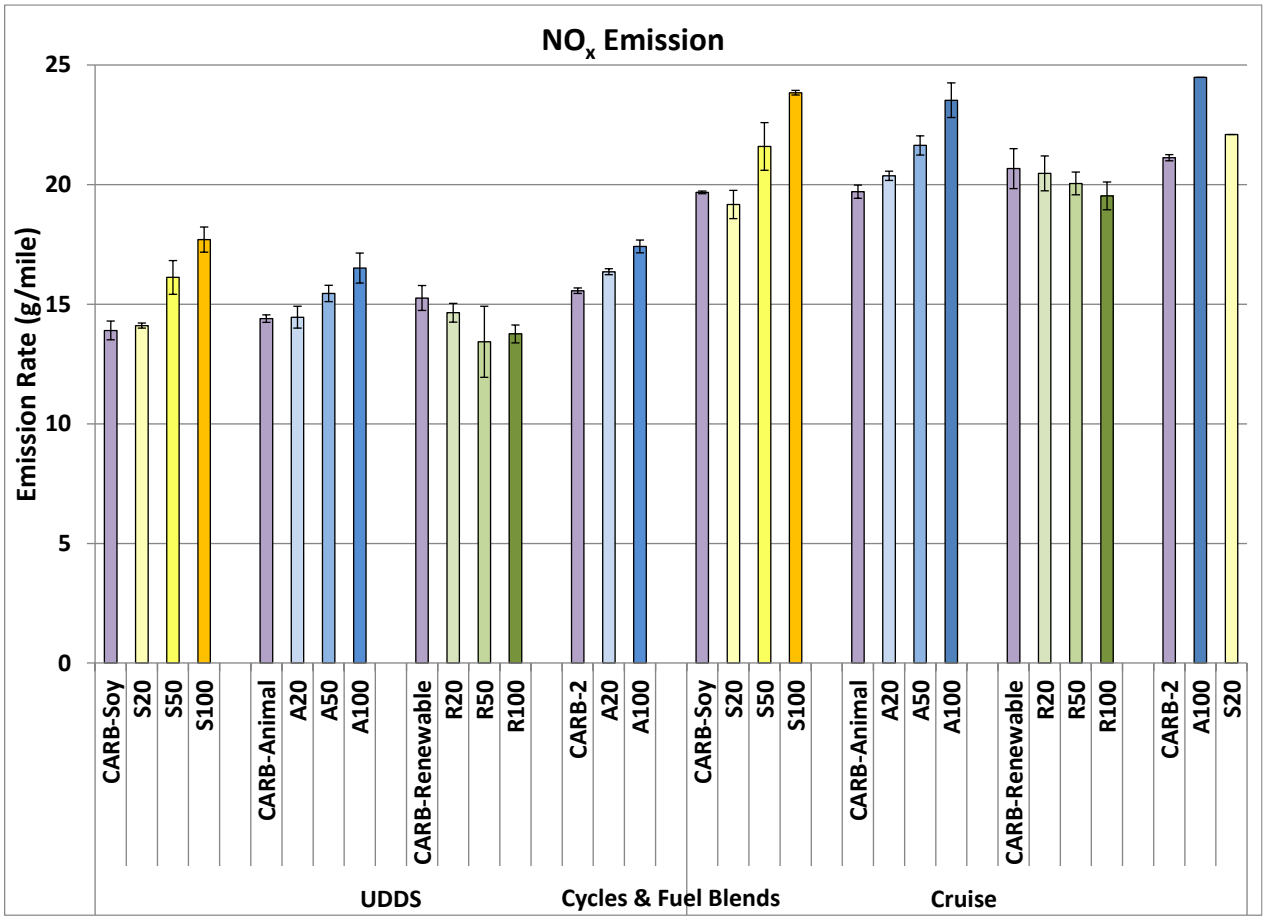


Figure 9-1. Average NO_x Emission Results for the Soy- and Animal-Biodiesel and Renewable Diesel Blends for 2000 C-15 Caterpillar

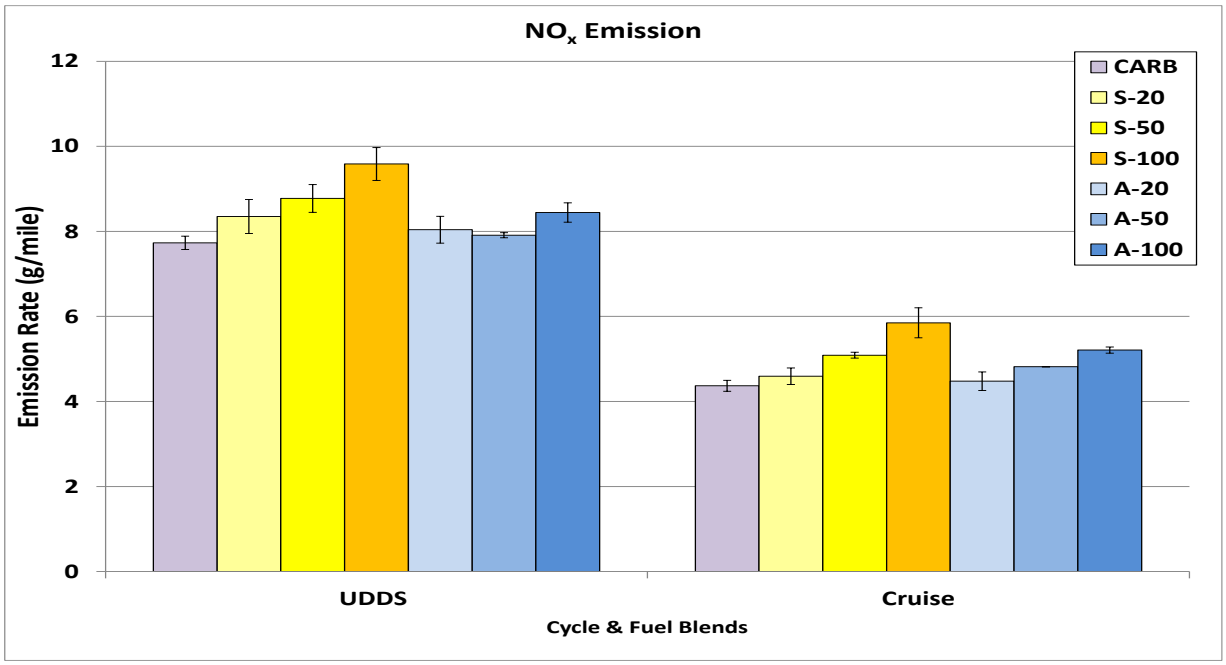


Figure 9-2 Average NO_x Emission Results for the Soy- and Animal-Biodiesel and Renewable Diesel Blends for 2006 Cummins ISM

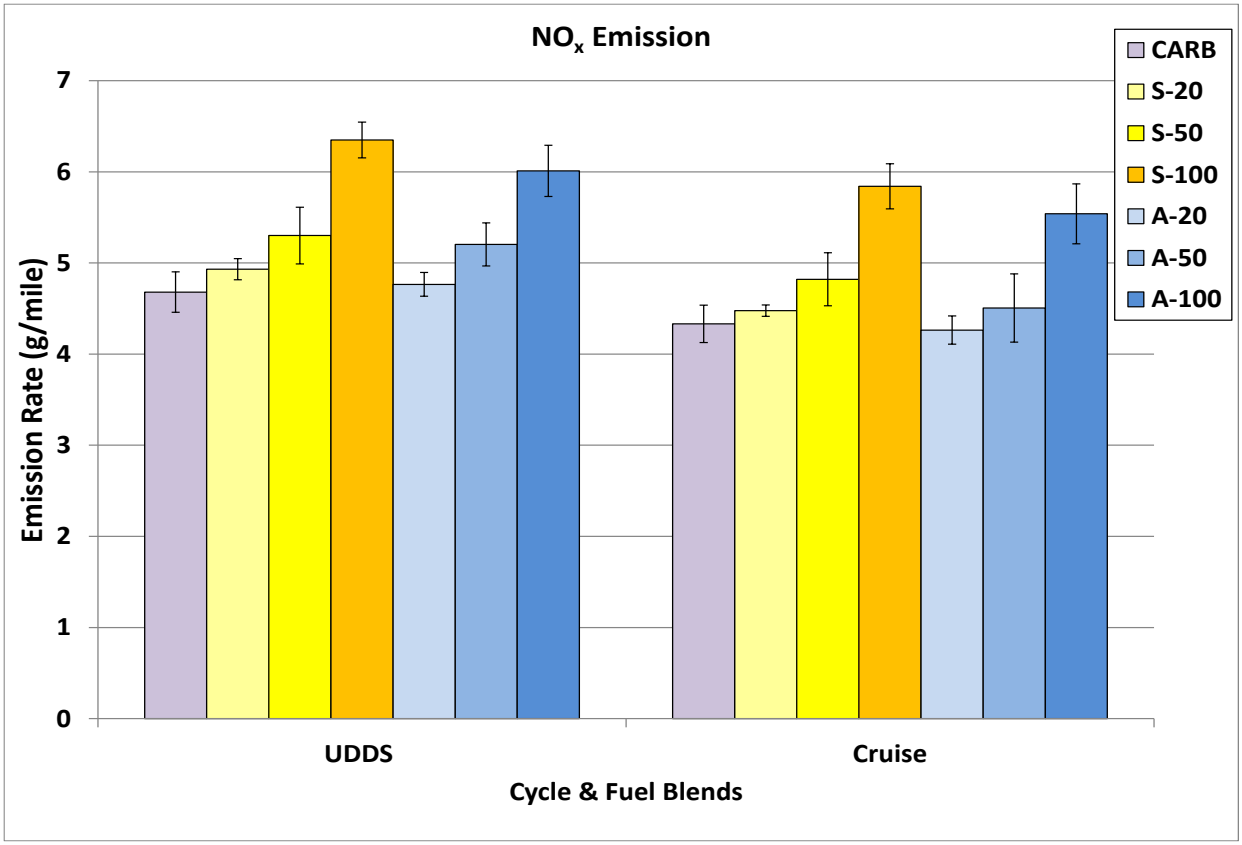


Figure 9-3 Average NO_x Emission Results for the Soy- and Animal-Biodiesel and Renewable Diesel Blends for 2007 MBE 4000

Table 9-1. NO_x Percentage Differences Between the Biodiesel and Renewable Diesel Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Renewable		Soy-based		Animal-based		Soy-based		Animal-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	1%	0.252	0%	0.779	-4%	0.027	8%	0.001	4%	0.019	5%	0.000	2%	0.318
	B50	16%	0.000	7%	0.000	-12%	0.003	14%	0.000	2%	0.018	13%	0.000	11%	0.000
	B100	27%	0.000	15%	0.000	-10%	0.000	24%	0.000	9%	0.000	36%	0.000	28%	0.000
	B20-2			5%	0.000										
	B100-2			12%	0.000										
50 mph Cruise	B20	-3%	0.334	3%	0.028	-1%	0.753	5%	0.059	2%	0.348	3%	0.286	-2%	0.556
	B50	10%	0.082	10%	0.002	-3%	0.306	16%	0.000	10%	0.000	11%	0.021	4%	0.354
	B100	21%	0.000	19%	0.001	-6%	0.101	34%	0.000	19%	0.000	35%	0.000	28%	0.000
	B20-2	5%													
	B100-2			16%											

9.2 PM Emissions

The PM emission results for the testing with the soy-based biodiesel blends, the animal-based biodiesel blends, and renewable diesel blends for each of the test cycles are presented in Figure 9-4, Figure 9-5, and Figure 9-6 for the Caterpillar C-15, 2006 Cummins ISM, and 2007 MBE4000, respectively. Table 9-2 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles relative to the CARB diesel, along with the associated p-values for statistical comparisons.

PM emissions showed consistent reductions for the all biodiesel blends and both cycles for the 2000 Caterpillar C-15 and the 2006 Cummins ISM, with the magnitude of the reductions increasing with blend level. These reductions were statistically significant for nearly all of the B50 and B100 cases, but for only a subset of the B20 results. The observation of reduced PM for biodiesel blends is consistent with previous studies as well as the results from the engine testing. The PM emissions reductions for the chassis dynamometer testing are similar to the reductions seen in the engine testing for the Cummins ISM engine for most testing combinations. The renewable blend also showed some statistically significant PM reductions for the R100 on the 2000 Caterpillar C-15, but no consistent trends for the other blend levels. PM emissions did not show any consistent trends for the DPF equipped 2007 MBE4000, since most of the combustion-related PM is eliminated in the DPF.

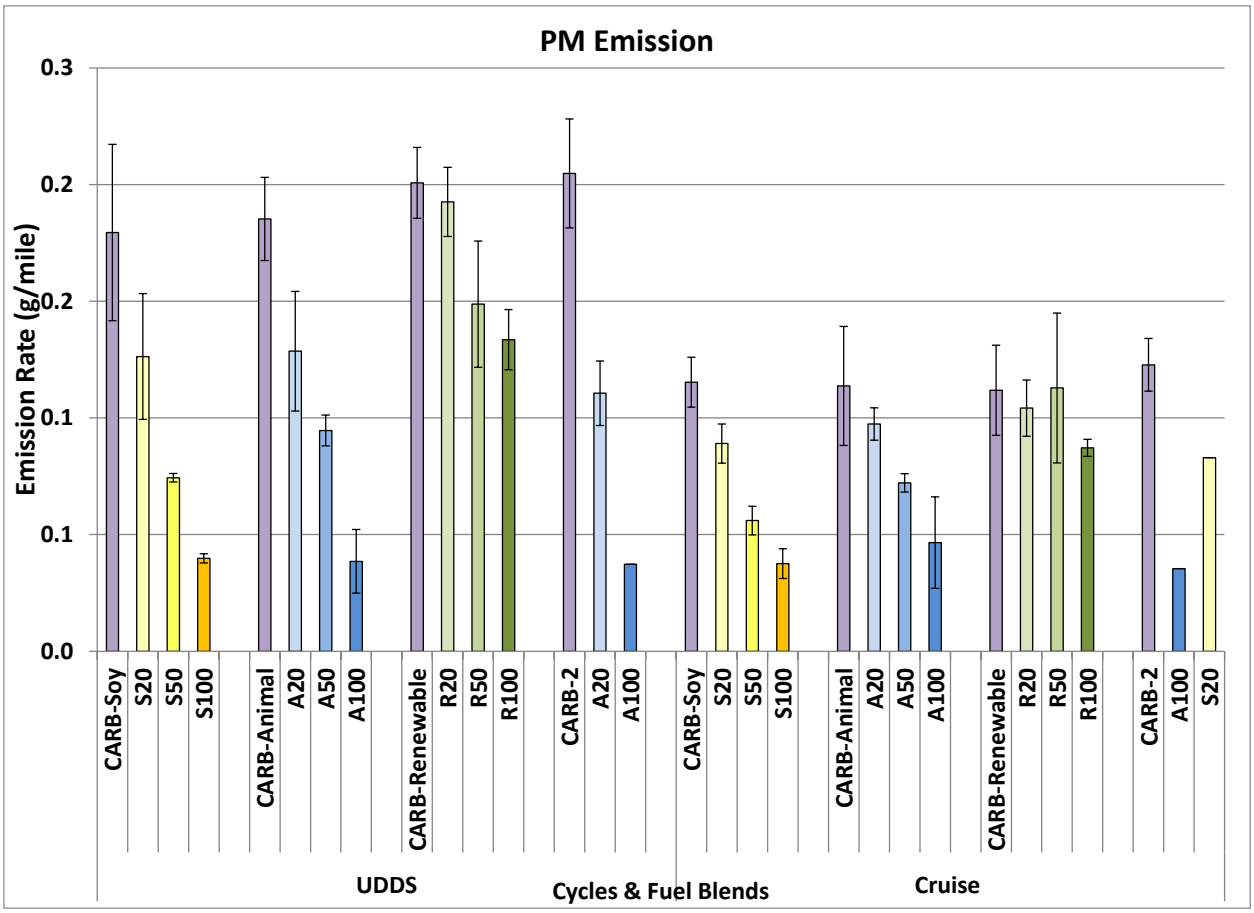


Figure 9-4. Average PM Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for C-15

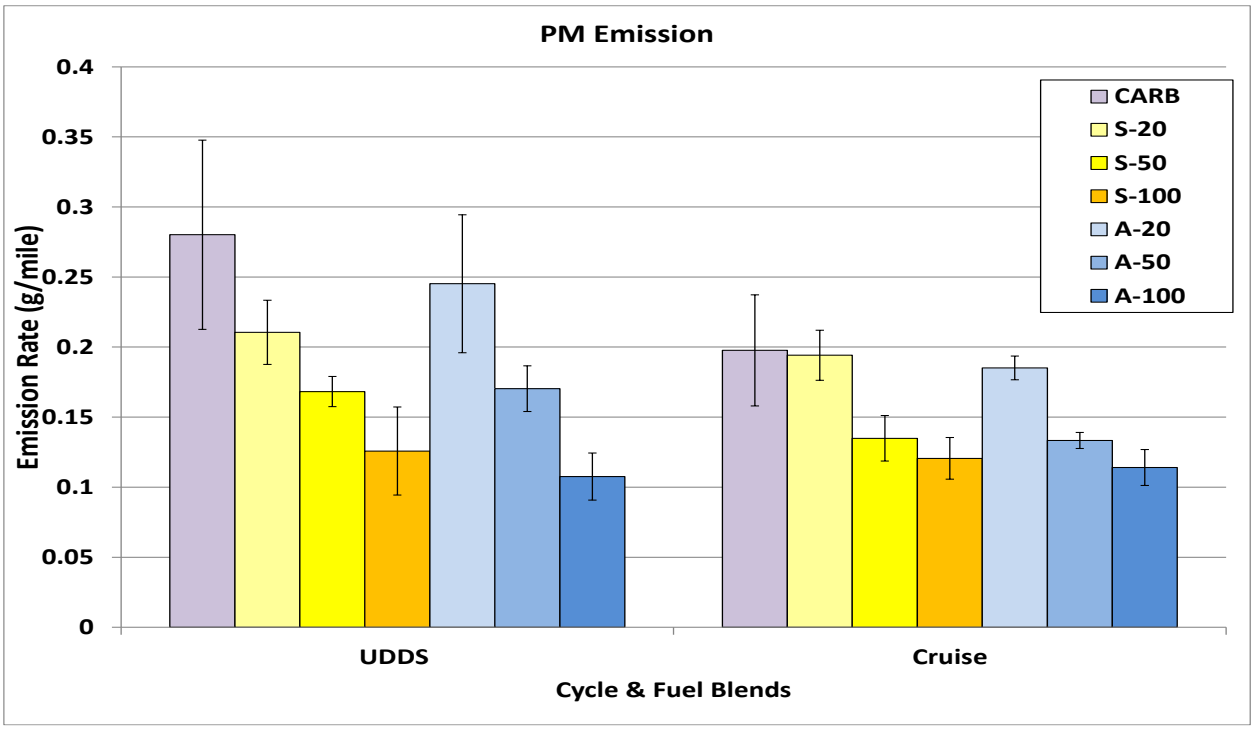


Figure 9-5 Average PM Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for 2006 Cummins ISM

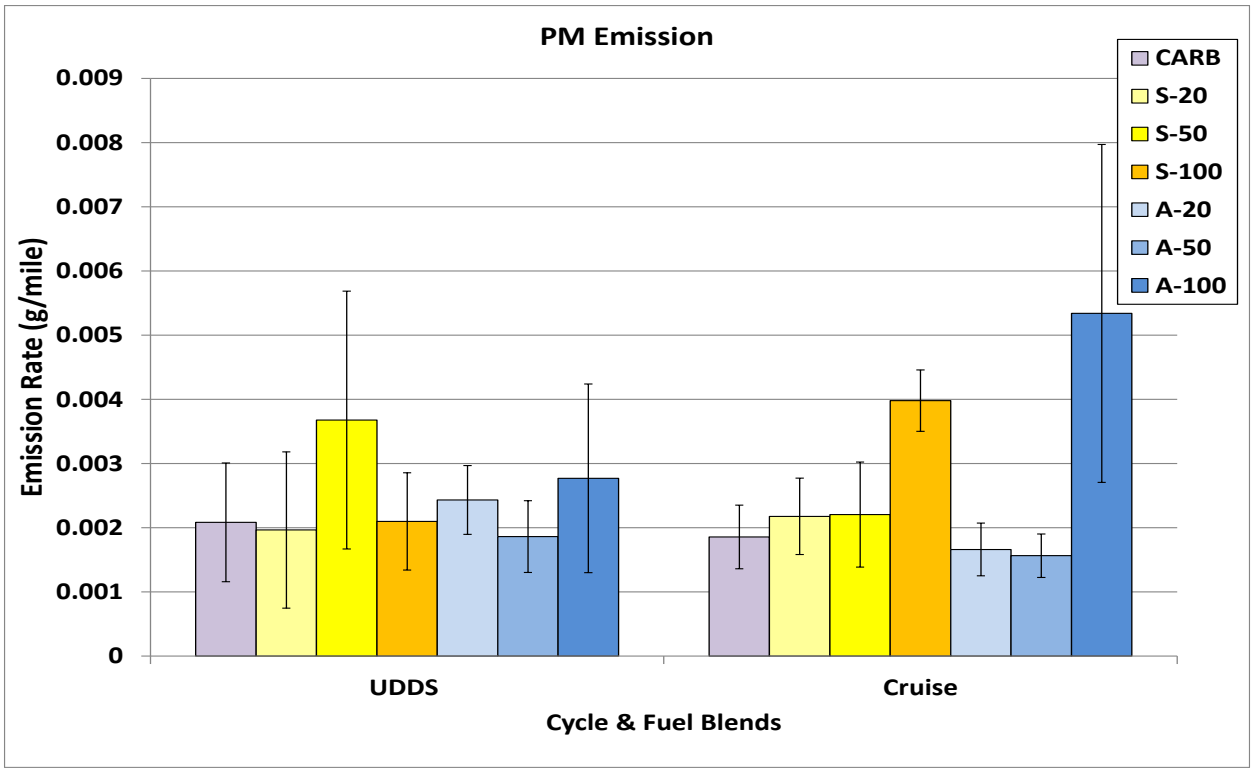


Figure 9-6 Average PM Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for 2007 MBE 4000.

Table 9-2. PM Percentage Differences Between the Biodiesel and Renewable Diesel Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Renewable		Soy-based		Animal-based		Soy-based		Animal-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	-30%	0.118	-31%	0.076	-4%	0.510	-25%	0.144	-12%	0.470	-6%	0.732	17%	0.478
	B50	-59%	0.009	-49%	0.003	-26%	0.022	-40%	0.033	-39%	0.036	76%	0.003	-11%	0.613
	B100	-78%	0.003	-79%	0.002	-33%	0.002	-55%	0.011	-62%	0.006	1%	0.959	33%	0.227
	B20-2			-46%	0.039										
	B100-2			-82%											
50 mph Cruise	B20	-23%	0.053	-14%	0.346	-7%	0.576	-2%	0.890	-6%	0.614	17%	0.419	-10%	0.502
	B50	-51%	0.004	-37%	0.050	1%	0.962	-32%	0.033	-33%	0.065	19%	0.442	-16%	0.294
	B100	-67%	0.002	-59%	0.023	-22%	0.086	-39%	0.005	-42%	0.008	114%	0.000	188%	0.012
	B20-2	-32%													
	B100-2			-71%											

9.3 THC Emissions

The THC emission results for the testing with the soy-based biodiesel blends, the animal-based biodiesel blends, and renewable diesel blends for each of the test cycles are presented in Figure 9-7, Figure 9-8, and Figure 9-9 for the Caterpillar C-15, 2006 Cummins ISM, and 2007 MBE4000, respectively. Table 9-3 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles and the corresponding p-values for the statistical analysis.

THC emissions showed reductions for the B100 for nearly all blend level/cycle combinations for the non-DPF equipped engines and for the B50 for the 2006 Cummins ISM and the animal-based biodiesel for the 2000 Caterpillar C-15. The reductions for the highest blend levels are less than those seen in the corresponding engine tests for the Cummins ISM and for the EPA estimates. The renewable diesel also showed lower THC emissions, but these were only statistically significant or marginally statistically significant for the R100 for the 2000 Caterpillar C-15 over the UDDS cycle. The absolute THC emissions for 2007 MBe4000 were considerably lower than those for the non-DPF equipped vehicles. Interestingly, the DPF equipped 2007 MBE4000 showed some reductions in THC for the B50 and B100 blends over the UDDS, albeit a very low levels, but no consistent differences over the 50-mph cruise.

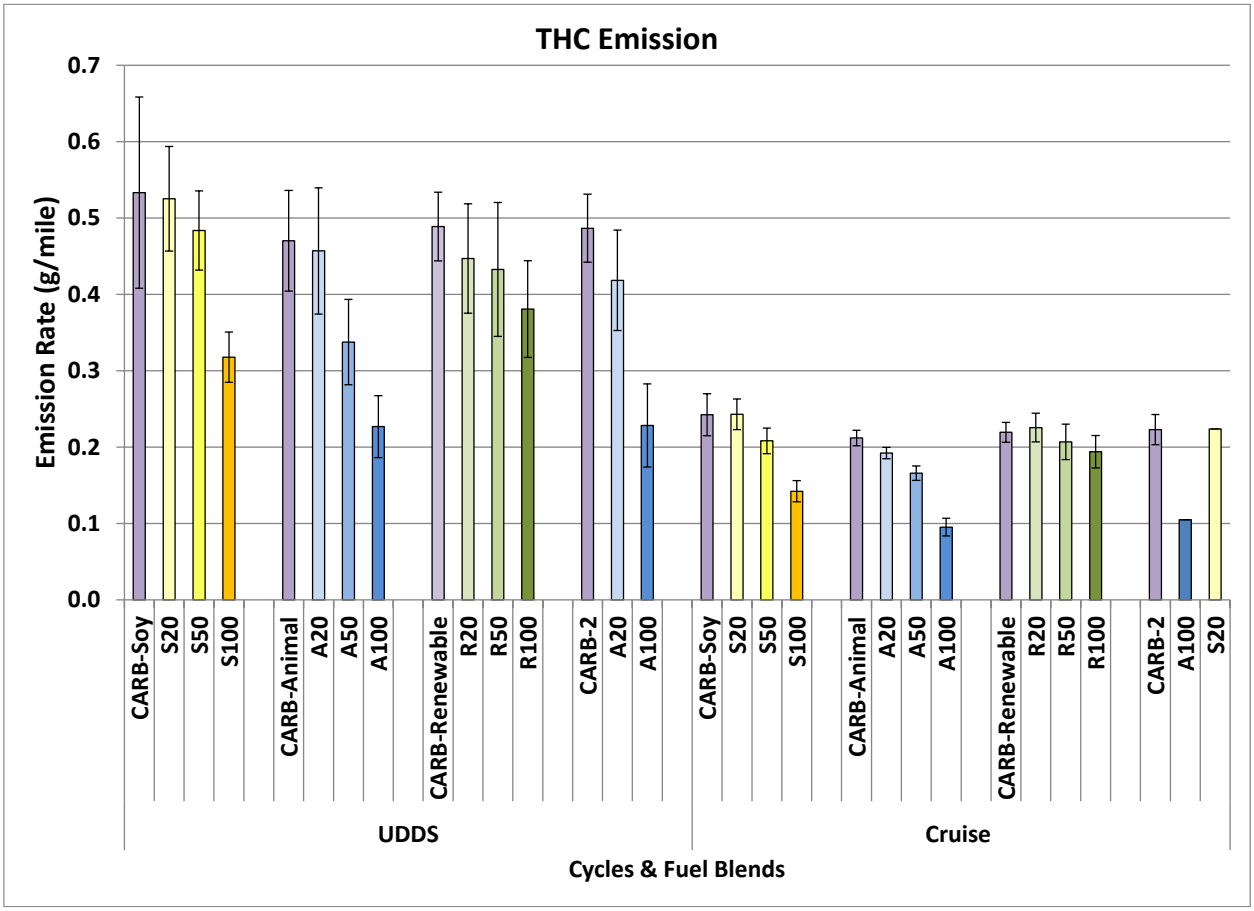


Figure 9-7. Average THC Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for C-15

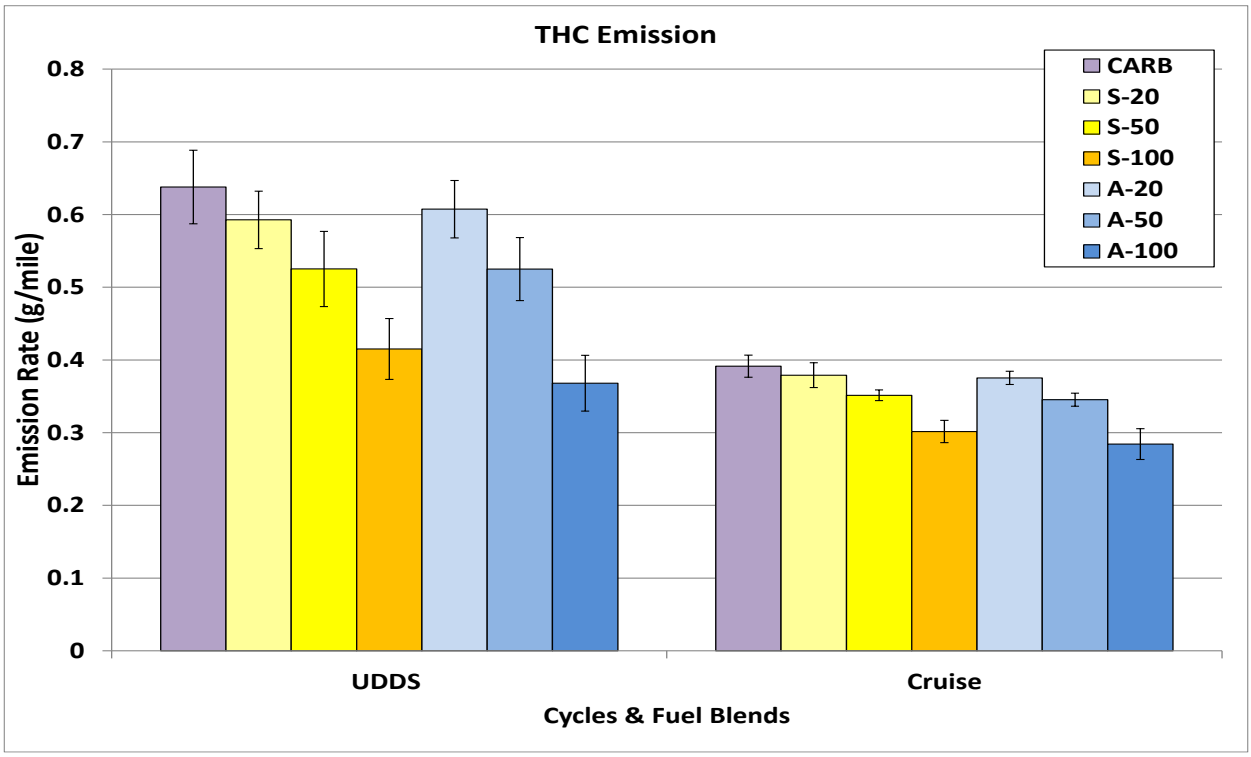


Figure 9-8. Average THC Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for 2006 Cummins ISM

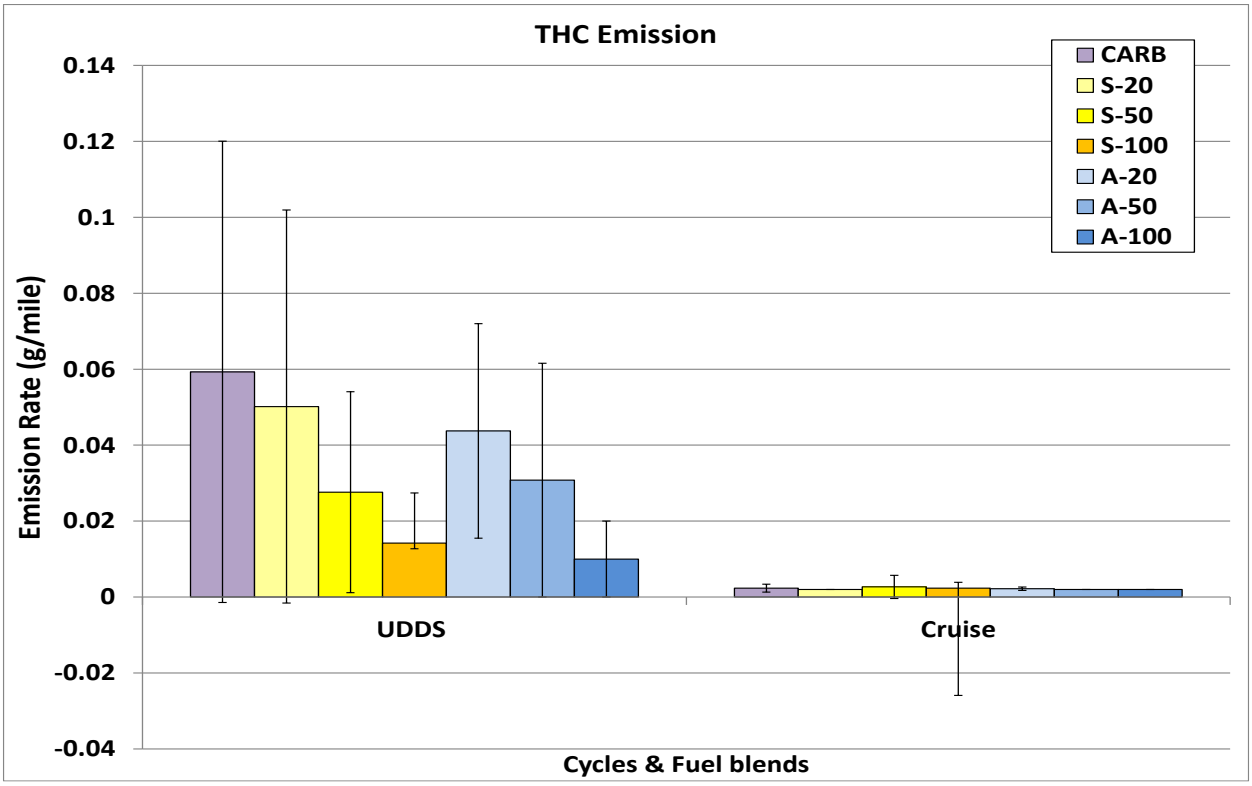


Figure 9-9. Average THC Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for 2007 MBE 4000.

Table 9-3. THC Percentage Differences Between the Biodiesel and Renewable Diesel Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Renewable		Soy-based		Animal-based		Soy-based		Animal-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	-2%	0.893	-3%	0.763	-9%	0.169	-7%	0.084	-5%	0.229	-15%	0.613	-26%	0.494
	B50	-9%	0.470	-28%	0.004	-11%	0.119	-18%	0.001	-18%	0.000	-53%	0.046	-48%	0.195
	B100	-40%	0.002	-52%	0.000	-22%	0.003	-35%	0.000	-42%	0.000	-76%	0.004	-83%	0.031
	B20-2			-14%	0.137										
	B100-2			-53%	0.003										
50 mph Cruise	B20	0%	0.982	-9%	0.054	3%	0.627	-3%	0.285	-4%	0.133	-14%	0.606	-6%	0.750
	B50	-14%	0.173	-22%	0.005	-6%	0.402	-10%	0.003	-12%	0.001	14%	0.806	-14%	0.750
	B100	-41%	0.011	-55%	0.000	-12%	0.103	-23%	0.000	-27%	0.000	0%	0.808	-14%	0.778
	B20-2	0%													
	B100-2			-53%											

9.4 CO Emissions

The CO emission results for the testing with the soy-based biodiesel blends, the animal-based biodiesel blends, and renewable diesel blends for each of the test cycles are presented in Figure 9-10, Figure 9-11, and Figure 9-12 for the Caterpillar C-15, 2006 Cummins ISM, and 2007 MBE4000, respectively. Table 9-4 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, and the corresponding p-values for the statistical analysis.

CO emission results showed consistent and generally significant reductions for all biodiesel blends for the non-DPF-equipped engines, with higher reductions with increasing blend levels. The CO reductions were statistically significant for most of the B50 and B100 blends. For the B20 blends, the reductions were statistically significant in some cases but not for others. For the engine testing, 2006 Cummins ISM engine only showed reductions in CO for the animal-based biodiesel, and these reductions were similar to or slightly less than those seen for the chassis testing on this vehicle. For the renewable diesel, both the R50 and R100 showed reductions in CO that were either statistically significant or marginally statistically significant. CO emissions did not show consistent trends at the low levels for the DPF equipped 2007 MBE4000, although statistically significant CO reductions were found for the B100 soy-based and animal-based blends for the UDDS cycle. For the engine dynamometer testing, the MBE4000 did show some CO reductions for the FTP for both the B50 and the B100 blends, but not for most of the other testing combinations.

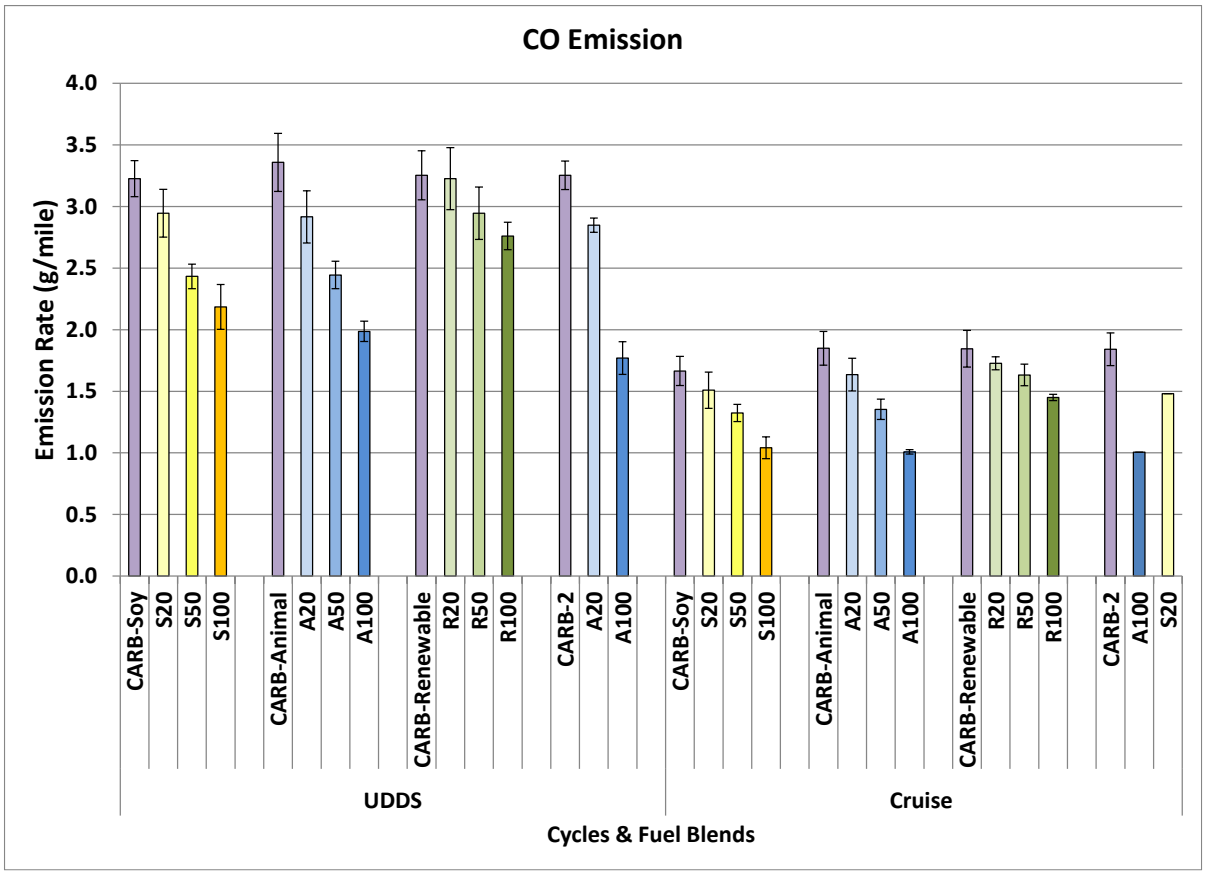


Figure 9-10. Average CO Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for C-15

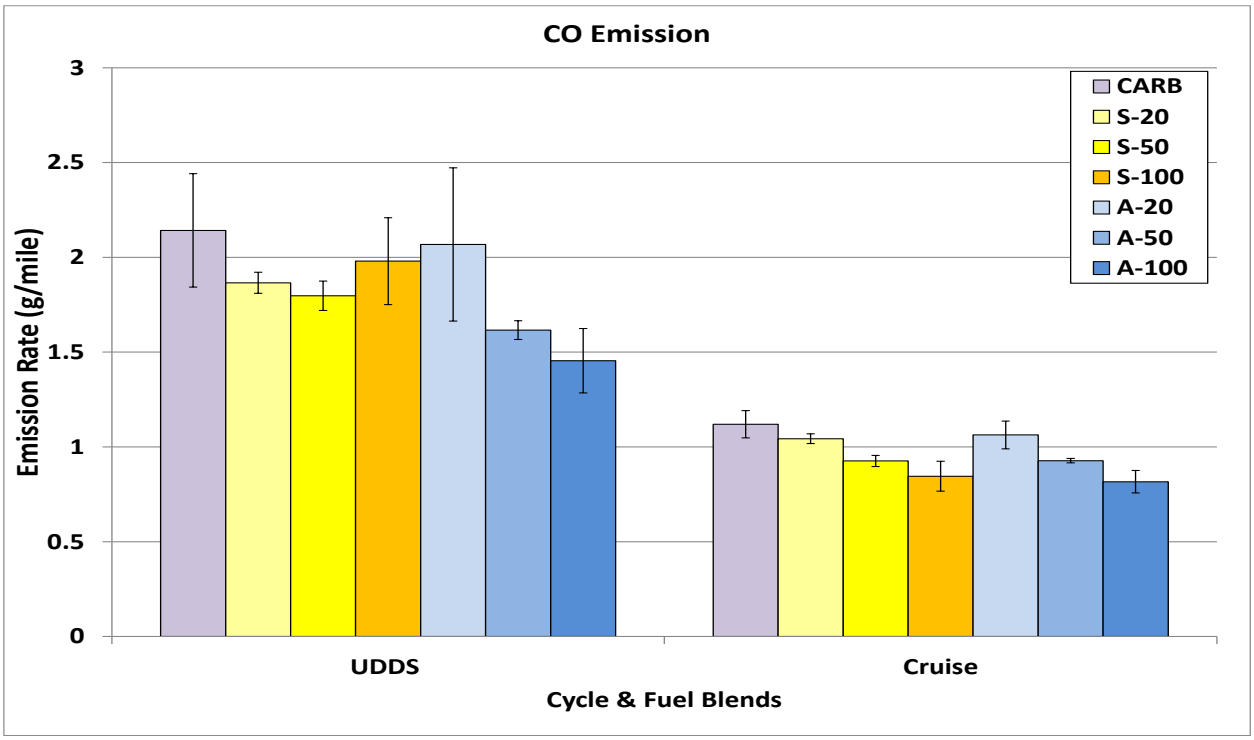


Figure 9-11 Average CO Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for 2006 Cummins ISM.

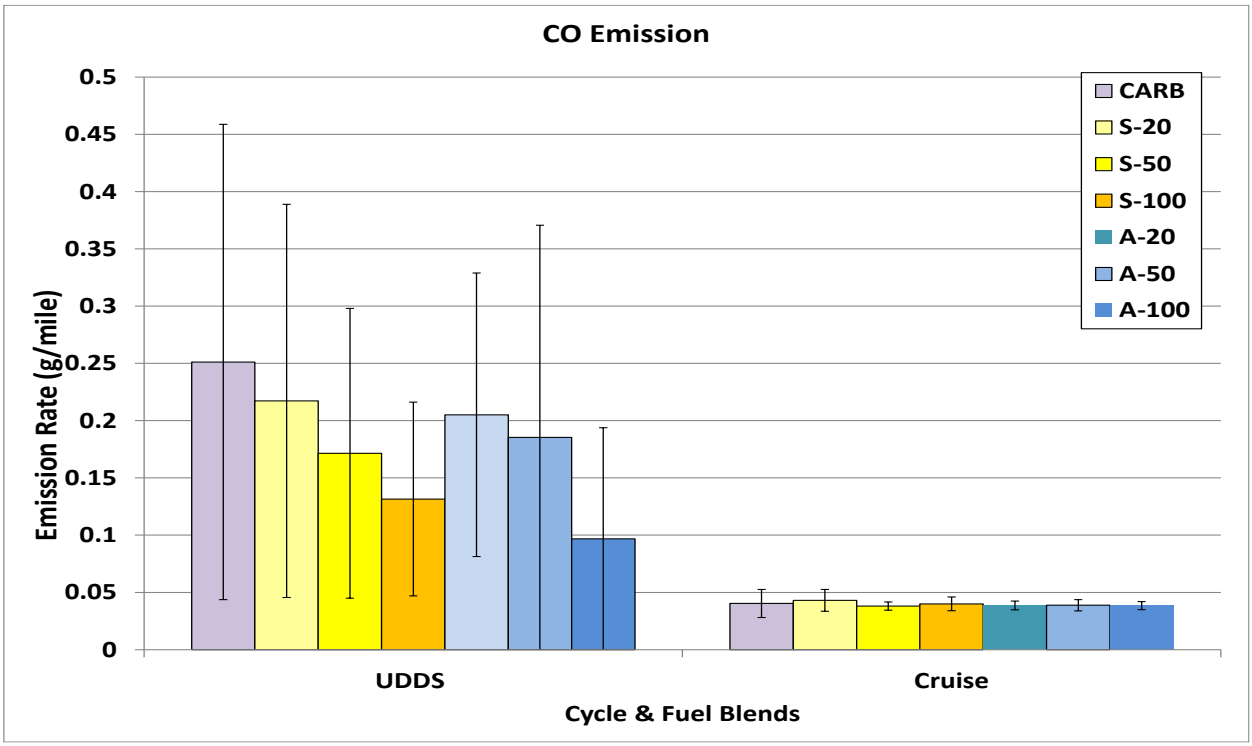


Figure 9-12 Average CO Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for 2007 MBE 4000.

Table 9-4. CO Percentage Differences Between the Biodiesel and Renewable Diesel Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Renewable		Soy-based		Animal-based		Soy-based		Animal-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	-9%	0.018	-13%	0.007	-1%	0.810	-13%	0.044	-3%	0.680	-14%	0.579	-18%	0.561
	B50	-25%	0.000	-27%	0.000	-9%	0.011	-16%	0.016	-25%	0.001	-32%	0.160	-26%	0.384
	B100	-32%	0.000	-41%	0.000	-15%	0.000	-8%	0.275	-32%	0.000	-48%	0.027	-61%	0.048
	B20-2			-12%	0.001										
	B100-2			-46%	0.000										
50 mph Cruise	B20	-9%	0.305	-12%	0.125	-6%	0.252	-7%	0.118	-5%	0.289	7%	0.753	-4%	0.770
	B50	-20%	0.025	-27%	0.006	-12%	0.081	-17%	0.002	-17%	0.002	-6%	0.763	-4%	0.800
	B100	-37%	0.006	-45%	0.000	-21%	0.007	-24%	0.000	-27%	0.000	-1%	0.793	-5%	0.782
	B20-2	-20%													
	B100-2			-45%											

9.5 CO_2 Emissions

The CO emission results for the testing with the soy-based biodiesel blends, the animal-based biodiesel blends, and renewable diesel blends for each of the test cycles are presented in Figure 9-13, Figure 9-14, and Figure 9-15 for the Caterpillar C-15, 2006 Cummins ISM, and 2007 MBE4000, respectively. Table 9-5 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

CO_2 emissions showed some reductions for the R100 and R50 fuels for the 2000 Caterpillar C-15 and some increases for the animal-based and soy-based biodiesel blends for the 2007 MBE4000. These trends are directionally consistent with the trends seen for the engine dynamometer testing, although they are not consistent across the range of vehicles/engines testing on the chassis dynamometer. The CO_2 increases for the 2007 MBE4000 fall within the 1-5% range that was seen in the heavy-duty engine dynamometer testing for the various biodiesel blends. The reductions in CO_2 for the R50 and R100 fuels were similar to the 2-3% CO_2 reductions seen for the R100 in the engine testing, which is also consistent with the results from previous studies with the renewable diesel fuel (Kleinschek 2005; Rantanen et al. 2005; Kuronen et al. 2007).

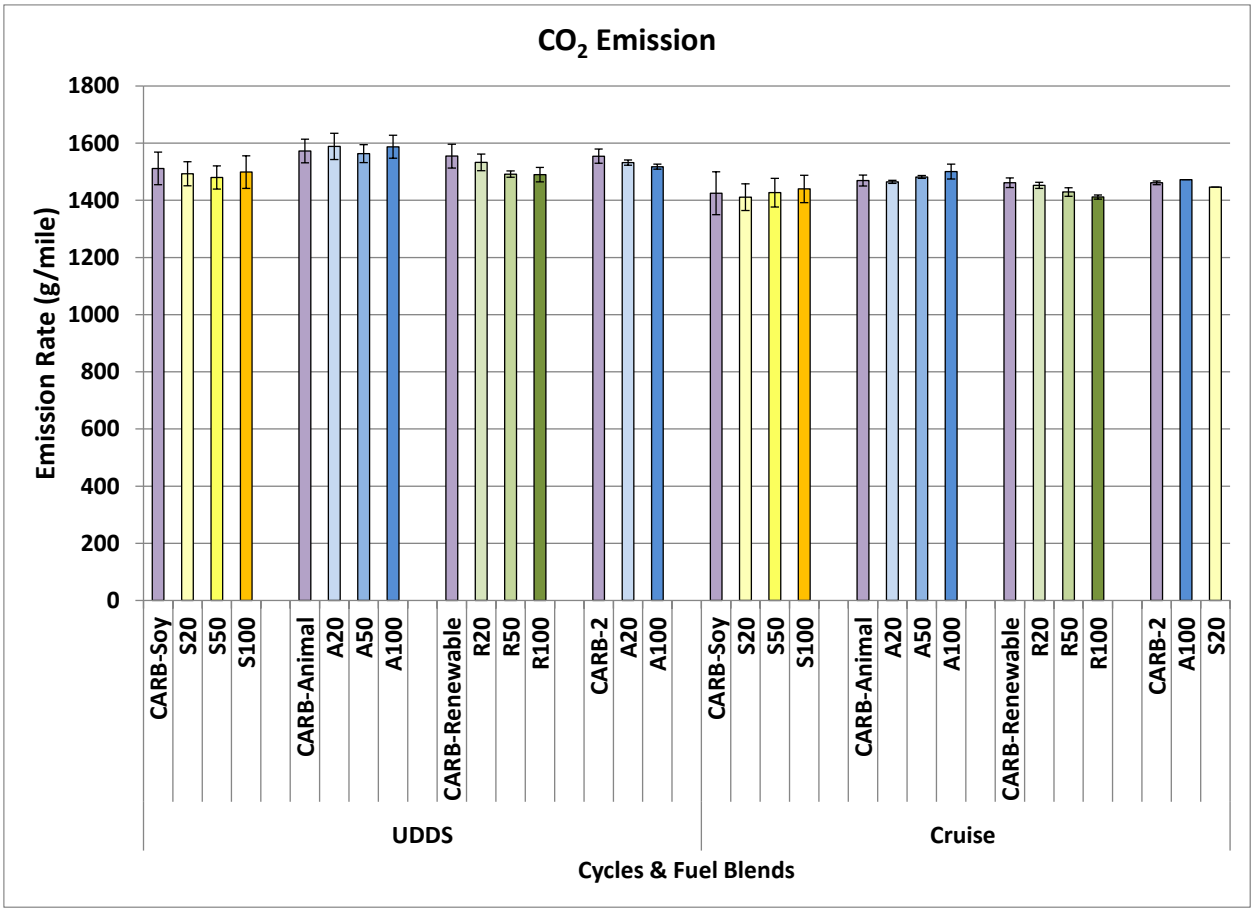


Figure 9-13.Average CO_2 Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for C-15

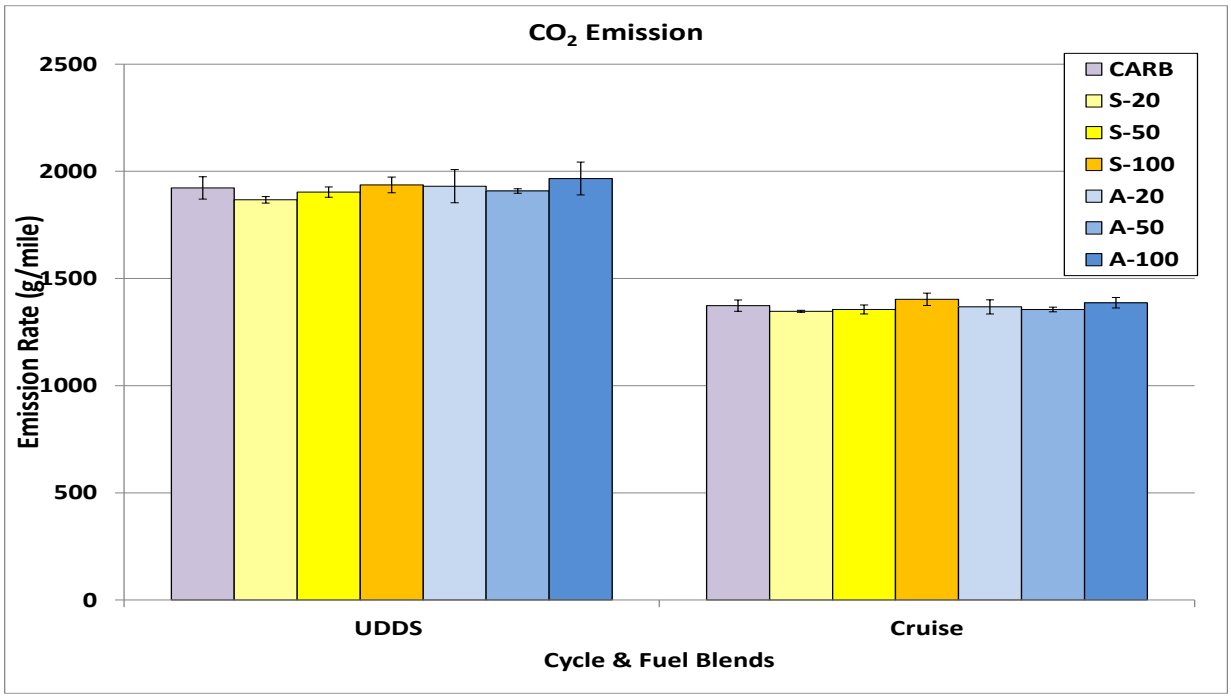


Figure 9-14 Average CO_2 Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for the 2006 Cummins ISM

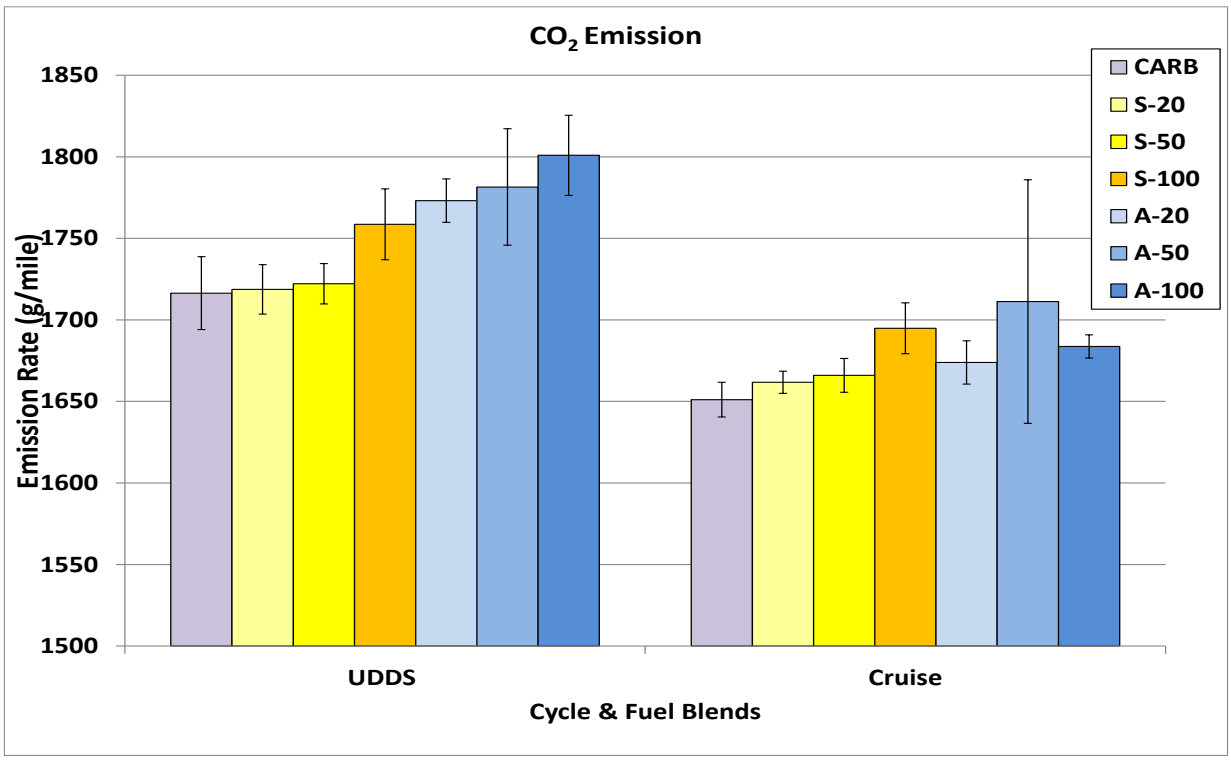


Figure 9-15 Average CO_2 Emission Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for the 2007 MBE 4000.

Table 9-5. CO_2 Percentage Differences Between the Biodiesel and Renewable Diesel Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Renewable		Soy-based		Animal-based		Soy-based		Animal-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	-1%	0.529	1%	0.534	-1%	0.279	-3%	0.024	0%	0.809	0%	0.714	3%	0.000
	B50	-2%	0.425	-1%	0.669	-4%	0.003	-1%	0.407	-1%	0.521	0%	0.330	4%	0.000
	B100	-1%	0.705	1%	0.542	-4%	0.004	1%	0.580	2%	0.195	2%	0.000	5%	0.000
	B20-2			-1%	0.141										
	B100-			-2%	0.128										
50 mph Cruise	B20	-1%	0.813	0%	0.713	-1%	0.454	-2%	0.133	0%	0.762	1%	0.165	1%	0.011
	B50	0%	0.970	1%	0.326	-2%	0.047	-1%	0.327	-1%	0.294	1%	0.087	4%	0.080
	B100	1%	0.794	2%	0.163	-3%	0.005	2%	0.098	1%	0.484	3%	0.001	2%	0.001
	B20-2	-1%													
	B100-2			1%											

9.6 Fuel Economy

The fuel economy results for the testing with the soy-based and animal-based biodiesel blends and the renewable diesel blends for each of the test cycles are presented in Figure 9-13, Figure 9-14, and Figure 9-15 for the Caterpillar C-15, 2006 Cummins ISM, and 2007 MBE4000, respectively, on a miles per gallon (mi/gal.) basis. The fuel economy was determined via carbon balance using the carbon weight fractions and densities of each fuel. Table 9-6 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

The biodiesel and renewable diesel blends showed reductions in fuel economy relative to the CARB ULSD. This trend was statistically significant for B100 and R100 in all cases, but only for a subset of the B20/R20 and B50/R50 blends. For the B100/R100 fuels, the reductions in fuel economy ranged from 4-10%, which was comparable to the corresponding increases in fuel consumption for these fuels that was seen in the heavy-duty engine testing.

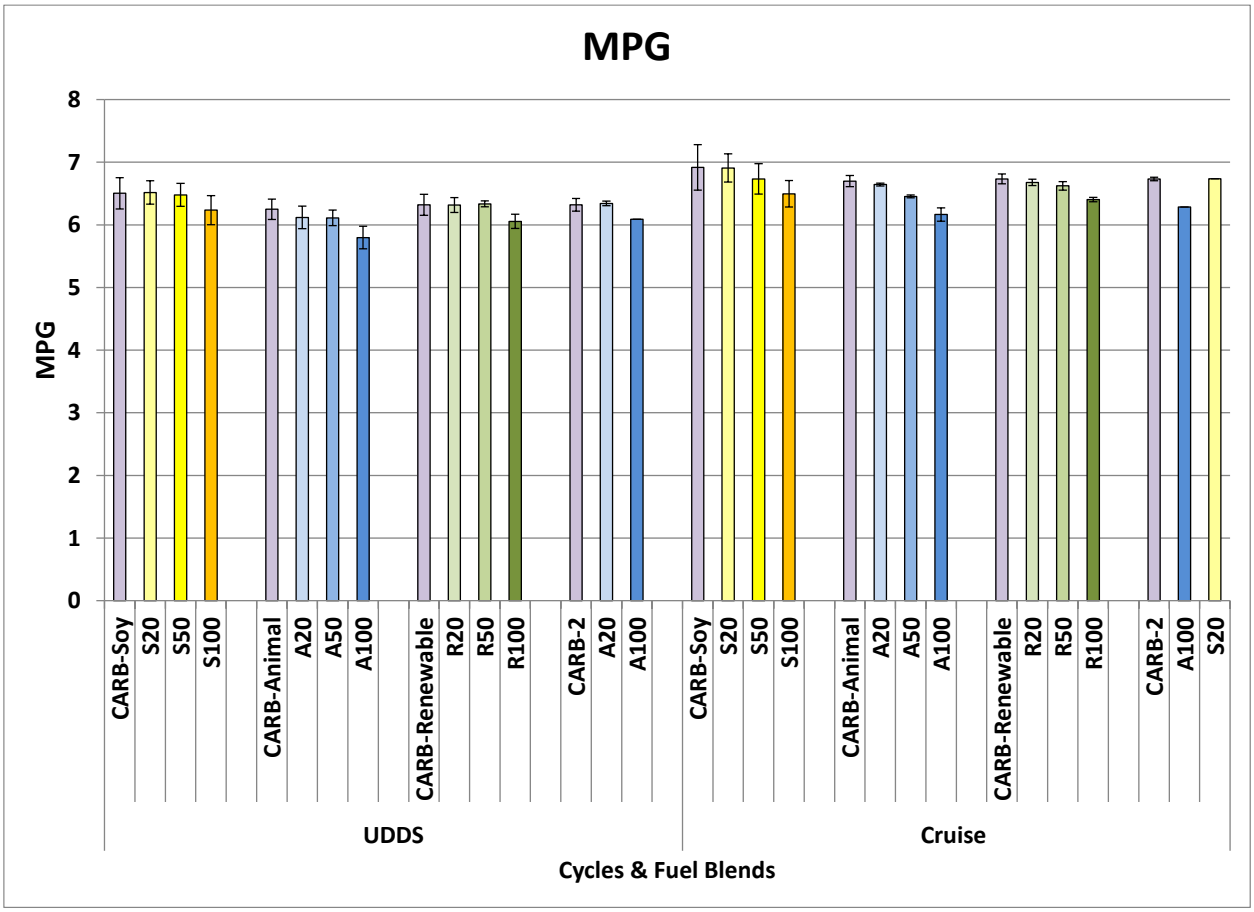


Figure 9-16. Average Fuel Economy Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for C-15

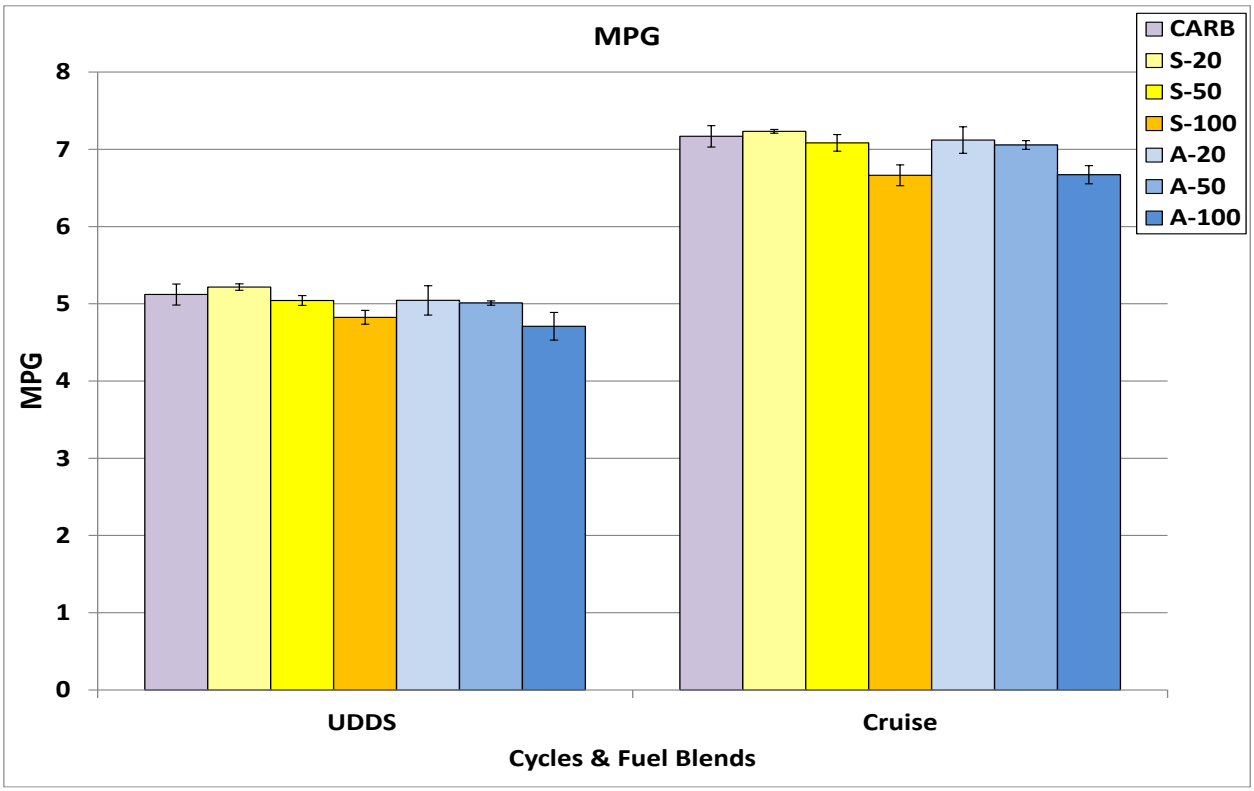


Figure 9-17 Average Fuel Economy Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for 2006 Cummins ISM

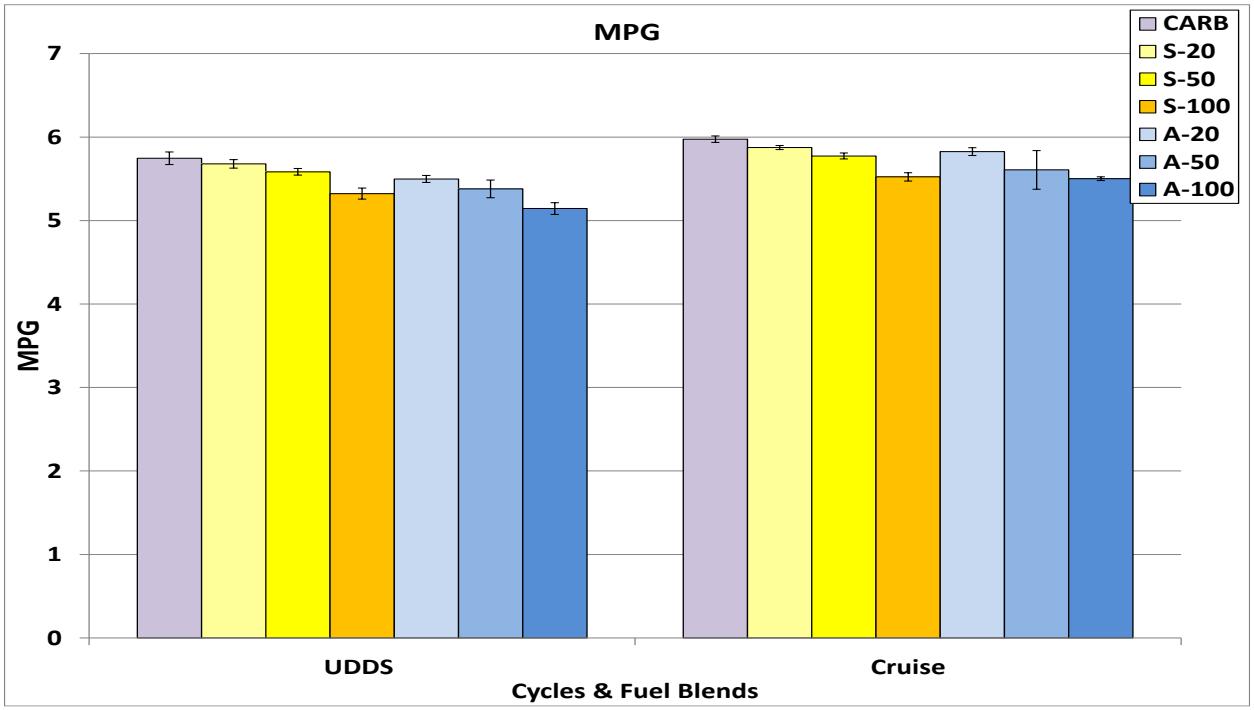


Figure 9-18 Average Fuel Economy Results for the Soy- and Animal-Based Biodiesel and the Renewable Diesel for each Cycle for 2007 MBE 4000

Table 9-6. Fuel Economy Percentage Differences Between the Biodiesel and Renewable Diesel Blends and the CARB ULSD base fuel for each Cycle.

	CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE4000			
		Soy-based		Animal-based		Renewable		Soy-based		Animal-based		Soy-based		Animal-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	B20	0.20%	0.920	-2%	0.216	-0.06%	0.963	2%	0.116	-1%	0.370	-1%	0.003	-4%	0.000
	B50	-0.39%	0.453	-2%	0.131	0.24%	0.837	-2%	0.218	-2%	0.076	-3%	0.000	-6%	0.000
	B100	-4%	0.082	-7%	0.080	-4%	0.130	-6%	0.000	-8%	0.000	-7%	0.000	-10%	0.000
	B20-2			0%											
	B100-2			-4%											
50 mph Cruise	B20	-0.12%	0.976	-1%	0.353	-1%	0.344	1%	0.454	-1%	0.642	-2%	0.005	-2%	0.000
	B50	-3%	0.535	-4%	0.009	-2%	0.112	-1%	0.376	-2%	0.224	-3%	0.000	-6%	0.004
	B100	-6%	0.189	-8%	0.003	-5%	0.001	-7%	0.000	-7%	0.001	-8%	0.000	-8%	0.000
	B20-2	0%													
	B100-2			-7%											

10.0 Heavy-Duty Chassis Dynamometer Testing – Unregulated Emissions

10.1 Volatile Organic Compounds

Volatile organic compound (VOC) emissions results for the testing with the soy-based, animal-based and renewable feedstock testing are shown in Figure 10-1 and Figure 10-2, respectively, for the UDDS and the 50-mph Cruise cycles for the 2000 Caterpillar C-15. VOC emissions for the 2006 Cummins ISM are shown in Figure 10-3. These figures show some of the most prominent VOC components. The results for the individual VOC components are shown in greater detail in separate figures below. The results for each test cycle (UDDS and 50 mph Cruise)/blend level combination represent the average of all test runs done on that particular combination. The error bars represent one standard deviation on the average value.

VOC emissions were typically higher on a g/mi basis for the UDDS cycle compared with the 50 mph Cruise cycle. Benzene emissions were the highest of the VOCs for both test cycles and each of the fuels for the 2000 Caterpillar C-15, while benzene and 1,3-butadiene were the highest VOCs for the 2006 Cummins ISM. The 1,3-Butadiene emissions showed the greatest reductions for the 2000 Caterpillar C-15 in comparing the 50 mph cruise with the UDDS cycle. The trends in emissions for the specific emissions components are discussed individually in the following subsections, but generally the reductions were found for the aromatic species for greater percentages of biodiesel or renewable diesel, consistent with the reduction of aromatics in the fuel.

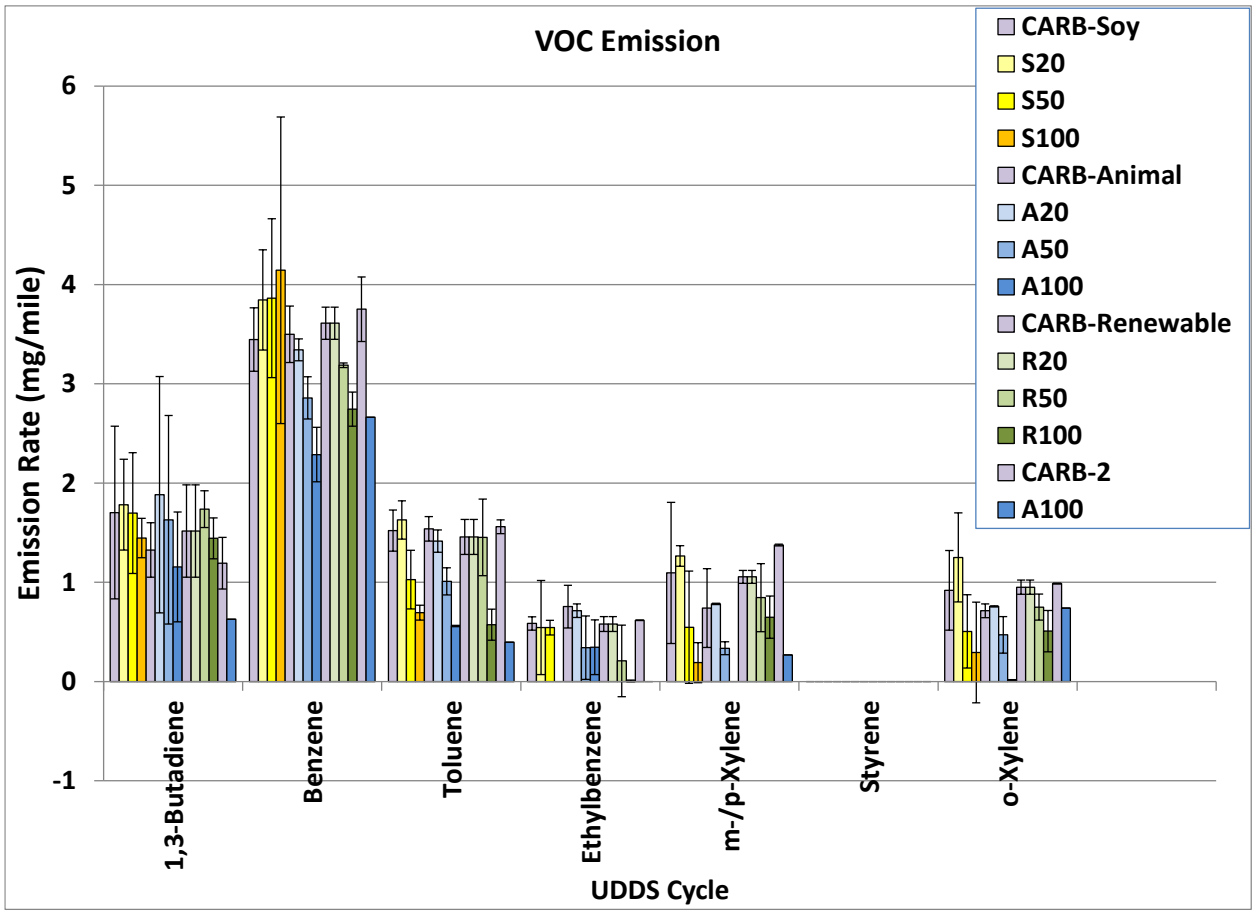


Figure 10-1. Average VOC Emission Results for the Soy-Biodiesel and Animal-Based and Renewable blends Testing for the UDDS Cycle for the 2000 Caterpillar C-15

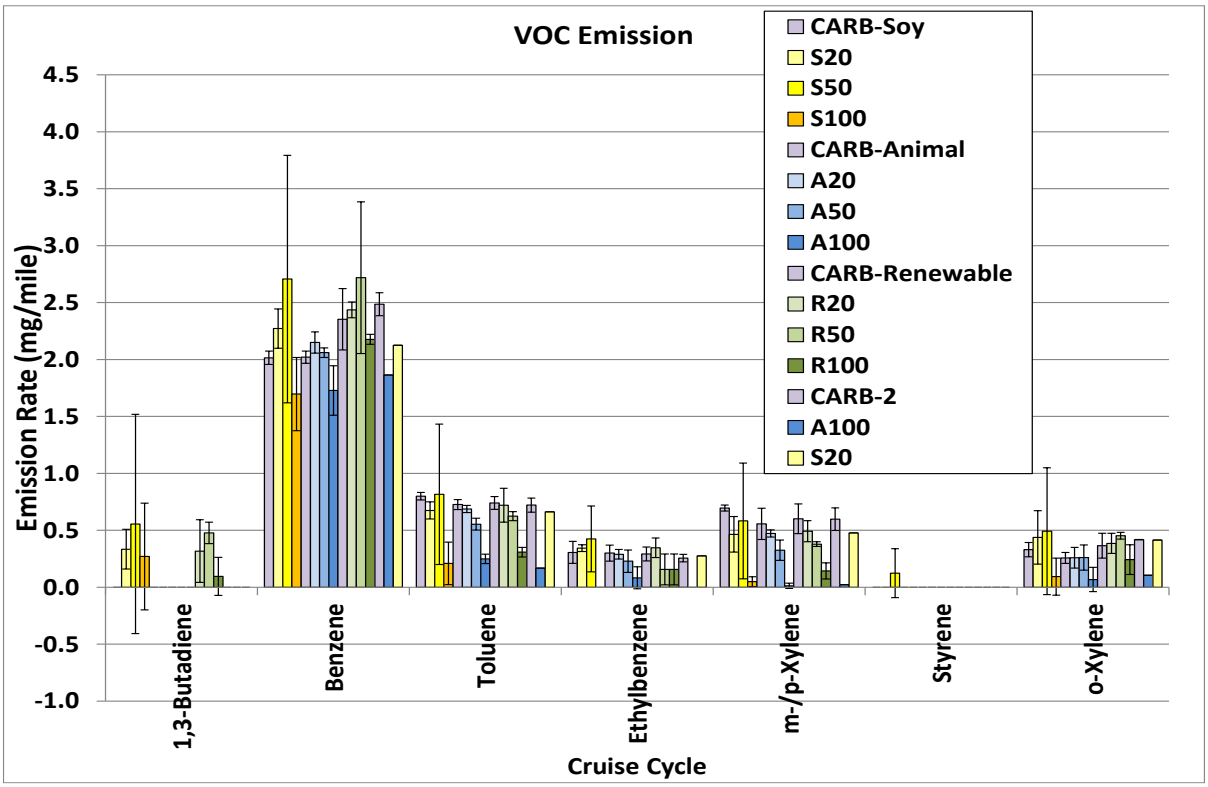


Figure 10-2. Average VOC Emission Results for the Soy-Biodiesel and Animal-Based and Renewable blends Testing for the 50-mph Cruise Cycle for the 2000 Caterpillar C-15

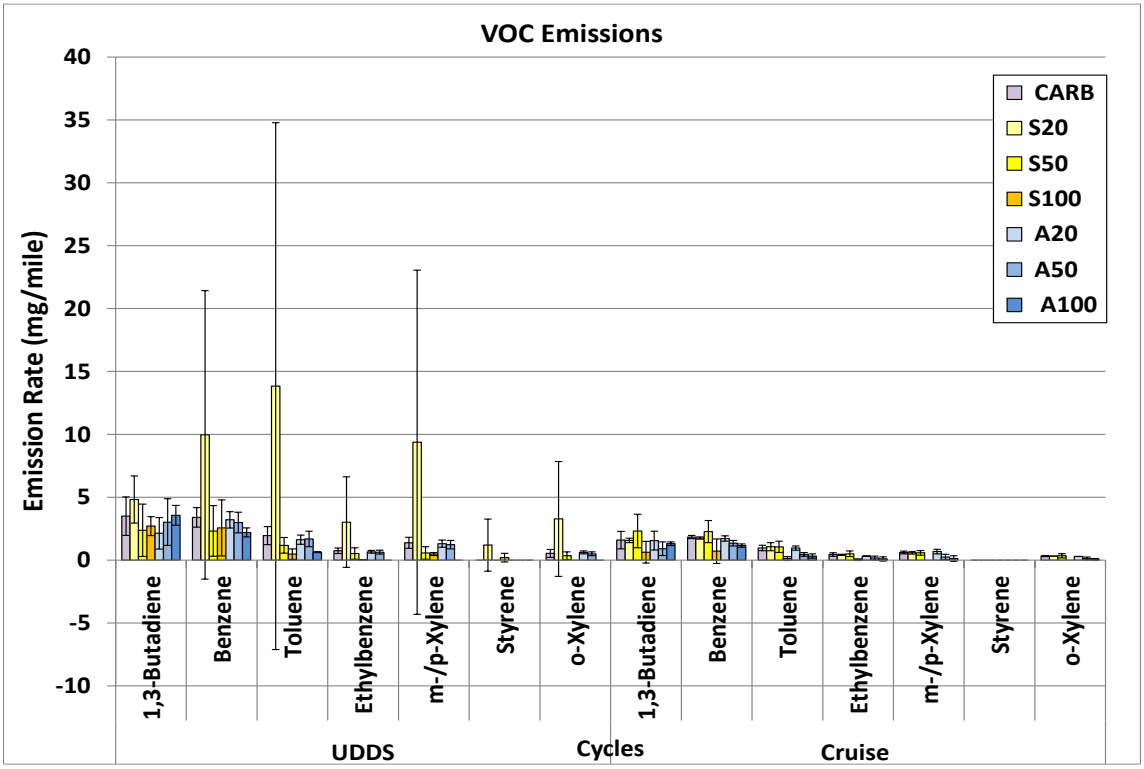


Figure 10-3. Average VOC Emission Results for the Soy-Biodiesel and Animal-Based and Renewable blends Testing for the 2006 Cummins ISM

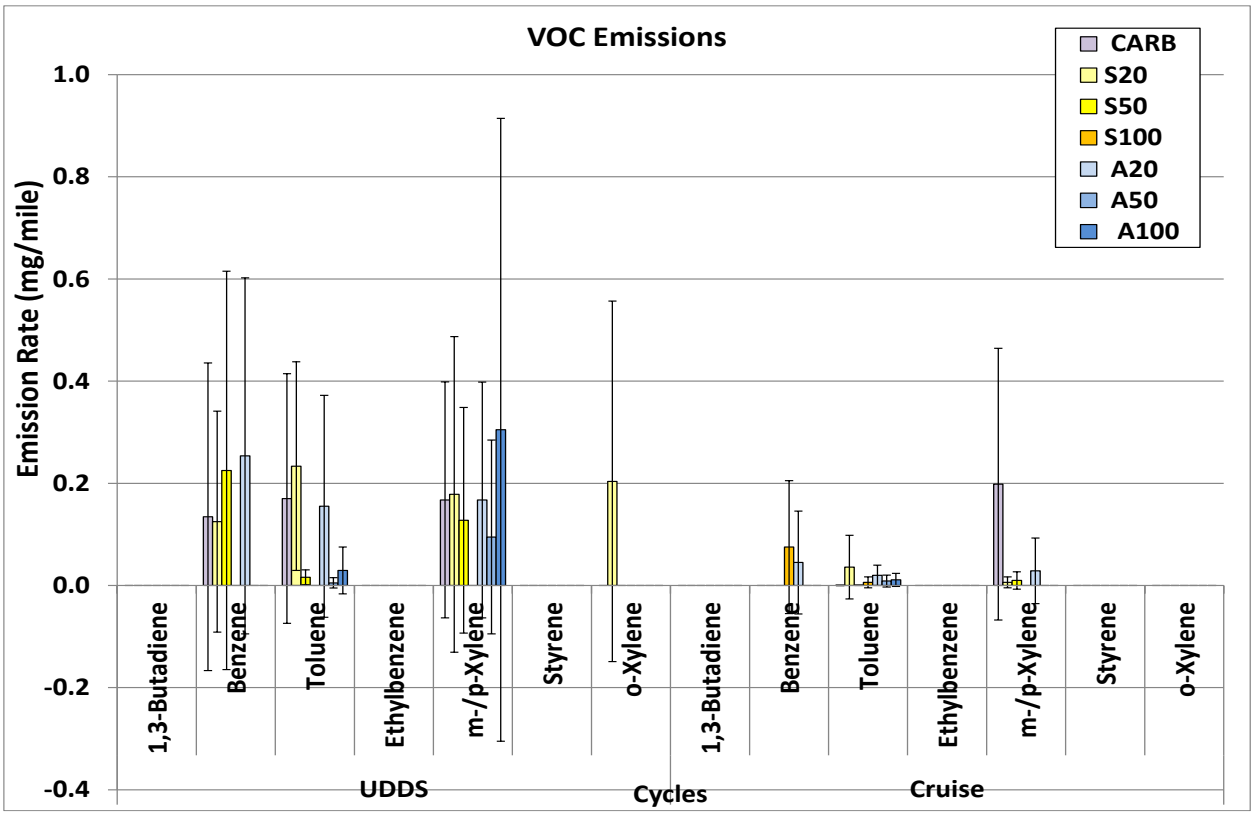


Figure 10-4. Average VOC Emission Results for the Soy-Biodiesel and Animal-Based and Renewable blends Testing for the 2007 MBE 4000

10.1.1 1,3-Butadiene

The 1,3-Butadiene emissions are presented in Figure 10-5 and Table 10-1. The table shows the percentage differences for the different feedstocks and blend levels for the two different test cycles, and the corresponding p-values for the statistical analysis. There are essentially no significant trends as a function of biodiesel blend level, and only a single statistically significant difference in all the testing combinations. The 1,3-Butadiene emissions for the CARB ULSD for the 2000 Caterpillar C-15 on the 50 mph Cruise cycle and the 2007 MBE4000 for the UDDS and 50 mph - Cruise were below the detection limit, and therefore the percentage differences and t-test values for these combinations are presented as "NA" or not available in the Table.

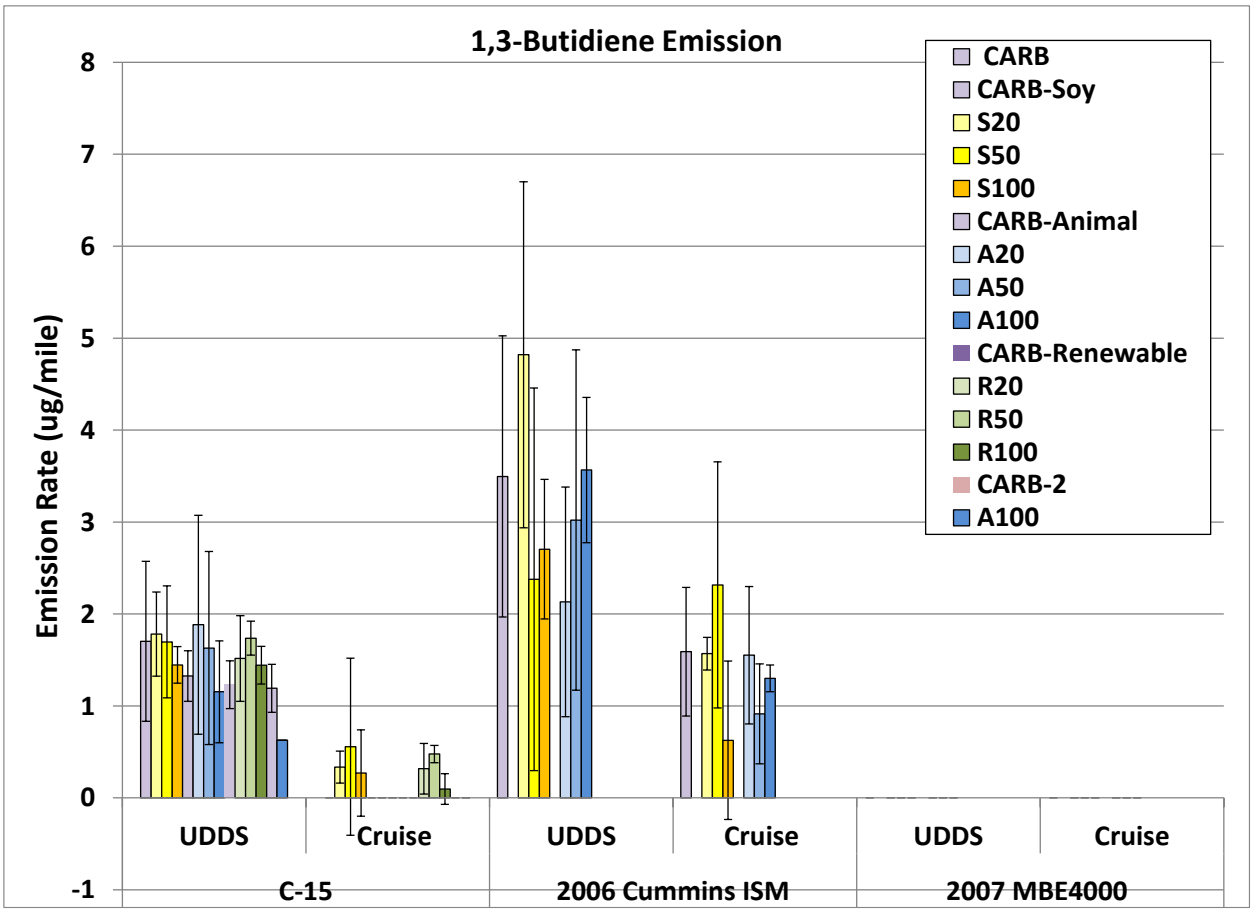


Figure 10-5. Average 1,3-Butadiene Emission Results for the Soy-Biodiesel, Animal-Based, and Renewable blend Testing.

Table 10-1. 1,3-Butadience Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for each Cycle and Vehicle and Corresponding t-test values.

		CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE 4000			
			Soy-based		Animal-based		Renewable		Soy-based		Animal-Based		Soy-based		Animal-based	
			% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	1,3-Butadiene	B20	5%	0.896	42%	0.473	23%	0.342	38%	0.316	-39%	0.243	NA	NA	NA	NA
		B50	0%	0.993	23%	0.652	41%	0.036	-32%	0.411	-14%	0.706	NA	NA	NA	NA
		B100	-15%	0.644	-13%	0.657	17%	0.298	-23%	0.444	2%	0.945	NA	NA	NA	NA
		B20-2														
		B100-2			-47%											
50-Cruise		B20	NA	NA	NA	NA	NA	NA	-1%	0.961	-2%	0.940	NA	NA	NA	NA
		B50	NA	NA	NA	NA	NA	NA	46%	0.277	-43%	0.178	NA	NA	NA	NA
		B100	NA	NA	NA	NA	NA	NA	-61%	0.058	-18%	0.510	NA	NA	NA	NA
		B20-2	NA	NA												
		B100-2			NA											

10.1.2 Benzene

Benzene emissions are shown in Figure 10-6 and Table 10-2. The results showed some statistically significant reductions for the higher biodiesel and renewable blends for the 2000 Caterpillar C-15 and the 2006 Cummins ISM, but not consistent trends across the different testing combinations. For the cases where statistically significant differences are found, the highest reductions were found for the B100/R100 fuels. The reductions in benzene emissions can be attributed to the fact that biodiesel contains no aromatics and the levels of aromatics in the renewable diesel are very low compared to those of the CARB diesel. For the 2007 MBE4000, the benzene emissions were near the detection limits, and did not show any significant fuel trends.

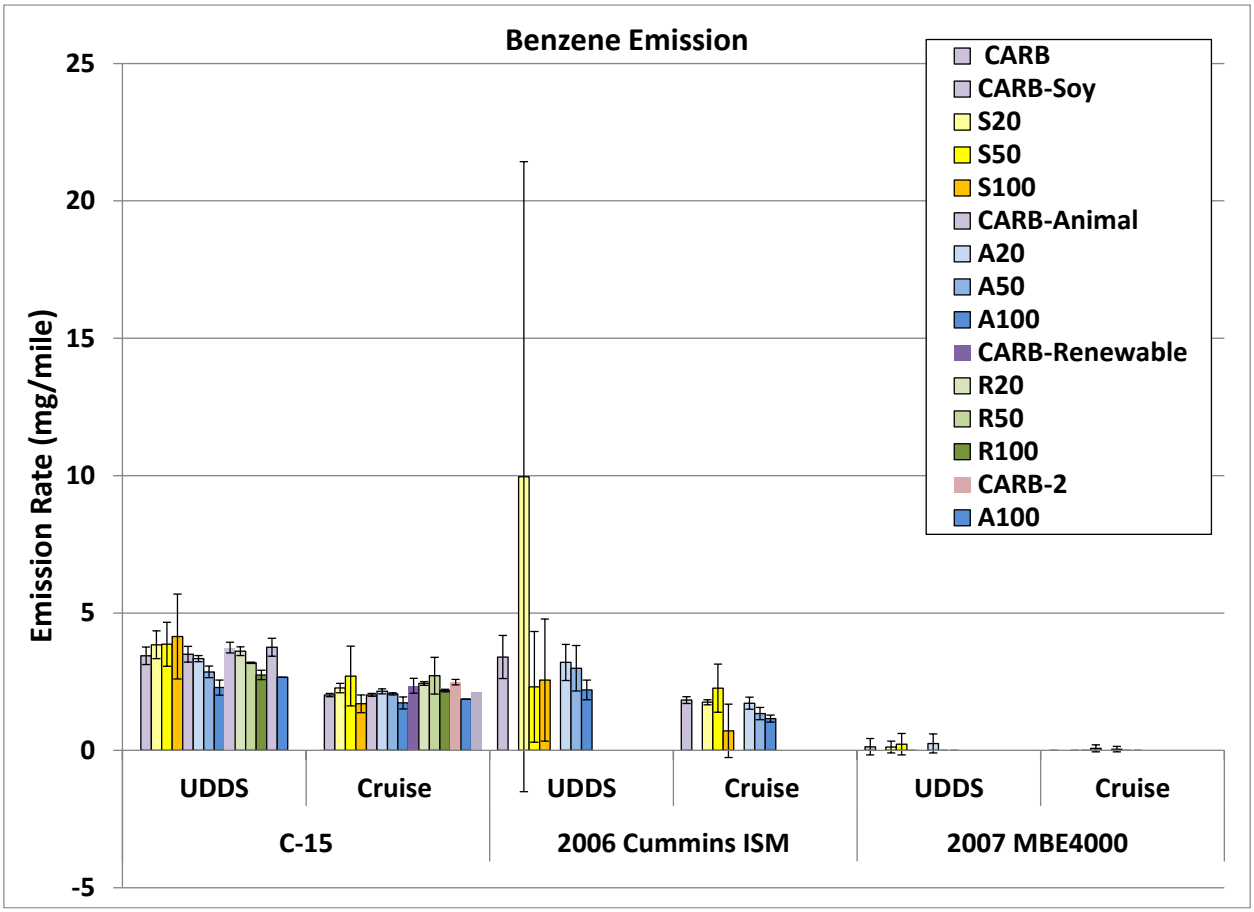


Figure 10-6. Benzene Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for each Cycle.

Table 10-2. Benzene Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for each Cycle and Vehicle and Corresponding t-test values.

		CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE 4000			
			Soy-based		Animal-based		Renewable		Soy-based		Animal-Based		Soy-based		Animal-based	
			% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	Benzene	B20	12%	0.311	-4%	0.424	-4%	0.388	193%	0.225	-6%	0.729	-7%	0.963	88%	0.579
		B50	12%	0.448	-18%	0.036	-15%	0.005	-32%	0.307	-12%	0.508	67%	0.482	-100%	0.407
		B100	20%	0.486	-35%	0.006	-27%	0.001	-25%	0.454	-35%	0.051	-100%	0.482	-100%	0.407
		B20-2														
		B100-2			-29%											
50-Cruise		B20	13%	0.147	6%	0.107	4%	0.629	-4%	0.355	-6%	0.314	NA	NA	0.347	NA
		B50	34%	0.456	2%	0.373	16%	0.356	24%	0.200	-27%	0.002	NA	NA	NA	NA
		B100	-16%	0.280	-14%	0.087	-7%	0.324	-61%	0.012	-37%	0.000	NA	0.220	NA	NA
		B20-2	-14%													
		B100-2			-25%											

10.1.3 Toluene

The results of toluene emissions are shown in Figure 10-7 and Table 10-3. The results for toluene show distinct reductions for the higher biodiesel and renewable blends. The reductions in toluene were statistically significant for all B100/R100 combinations for the 2000 Caterpillar C-15 and the 2006 Cummins ISM. Reductions were also found for various testing combinations with the B50 fuel for the 2000 Caterpillar C-15 and the 2006 Cummins ISM. The largest reductions were always found for the B100/R100 fuels, indicating that toluene emissions decrease as a function of increasing biodiesel/renewable diesel level. The reductions in toluene emissions can be attributed to the fact that biodiesel contains no aromatics and the levels of aromatics in the renewable diesel are very low compared to those of the CARB diesel. Again, this is consistent with the aromatic differences in the fuels. For the 2007 MBE4000, the benzene emissions were near the detection limits, and did not show any significant fuel trends.

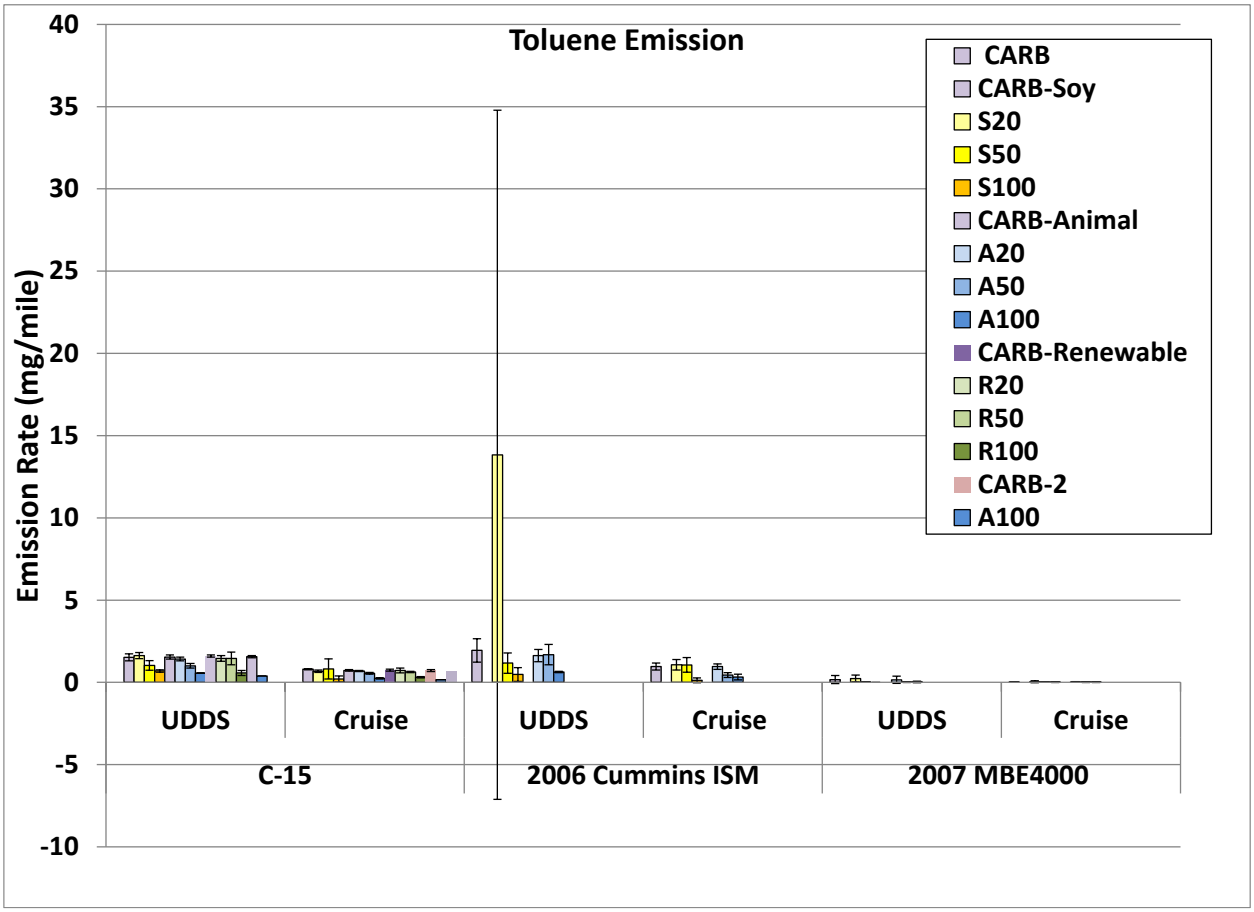


Figure 10-7.Toluene Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for each Cycle

		CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE 4000			
			Soy-based		Animal-based		Renewable		Soy-based		Animal-Based		Soy-based		Animal-based	
			% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	Toluene	B20	7%	0.548	-8%	0.272	-9%	0.186	613%	0.227	-16%	0.512	37%	0.721	-9%	0.919
		B50	-32%	0.076	-34%	0.008	-9%	0.475	-40%	0.176	-13%	0.627	-91%	0.287	-97%	0.225
		B100	-54%	0.003	-64%	0.000	-64%	0.000	-75%	0.019	-67%	0.022	-100%	0.287	-83%	0.299
		B20-2														
		B100-2			-75%											
50-Cruise		B20	-16%	0.123	-5%	0.278	-3%	0.813	11%	0.562	-1%	0.962	23016%	0.222	12664%	0.057
		B50	2%	0.974	-24%	0.012	-16%	0.031	10%	0.646	-54%	0.006	35%	0.839	5521%	0.138
		B100	-74%	0.025	-66%	0.000	-58%	0.000	-87%	0.000	-66%	0.002	3865%	0.231	7017%	0.093
		B20-2	-8%													
		B100-2			-77%											

Table 10-3. Toluene Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for each Cycle and Vehicle and Corresponding t-test values.

10.1.4 Ethylbenzene

The results of ethylbenzene emissions are shown in Figure 10-8 and Table 10-4. The B100 blends showed statistically significant reductions in ethylbenzene for nearly all testing combinations for the 2000 Caterpillar C-15 and 2006 Cummins ISM. No significant differences were found for the other biodiesel blends, however, with the exception of the animal-based B50 for the 2006 Cummins ISM. The data for the R50 and R100 renewable blends showed statistically significant decreases for the UDDS but not the 50-mph cruise for the 2000 Caterpillar C-15. Again, this is consistent with the aromatic content differences in the fuels. For the 2007 MBE4000, the ethylbenzene emissions were below the detection limit for the tests on the CARB diesel, hence the percentage differences and t-tests are not available, as denoted in the table.

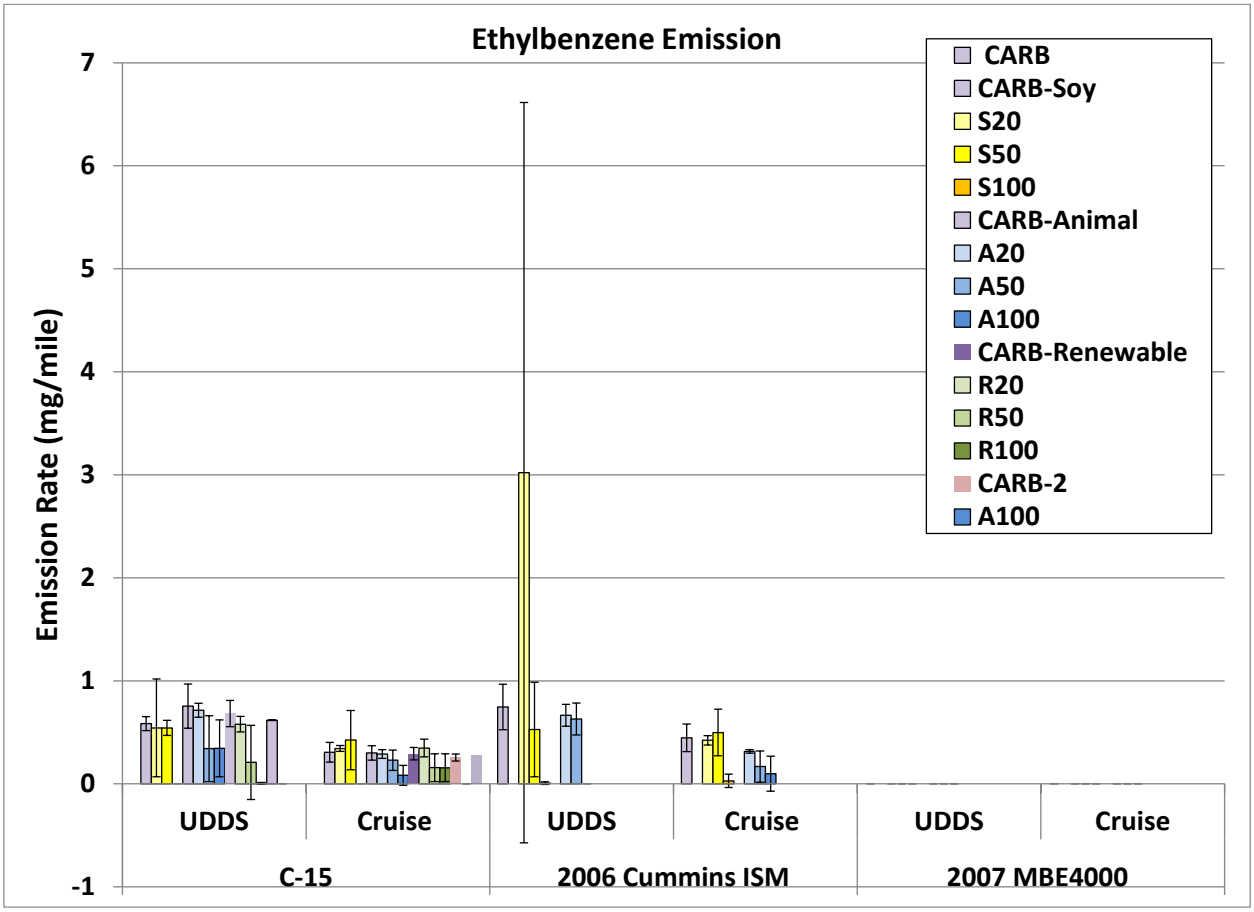


Figure 10-8. Ethylbenzene Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for each Cycle

Table 10-4. Ethylbenzene Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for each Cycle and Vehicle and Corresponding t-test values

		CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE 4000			
			Soy-based		Animal-based		Renewable		Soy-based		Animal-Based		Soy-based		Animal-based	
			% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	Ethylbenzene	B20	-7%	0.887	-5%	0.773	-15%	0.271	305%	0.185	-11%	0.578	NA	NA	NA	NA
		B50	-7%	0.511	-55%	0.137	-70%	0.054	-29%	0.384	-16%	0.456	NA	NA	NA	NA
		B100	-100%	0.000	-54%	0.112	-99%	0.000	-99%	0.001	-100%	0.001	NA	NA	NA	NA
		B20-2														
		B100-2														
50-Cruise		B20	12%	0.549	-3%	0.840	19%	0.366	-5%	0.772	-29%	0.140	NA	NA	NA	NA
		B50	39%	0.630	-24%	0.370	-46%	0.130	12%	0.657	-62%	0.020	NA	NA	NA	NA
		B100	-100%	0.009	-72%	0.035	-46%	0.129	-93%	0.000	-78%	0.008	NA	NA	NA	NA
		B20-2	8%													
		B100-2			-100%											

NA = not available because values were below detection limit.

10.1.5 *m-/p*-xylene

The results of *m-/p*-xylene emissions are shown in Figure 8-6 and Table 10-5. Statistically significant decreases are seen for the B100 and R100 blends for nearly all testing combinations for the 2000 Caterpillar C-15 and the 2006 Cummins ISM. About half of the testing combinations for the 2000 Caterpillar C-15 and the 2006 Cummins ISM also showed statistically significant reductions for the B50 blend, and the R50 blend showed reductions for both the UDDS and the 50-mph cruise for the 2000 Caterpillar C-15. In each case, the highest reductions were seen for the B100/R100 fuels. These reductions can be attributed to the reductions in aromatics when the biodiesel and renewable fuels are blended with the CARB diesel. For the 2007 MBE4000, the *m-/p*-xylene emissions were near the detection limits, and did not show any significant fuel trends.

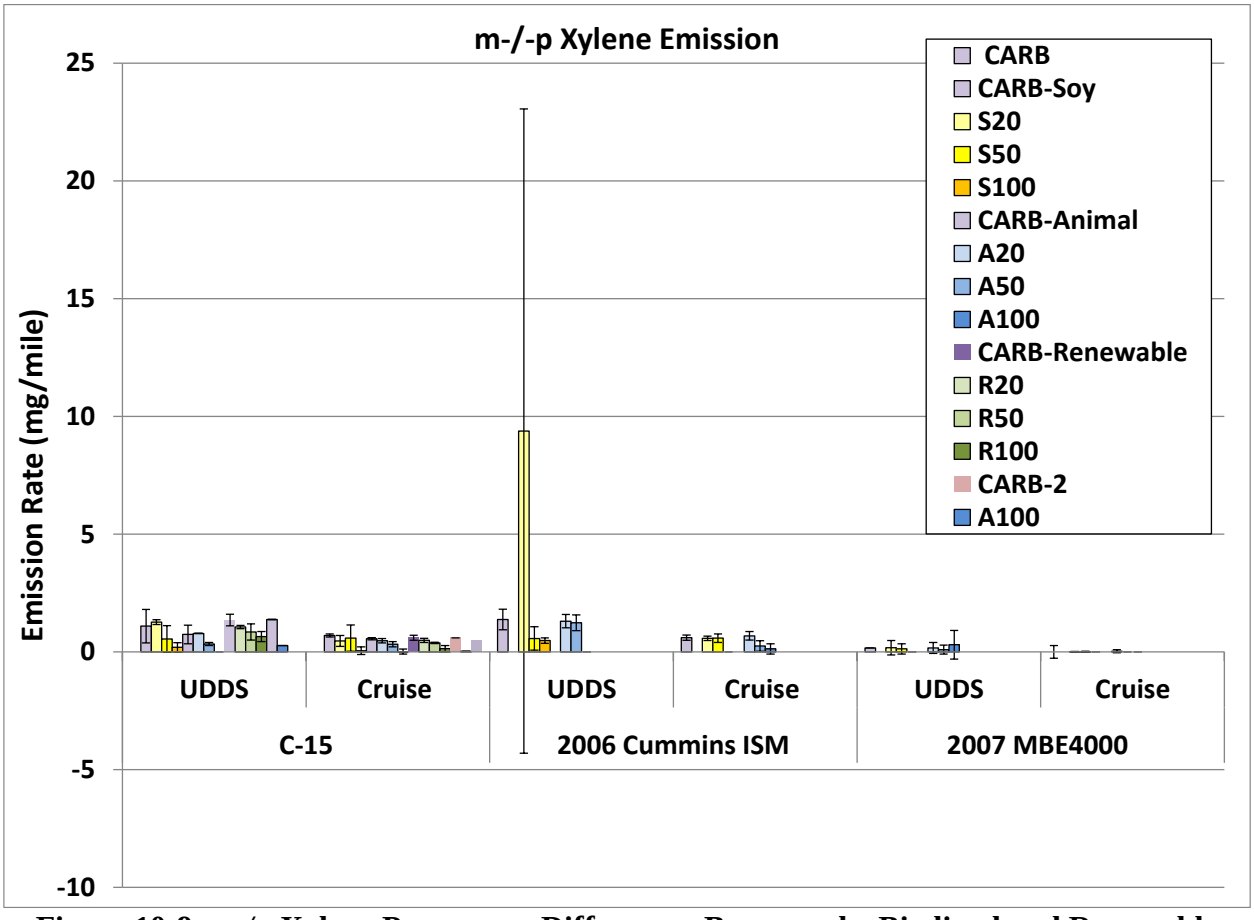


Figure 10-9. *m-/p*-Xylene Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for each Cycle

Table 10-5. *m-/p*-xylene Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for each Cycle and Vehicle and Corresponding t-test values.

		CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE 4000			
			Soy-based		Animal-based		Renewable		Soy-based		Animal-Based		Soy-based		Animal-based	
			% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	m-/p-Xylene	B20	16%	0.703	6%	0.861	-22%	0.106	583%	0.215	-5%	0.819	6%	0.956	0%	0.999
		B50	-50%	0.355	-55%	0.155	-37%	0.072	-59%	0.053	-10%	0.657	-24%	0.270	-43%	0.629
		B100	-83%	0.102	-100%	0.032	-52%	0.011	-65%	0.015	-100%	0.002	-100%	0.270	82%	0.653
		B20-2														
		B100-2														
50-Cruise		B20	-33%	0.144	-15%	0.360	-18%	0.275	-4%	0.761	13%	0.414	-97%	0.271	-86%	0.203
		B50	-16%	0.785	-42%	0.071	-37%	0.036	-3%	0.835	-58%	0.008	-95%	0.280	-100%	0.134
		B100	-93%	0.000	-98%	0.003	-76%	0.003	-100%	0.000	-79%	0.001	-100%	0.258	-100%	0.185
		B20-2	-20%													
		B100-2			-96%											

10.1.6 *o*-xylene

The results of *o*-xylene emissions are shown in Figure 10-10 and Table 10-6. The results showed reductions in *o*-xylene for the higher biodiesel and renewable diesel blends, although these trends were not statistically significant for many of the testing combinations. Where reductions were found, the highest reductions were also found for the B100/R100 fuels. Although the reductions for o-xylene were not as strong as those for the toluene and the *m-/p*-xylene, they are consistent with those results and trend with the lower aromatic levels in the fuels blended with biodiesel and renewable diesel. For the 2007 MBE4000, the *o*-xylene emissions were below the detection limit for the tests on the CARB diesel, hence the percentage differences and t-tests are not available, as denoted in the table.

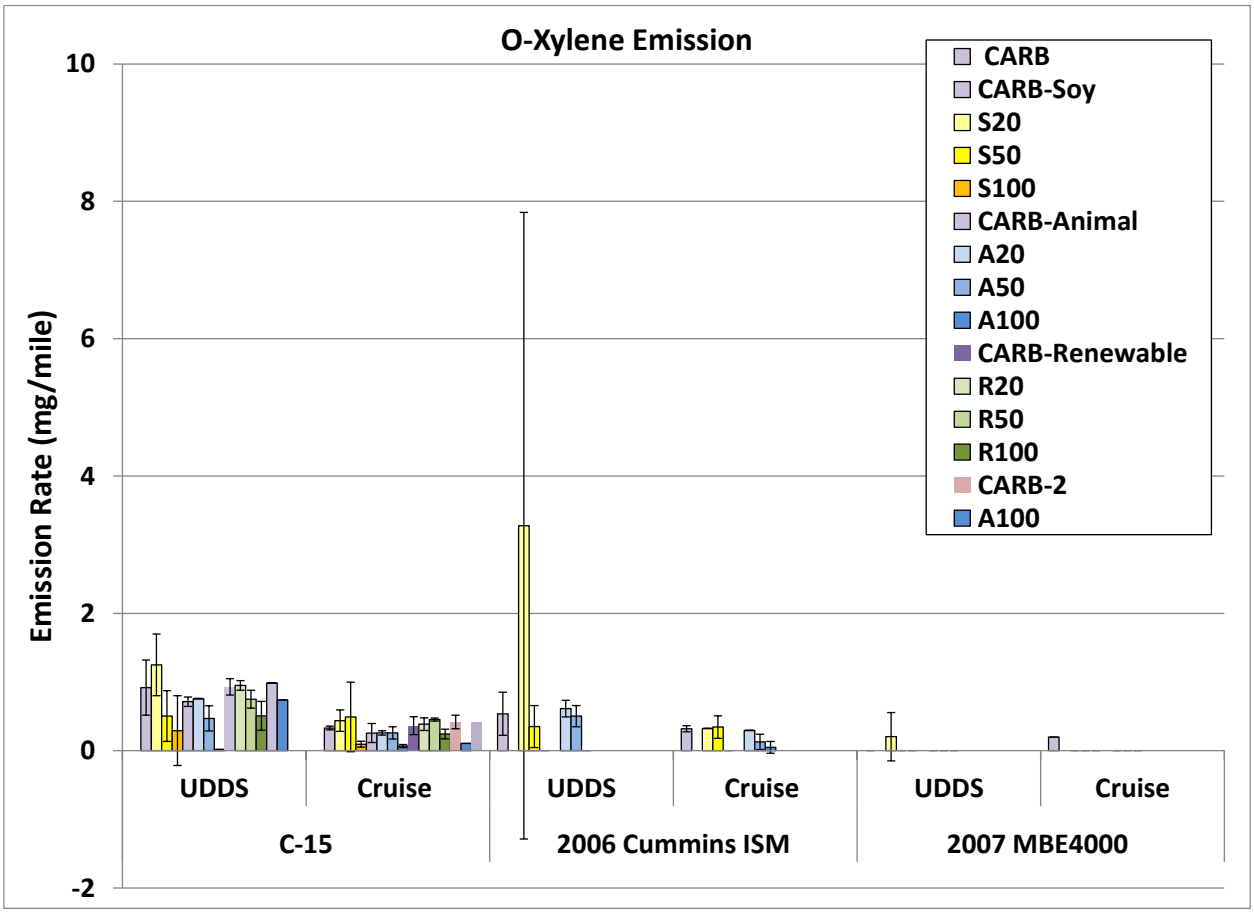


Figure 10-10. o- Xylene Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for each Cycle

Table 10-6. *o*-xylene Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for each Cycle and Vehicle and Corresponding t-test values.

		CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE 4000			
			Soy-based		Animal-based		Renewable		Soy-based		Animal-Based		Soy-based		Animal-based	
			% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	o-Xylene	B20	36%	0.395	6%	0.340	2%	0.804	510%	0.206	14%	0.709	NA	NA	NA	NA
		B50	-45%	0.259	-34%	0.098	-19%	0.118	-35%	0.443	-6%	0.869	NA	NA	NA	NA
		B100	-68%	0.169	-98%	0.000	-45%	0.019	-100%	0.028	-100%	0.028	NA	NA	NA	NA
		B20-2														
		B100-2														
50-Cruise		B20	33%	0.587	1%	0.975	6%	0.802	1%	0.895	-8%	0.380	NA	NA	NA	NA
		B50	49%	0.723	1%	0.965	24%	0.238	7%	0.715	-60%	0.004	NA	NA	NA	NA
		B100	-72%	0.156	-74%	0.048	-33%	0.234	-100%	0.000	-85%	0.000	NA	NA	NA	NA
		B20-2	-1%													
		B100-2			-75%											

10.2 Carbonyls Emissions

Carbonyl emissions results for the testing with the soy-based biodiesel, animal-based biodiesel, and renewable diesel are shown in Figure 10-11 and Figure 10-12, respectively for the UDDS and the 50-mph Cruise cycles for the 2000 Caterpillar C-15. Carbonyl emissions for the 2006 Cummins ISM and the 2007 MBE4000 are shown in Figure 10-13 and Figure 10-14, respectively. These figures provide an overview of all the carbonyl components measured in a single graph. The results for the individual carbonyls components are shown in greater detail in separate figures below.

The results show that formaldehyde and acetaldehyde were the most prominent carbonyls, consistent with previous studies. Acetone emissions were also prominent for the 2000 Caterpillar C-15. The carbonyl emissions for the 2000 Caterpillar C-15 and the 2006 Cummins ISM were considerably higher than those for the DPF-equipped 2007 MBE4000. There was also a trend of higher emissions for the UDDS than the 50-mph cruise for the 2000 Caterpillar C-15 and for formaldehyde and acetaldehyde for the 2007 MBE4000. This trend was not seen for the 2006 Cummins ISM.

Carbonyl emissions did not show consistent trends as a function of biodiesel or renewable diesel blend level. The percentage differences for the biodiesel and renewable diesel relative to the CARB diesel are provided in Table 10-7 for all species, along with the corresponding t-test values. A number of species showed lower emissions for the animal-based B100 for the 2000 Caterpillar C-15, but this trend was not seen for the other vehicle/fuel combinations. There were also some trends for the 2006 Cummins ISM of lower acetaldehyde emissions for the soy-based biodiesel blends for the UDDS, lower methacrolein emissions for the soy-based biodiesel blends for the 50-mph cruise, and lower acetone and propionaldehyde emissions for the soy-based B100 fuel. Again, these trends were not seen for other vehicle/fuel/cycle combinations. Emissions comparisons for formaldehyde, acetaldehyde, and acetone are provided in Figure 10-15, Figure 10-16 , and Figure 10-17, respectively. Plots of other carbonyls are provided in Appendix J.

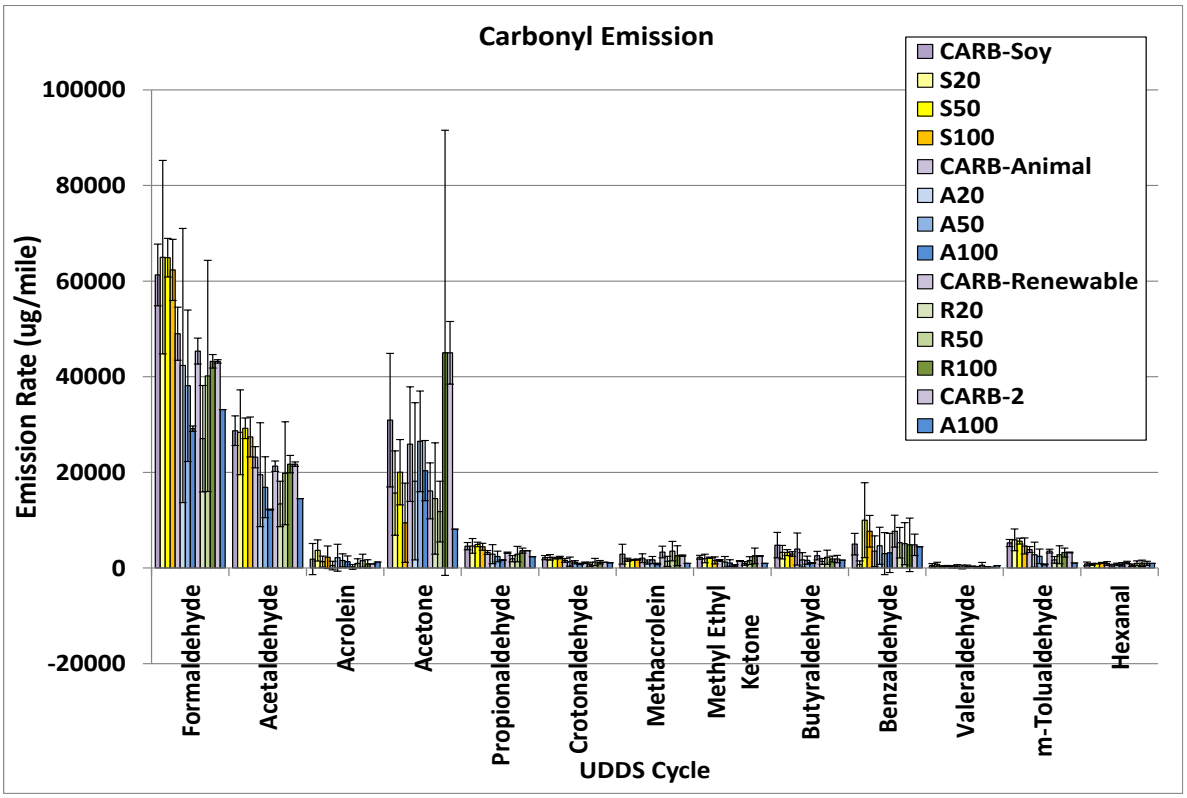


Figure 10-11. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for UDDS Cycle for the 2000 Caterpillar C-15.

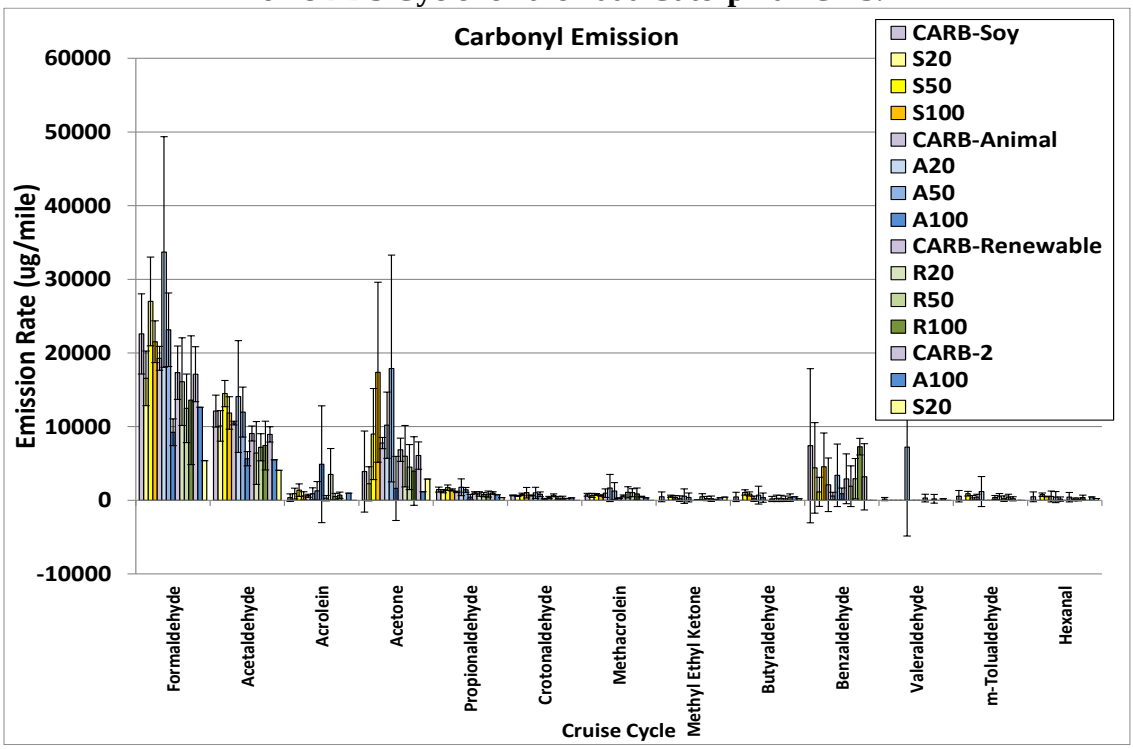


Figure 10-12. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for Cruise Cycle for the 2000 Caterpillar C-15.

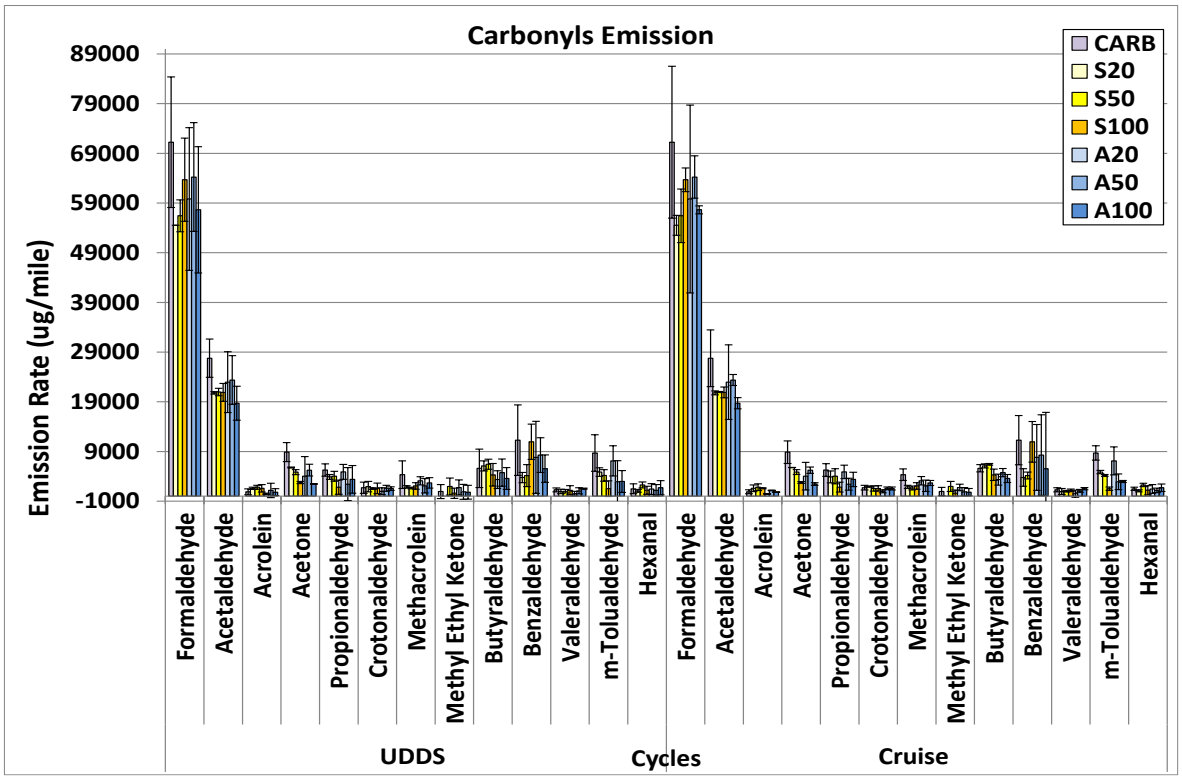


Figure 10-13. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for the 2006 Cummins ISM.

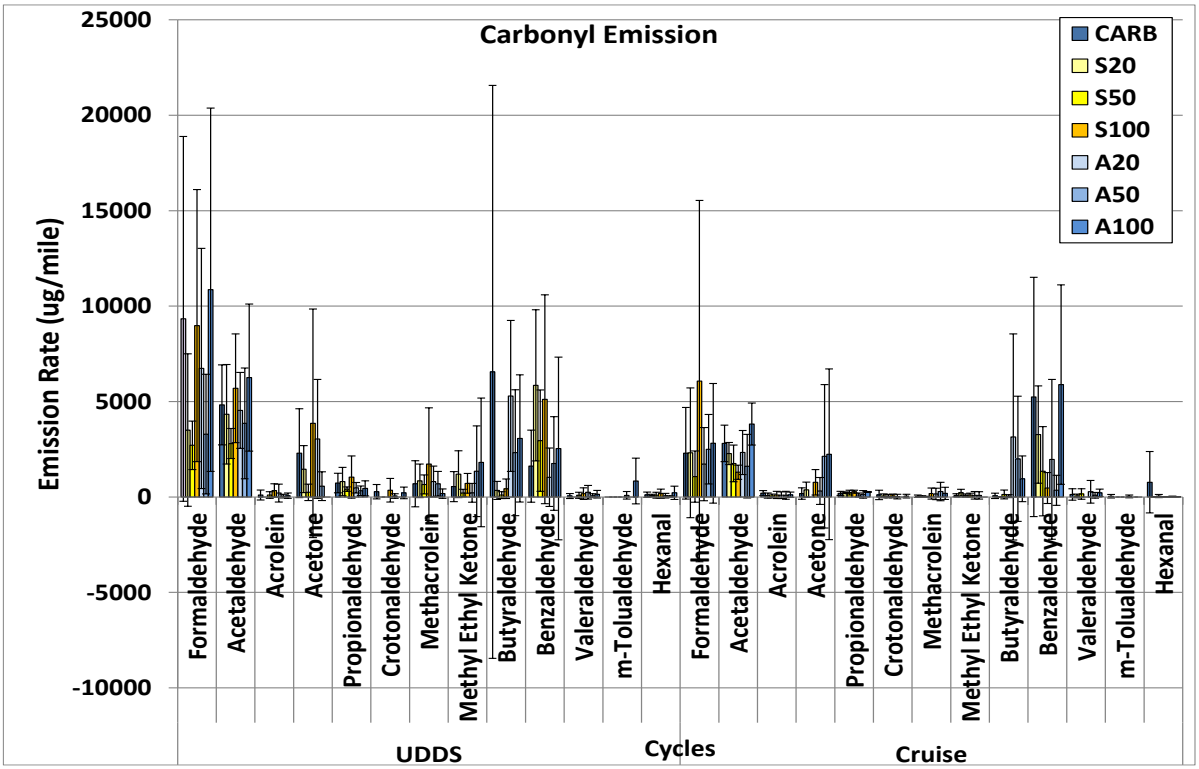


Figure 10-14. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for the 2007 MBE4000

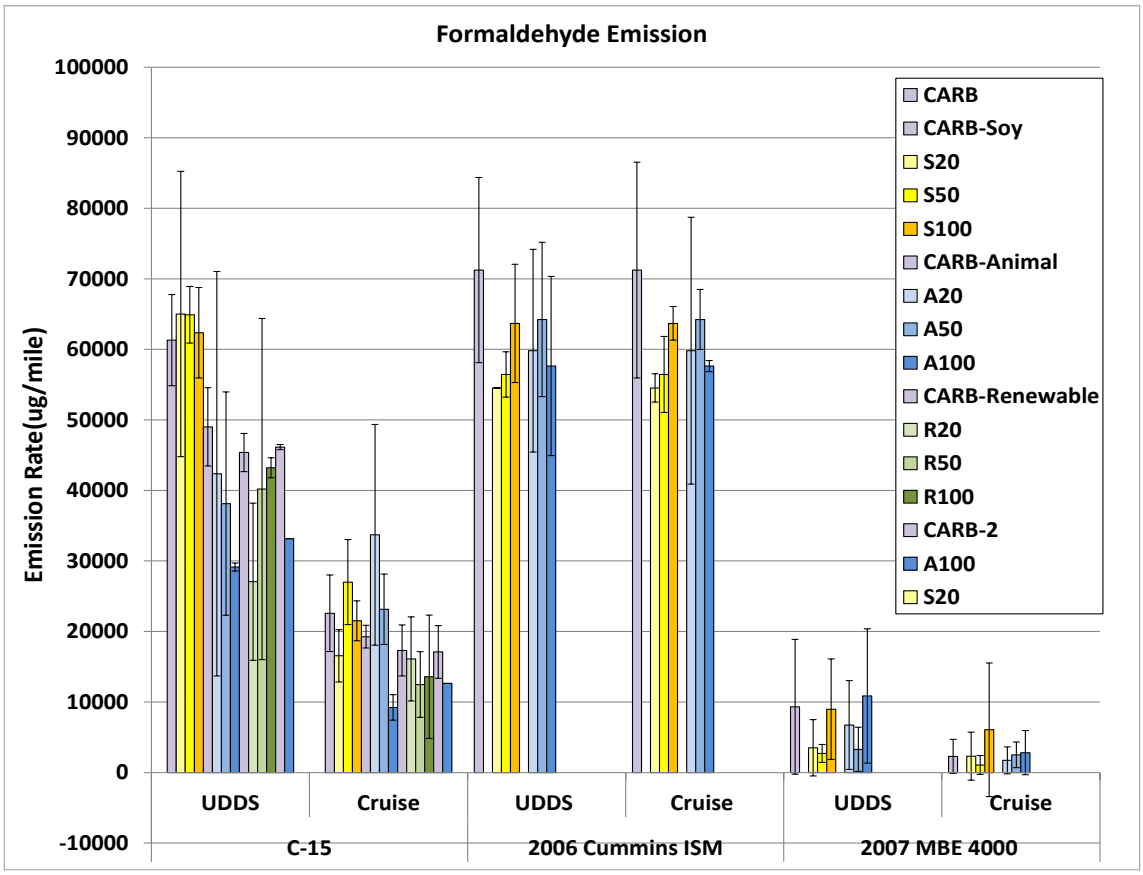


Figure 10-15. Formaldehyde Emissions for the Chassis Dynamometer Testing.

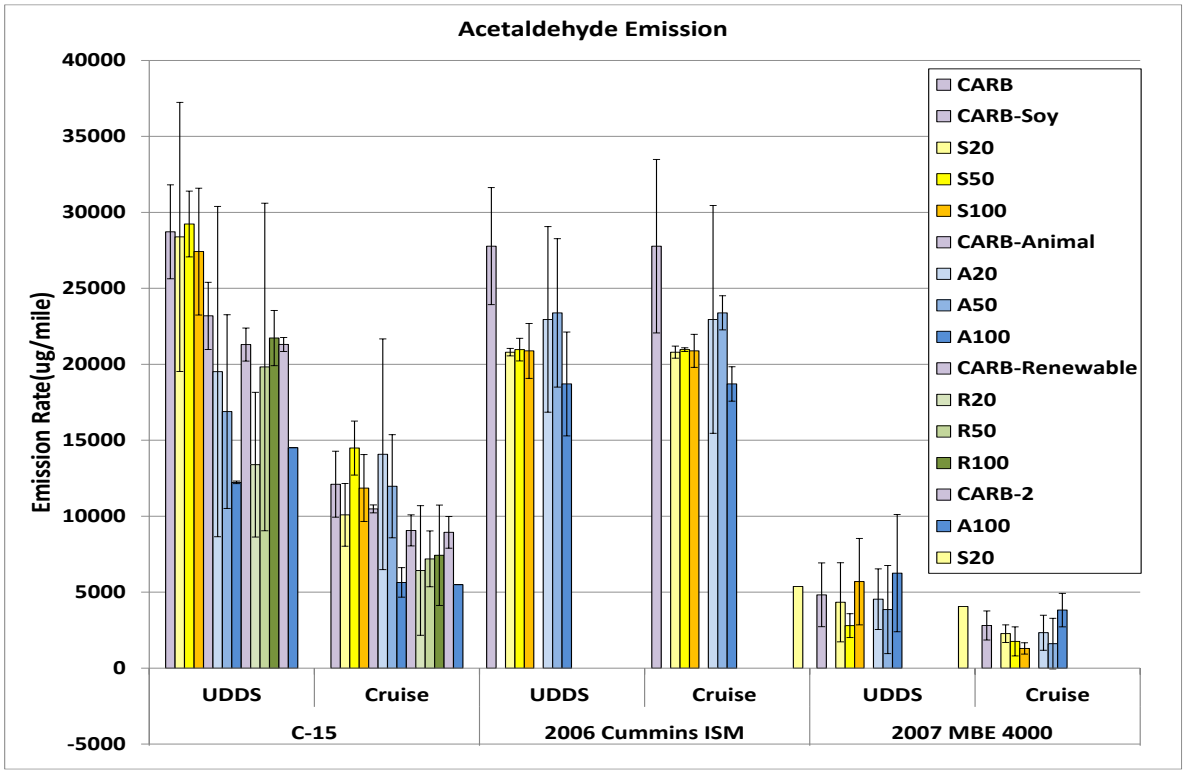


Figure 10-16. Acetaldehyde Emissions for the Chassis Dynamometer Testing.

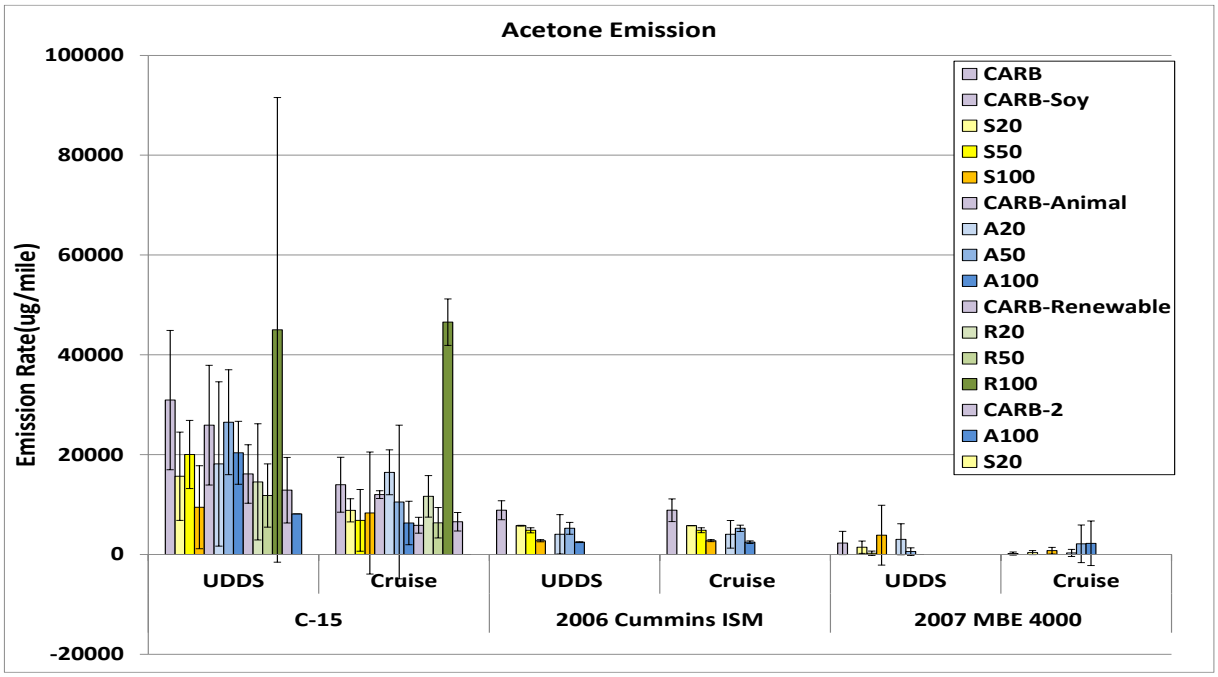


Figure 10-17. Acetone Emissions for the Chassis Dynamometer Testing.

Table 10-7. Percentage Differences and t-test values for Carbonyl Species for the Chassis Dynamometer Testing.

		CARB vs.	2000 C-15 Caterpillar						2006 Cummins ISM				2007 MBE 4000			
			Soy-based		Animal-based		Renewable		Soy-based		Animal-Based		Soy-based		Animal-based	
			% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
UDDS	Formaldehyde	B20	6%	0.778	-14%	0.713	-40%	0.022	-23%	0.077	-16%	0.292	-62%	0.357	-28%	0.616
		B50	6%	0.458	-22%	0.324	-11%	0.679	-21%	0.112	-10%	0.470	-71%	0.286	-65%	0.212
		B100	2%	0.851	-41%	0.003	-5%	0.272	-11%	0.413	-19%	0.201	-4%	0.957	16%	0.810
		B20-2														
		B100-2			-28%											
50-Cruise		B20	-27%	0.123	75%	0.187	-7%	0.749	-23%	0.314	5%	0.843	1%	0.992	-25%	0.690
		B50	20%	0.468	20%	0.270	-28%	0.179	-28%	0.237	-17%	0.455	-53%	0.458	9%	0.881
		B100	-5%	0.785	-52%	0.002	-22%	0.466	-24%	0.223	-18%	0.431	165%	0.407	23%	0.784
		B20-2	-69%													
		B100-2			-26%											
UDDS	Acetaldehyde	B20	-1%	0.953	-16%	0.597	-37%	0.021	-25%	0.023	-17%	0.212	-10%	0.768	-6%	0.823
		B50	2%	0.826	-27%	0.181	-7%	0.790	-25%	0.026	-16%	0.204	-42%	0.160	-20%	0.537
		B100	-5%	0.686	-47%	0.001	2%	0.710	-25%	0.029	-33%	0.016	18%	0.614	30%	0.465
		B20-2														
		B100-2			-32%											
50-Cruise		B20	-17%	0.222	34%	0.458	-29%	0.274	-27%	0.206	-4%	0.872	-19%	0.423	-17%	0.498
		B50	20%	0.267	14%	0.491	-21%	0.141	-29%	0.176	-24%	0.251	-37%	0.185	-42%	0.202
		B100	-2%	0.908	-46%	0.001	-18%	0.382	-38%	0.052	-34%	0.125	-54%	0.043	36%	0.181
		B20-2	-55%													
		B100-2			-39%											
UDDS	Acrolein	B20	96%	0.470	311%	0.396	309%	0.225	79%	0.103	-47%	0.290	-100%	0.516	96%	0.657
		B50	-29%	0.800	203%	0.329	526%	0.135	103%	0.059	30%	0.713	-6%	0.971	-59%	0.625
		B100	21%	0.875	158%	0.391	259%	0.265	77%	0.198	-8%	0.884	218%	0.294	-36%	0.797
		B20-2														
		B100-2			NA											
50-Cruise		B20	152%	0.625	46%	0.587	1100%	0.118	77%	0.273	-39%	0.424	-62%	0.248	-54%	0.295
		B50	280%	0.240	109%	0.418	71%	0.520	77%	0.270	-40%	0.409	-72%	0.159	-54%	0.347
		B100	67%	0.655	696%	0.404	136%	0.239	-14%	0.742	-40%	0.407	-47%	0.425	-43%	0.377

		B20-2	NA													
		B100-2			NA											
UDDS	Acetone	B20	-49%	0.185	-30%	0.545	-10%	0.820	-35%	0.035	-54%	0.054	-37%	0.586	32%	0.660
		B50	-35%	0.291	2%	0.952	-27%	0.394	-45%	0.013	-41%	0.027	-89%	0.188	-75%	0.150
		B100	-69%	0.084	-21%	0.518	179%	0.260	-69%	0.002	-72%	0.001	68%	0.575	-100%	0.090
		B20-2														
		B100-2			-37%											
50-Cruise		B20	-42%	0.488	31%	0.409	-13%	0.710	-31%	0.285	-16%	0.636	110%	0.454	74%	0.706
		B50	131%	0.419	130%	0.319	-34%	0.237	-44%	0.145	-45%	0.146	-100%	0.355	1081%	0.280
		B100	346%	0.253	-79%	0.074	-42%	0.289	-68%	0.018	-68%	0.038	325%	0.129	1138%	0.331
		B20-2	-52%													
		B100-2			-81%											
UDDS	Propionaldehyde	B20	1%	0.962	-11%	0.771	-39%	0.013	-26%	0.121	-7%	0.723	11%	0.858	-34%	0.363
		B50	8%	0.543	-26%	0.286	-9%	0.726	-24%	0.194	-54%	0.123	-44%	0.337	-55%	0.145
		B100	-3%	0.843	-49%	0.003	13%	0.182	-65%	0.012	-36%	0.224	42%	0.569	-39%	0.380
		B20-2														
		B100-2			-28%											
50-Cruise		B20	-15%	0.267	56%	0.391	-14%	0.446	-50%	0.103	11%	0.712	20%	0.594	-47%	0.225
		B50	18%	0.488	25%	0.225	-25%	0.201	-36%	0.240	-19%	0.497	21%	0.652	-26%	0.637
		B100	-3%	0.857	-63%	0.030	-17%	0.476	-58%	0.032	-56%	0.083	47%	0.260	39%	0.221
		B20-2	-63%													
		B100-2			-24%											
UDDS	Crotonaldehyde	B20	2%	0.915	-16%	0.683	-28%	0.222	13%	0.791	-41%	0.371	-100%	0.263	-80%	0.245
		B50	-4%	0.798	-25%	0.245	15%	0.689	-10%	0.815	-6%	0.887	-100%	0.263	-100%	0.142
		B100	1%	0.920	-46%	0.038	10%	0.596	-8%	0.871	-10%	0.816	30%	0.808	-21%	0.810
		B20-2														
		B100-2			14%											
50-Cruise		B20	-9%	0.364	56%	0.455	82%	0.066	-36%	0.206	-48%	0.121	-46%	0.750	-80%	0.492
		B50	21%	0.362	26%	0.431	-22%	0.611	-72%	0.049	-42%	0.158	-54%	0.706	-100%	0.347
		B100	56%	0.539	-78%	0.004	-20%	0.661	-24%	0.427	-31%	0.289	-48%	0.741	-55%	0.658
		B20-2	-100%													
		B100-2			36%											
UDDS	Methacrolein	B20	-41%	0.386	-40%	0.241	-58%	0.079	-57%	0.190	-28%	0.495	23%	0.850	18%	0.851
		B50	-42%	0.368	-18%	0.618	5%	0.891	-62%	0.157	-52%	0.253	-5%	0.967	1%	0.993

		B100	-39%	0.404	-58%	0.091	-23%	0.567	-52%	0.225	-38%	0.371	149%	0.462	-74%	0.434
		B20-2														
		B100-2			-76%											
50-Cruise		B20	-11%	0.596	72%	0.565	82%	0.257	-74%	0.021	-26%	0.378	-39%	0.725	309%	0.393
		B50	5%	0.803	31%	0.707	73%	0.176	-72%	0.025	-43%	0.179	-50%	0.625	622%	0.293
		B100	-13%	0.487	-71%	0.115	46%	0.529	-65%	0.022	-27%	0.328	352%	0.317	381%	0.324
		B20-2	-100%													
		B100-2			-32%											
UDDS	Methyl Ethyl Ketone	B20	-12%	0.651	-21%	0.639	-37%	0.028	-100%	0.303	86%	0.469	119%	0.356	-60%	0.442
		B50	-5%	0.687	-33%	0.254	4%	0.880	109%	0.390	-8%	0.946	-61%	0.508	147%	0.453
		B100	-29%	0.248	-72%	0.003	68%	0.252	-36%	0.729	-15%	0.896	31%	0.749	232%	0.389
		B20-2														
		B100-2			-36%											
50-Cruise		B20	-100%	0.178	152%	0.608	1497%	0.078	-100%	0.226	35%	0.690	160%	0.166	0%	0.999
		B50	17%	0.847	72%	0.719	668%	0.229	78%	0.429	-25%	0.786	-5%	0.940	-2%	0.986
		B100	-18%	0.849	-100%	0.370	618%	0.358	-12%	0.877	-35%	0.692	17%	0.824	-100%	0.070
		B20-2	648%													
		B100-2			507%											
UDDS	Butyral dehyde	B20	-31%	0.440	-57%	0.344	-47%	0.108	9%	0.842	-41%	0.384	-95%	0.511	-19%	0.860
		B50	-32%	0.378	-59%	0.304	-13%	0.717	14%	0.742	-15%	0.751	-98%	0.495	-65%	0.555
		B100	-39%	0.297	-74%	0.205	-27%	0.304	-23%	0.620	-36%	0.441	-93%	0.517	-53%	0.666
		B20-2														
		B100-2			-49%											
50-Cruise		B20	-100%	0.178	239%	0.536	42%	0.812	31%	0.177	5%	0.862	-93%	0.514	4883%	0.238
		B50	134%	0.258	76%	0.726	40%	0.821	32%	0.149	-18%	0.471	111%	0.606	3071%	0.223
		B100	88%	0.386	-100%	0.374	19%	0.905	-16%	0.551	-27%	0.283	-27%	0.859	1413%	0.137
		B20-2	-40%													
		B100-2			36%											
UDDS	Benzald ehyde	B20	-85%	0.036	32%	0.720	-31%	0.381	-67%	0.127	-31%	0.531	262%	0.059	-36%	0.594
		B50	100%	0.348	-14%	0.883	-34%	0.412	-63%	0.151	-27%	0.527	83%	0.406	8%	0.919
		B100	54%	0.311	-10%	0.913	-37%	0.434	-3%	0.943	-51%	0.239	217%	0.181	57%	0.674
		B20-2														
		B100-2			-26%											
50-Cruise		B20	-41%	0.555	-72%	0.513	-34%	0.697	-23%	0.744	142%	0.133	-38%	0.630	-62%	0.360

		B50	-85%	0.353	61%	0.712	1%	0.995	-91%	0.216	113%	0.259	-74%	0.353	-93%	0.122
		B100	-39%	0.690	-58%	0.599	150%	0.089	-15%	0.825	97%	0.410	-91%	0.251	12%	0.873
		B20-2	-100%													
		B100-2			-100%											
UDDS	Valeral dehyde	B20	44%	0.491	34%	0.722	-49%	0.116	-25%	0.318	-61%	0.045	-100%	0.516	380%	0.230
		B50	-37%	0.432	-18%	0.857	67%	0.453	-22%	0.350	-16%	0.575	71%	0.711	31%	0.825
		B100	-24%	0.583	22%	0.799	-52%	0.079	-7%	0.843	18%	0.366	234%	0.403	179%	0.386
		B20-2														
		B100-2			68%											
50-Cruise		B20	-100%	0.178	NA	0.359	NA	0.286	-50%	0.208	-28%	0.502	-58%	0.685	104%	0.652
		B50	-100%	0.272	NA	NA	NA	NA	-32%	0.304	21%	0.512	18%	0.912	-32%	0.781
		B100	-100%	0.272	NA	NA	NA	NA	-7%	0.808	29%	0.347	-100%	0.482	65%	0.634
		B20-2	NA													
		B100-2			NA											
UDDS	m-Toluald ehyde	B20	12%	0.663	-28%	0.524	-52%	0.006	-44%	0.137	-18%	0.557	NA	NA	NA	0.297
		B50	7%	0.528	-37%	0.205	-21%	0.457	-52%	0.092	-66%	0.088	NA	NA	NA	NA
		B100	-12%	0.584	-81%	0.001	-9%	0.579	-82%	0.021	-66%	0.053	NA	NA	NA	0.116
		B20-2														
		B100-2			-68%											
50-Cruise		B20	-100%	0.178	171%	0.568	29%	0.701	-17%	0.610	30%	0.537	-100%	0.482	-22%	0.865
		B50	64%	0.509	-100%	0.116	-42%	0.538	-26%	0.430	-11%	0.768	-100%	0.482	-100%	0.347
		B100	-39%	0.684	-100%	0.116	13%	0.848	-75%	0.022	-47%	0.173	-100%	0.482	-100%	0.407
		B20-2	-100%													
		B100-2			-100%											
UDDS	Hexanal	B20	-9%	0.787	-56%	0.154	-47%	0.041	-28%	0.515	-3%	0.949	-33%	0.664	-42%	0.544
		B50	9%	0.758	-15%	0.617	-14%	0.590	52%	0.278	-21%	0.693	-19%	0.830	-75%	0.199
		B100	25%	0.431	-17%	0.616	-13%	0.678	-20%	0.683	14%	0.810	52%	0.631	87%	0.531
		B20-2														
		B100-2			-19%											
50-Cruise		B20	-100%	0.178	-17%	0.894	-73%	0.472	-4%	0.870	39%	0.365	-100%	0.451	-99%	0.314
		B50	62%	0.508	-68%	0.480	-72%	0.477	71%	0.026	10%	0.729	-94%	0.476	-98%	0.323
		B100	9%	0.916	-100%	0.288	-16%	0.878	34%	0.444	-10%	0.785	-99%	0.451	-99%	0.376
		B20-2	NA													
		B100-2			NA											

10.3 Reactive Carbonyls

Reactive carbonyls emissions were reported for CARB, soy biodiesel, animal biodiesel, and renewable diesel for the 2000 Caterpillar C-15 and for CARB and soy biodiesel for the 2007 MBE4000. Blend levels were at the 50% and 100% level. The reactive carbonyls emissions were taken from the emissions of the vehicles operating over the UDDS and 50 mph cruise cycles for the 2000 Caterpillar C-15 and the UDDS for the 2007 MBE4000.

10.3.1 2000 Caterpillar C-15 Vehicle Results

The reactive carbonyl results from the different fuel blends showed that the different fuel blends gave different carbonyl emissions. The first observation is the acrolein emissions were higher for soy and animal blends than the CARB diesel (Figure 10-18 and Figure 10-20). This is not unexpected since plant and animal fatty acids contain more unsaturated sites (or double bonds) than petroleum alkanes. Therefore, they would be expected to generate the unsaturated aldehydes more easily than the more saturated petroleum-based fuel. However, the intermediate fuel blends (e.g., soy 50) tended to have slightly higher concentrations of the carbonyls compared to the 100% soy or animal biodiesels. This trend is repeated for many different carbonyl species. The mechanism for higher carbonyl emissions from the blends compared to the individual fuels is not known, but it probably arises from the combustion process. Typically, the acrolein emissions from the soy blends were double that of the CARB fuel, while the animal fuel had increases in the 25 to 50% range. The renewable diesel did not show any increase in acrolein emissions when compared to the CARB diesel, and thus, was the only biofuel tested that did not cause an increase in acrolein emissions.

Although acrolein was the main focus of the reactive carbonyl sampling due to regulatory concerns, many other carbonyls were also determined during the sample collection and analysis. Another group of chemicals that showed a very different pattern of emissions were the aromatic aldehydes. In general, the concentrations of aromatic aldehydes (as exemplified by the tolualdehydes) were lower in the pure biodiesel fuels compared to the CARB diesel (Figure 10-19). As a group, the aromatic aldehydes are likely to arise from the oxidation of aromatic components in the fuel and/or lubrication oil, thus fuels with lower aromatic fractions would be expected to have lower emissions of the aromatic aldehydes. Petroleum fuels, depending on their processing, can have significant aromatic hydrocarbon fractions, while the biofuels will have a lower aromatic character. Once again, the intermediate fuel blends gave higher concentrations of the aldehydes compared to either the pure CARB diesel or the pure biodiesel.

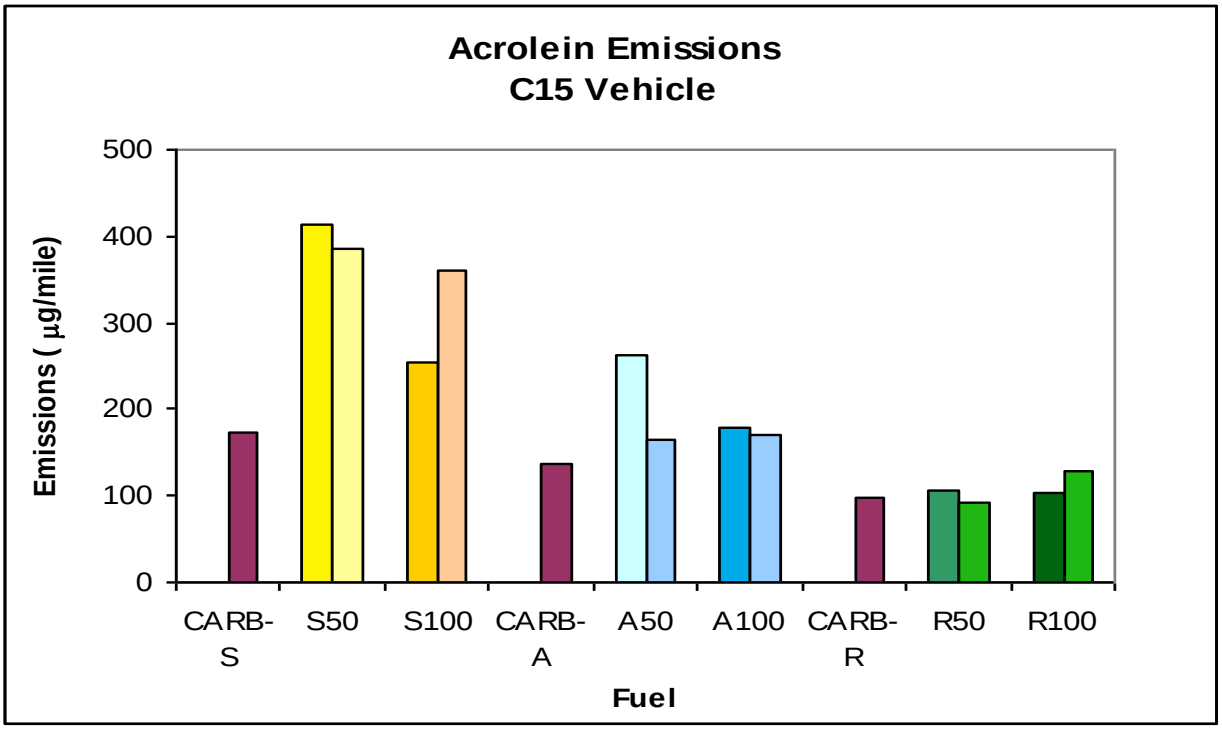


Figure 10-18. Acrolein Emissions for the 2000 Caterpillar C-15 with the UDDS cycle. Each bar represents individual samples.

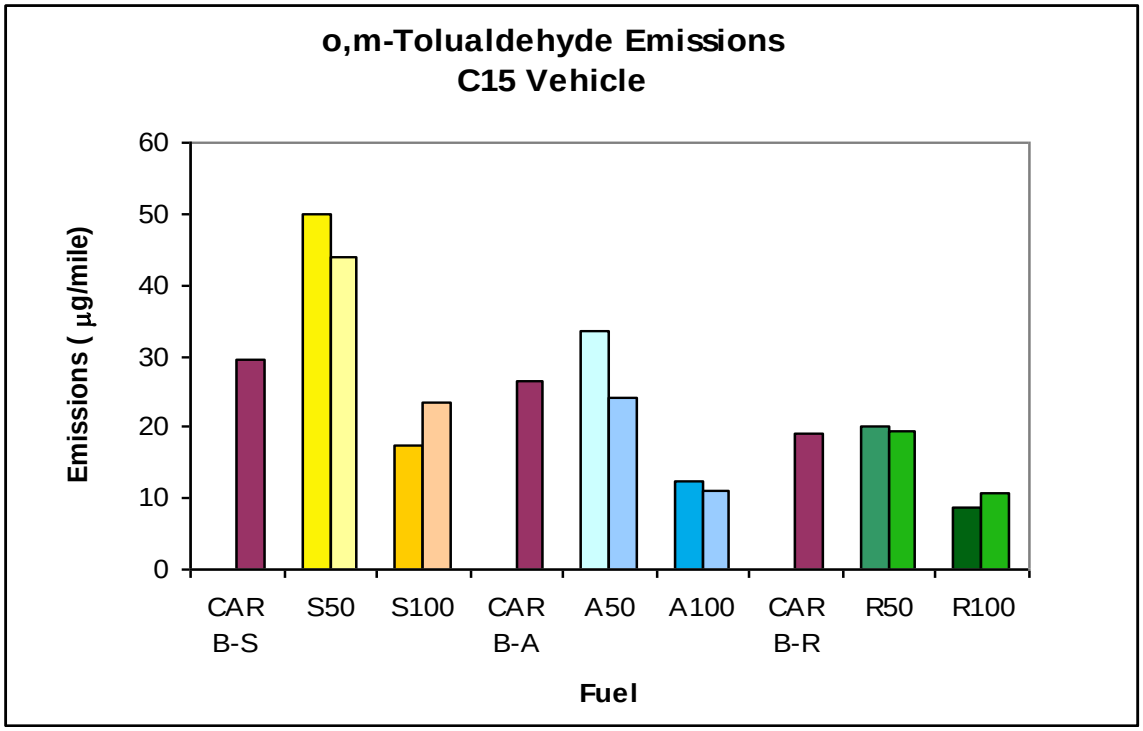


Figure 10-19. o,mtolualdehyde Emissions for the 2000 Caterpillar C-15 with the UDDS cycle. Each bar represents individual samples.

Table 10-8. UDDS emission (mean± SD) results in μg/mile for the 2000 Caterpillar C-15 Vehicle. Values rounded to three significant digits. The three CARB tests were intermixed with the other biofuel tests and hence they may have greater variability as a result of "carryover effects" from the most recent biofuel tested. Hexanal and heptanal are not reported due to high reagent blanks.

	CARB (n=3)	Soy 50 (n=2)	Soy 100 (n=2)	Animal 50 (n=2)	Animal 100 (n=2)	Renew. 50 (n=2)	Renew. 100 (n=2)
Saturated aldehydes							
butanal	ND	ND	ND	ND	ND	ND	ND
pentanal	11.9 ± 13.1[a]	34.6 ± 5.7	24.5 ± 2.8	22.7 ± 1.9	19.6 ± 3.8	ND	3.2 ± 4.5[a]
hexanal	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported
heptanal	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported
octanal	38.2 ± 24.5	20.7 ± 3.0	23.3 ± 4.6	33.0 ± 11.8	30.6 ± 8.8	52.0 ± 23.7	50.0 ± 12.4
nonanal	35.5 ± 31.2[a]	55.3 ± 15.0	60.8 ± 5.8	41.6 ± 58.8	86.7 ± 11.3	66.0 ± 28.9	58.4 ± 12.3
decanal	32.6 ± 28.9[a]	ND	22.5 ± 31.9	ND	25.0 ± 35.4[a]	96.8 ± 5.1	69.9 ± 98.8[a]
Unsaturated aldehydes							
acrolein	135 ± 37.5	399 ± 20.6	307 ± 73.8	213 ± 70.4	174 ± 5.5	99.3 ± 11.2	116 ± 17.1
methacrolein	10.4 ± 3.1	21.5 ± 0.5	10.8 ± 2.1	12.4 ± 3.6	6.3 ± 0.1	7.3 ± 0.5	7.4 ± 1.2
crotonaldehyde	66.3 ± 7.6	161 ± 18.3	106 ± 20.9	86.6 ± 19.0	60.1 ± 8.3	72.9 ± 3.6	65.6 ± 10.1
2-methyl-2-butenal	8.8 ± 3.5	17.3 ± 2.7	12.4 ± 3.3	8.5 ± 2.1	5.7 ± 0.8	7.3 ± 0.4	7.1 ± 0.5
3-methyl-2-butenal	20.9±5.1	31.6±2.2	18.7±3.5	20.0±6.1	12.2±0.4	35.2±0.7	34.9±4.3
2-hexenal	4.1 ± 3.6[a]	16.6 ± 2.5	6.9 ± 9.8[a]	ND	7.4 ± 0.4	9.0 ± 0.5	7.9 ± 1.6
2,4-hexadienal	38.8 ± 20.3	1320 ± 11.3	95.1 ± 15.5	45.4 ± 9.3	36.1 ± 2.5	29.6 ± 2.7	24.5 ± 4.3
2-heptenal	10.0 ± 4.5	20.5 ± 5.0	18.2 ± 6.9	9.7 ± 3.7	8.5 ± 0.3	3.8 ± 0.1	7.3 ± 4.2
2,4-heptadienal	5.6 ± 7.0[a]	ND	ND	14.8 ± 3.0	13.0 ± 0.5	3.5 ± 0.9	3.2 ± 0.8
4-decenal	16.3 ± 14.5[a]	ND	ND	23.2 ± 3.7	9.0 ± 12.7[a]	4.7 ± 6.4	28.0 ± 3.4
Aromatic aldehydes							
benzaldehyde	91.7 ± 14.6	128 ± 12.5	74.6 ± 25.5	117 ± 35.0	55.5 ± 2.4	65.0 ± 12.0	24.5 ± 34.7[a]
o,*m*-tolualdehyde	25.1 ± 5.3	47.0 ± 4.4	20.4 ± 4.3	28.9 ± 6.8	11.7 ± 0.9	19.8 ± 0.3	9.7 ± 1.4
p-tolualdehyde	22.8 ± 4.1	40.8 ± 5.3	19.4 ± 4.2	26.0 ± 5.3	11.7 ± 1.0	20.2 ± 0.4	11.0 ± 1.1
2-ethylbenzaldehyde	5.6 ± 3.1	6.6 ± 0.4	4.0 ± 0.8	8.5 ± 1.6	6.5 ± 1.3	3.0 ± 0.4	1.8 ± 0.1
3,4-dimethylbenzaldehyde	14.9 ± 4.5	25.9 ± 4.4	14.8 ± 3.0	16.1 ± 3.4	8.8 ± 1.5	10.4 ± 0.1	4.5 ± 0.3
4-methoxybenzaldehyde	2.5 ± 2.2[a]	5.0 ± 0.5	3.9 ± 1.2	7.1 ± 1.4	2.5 ± 3.5[a]	4.3 ± 0.7	3.7 ± 0.5
1-naphthaldehyde	54.8 ± 17.6	55.5 ± 3.1	44.7 ± 0.9	30.4 ± 10.2	19.7 ± 0.1	52.3 ± 3.0	16.0 ± 1.8
Misc. carbonyls							
2-methyl-1-propanal	ND	ND	ND	12.9 ± 18.2[a]	3.7 ± 7.0	17.6 ± 24.9	19.6 ± 27.7[a]
3-methylbutanal	ND	ND	ND	4.1 ± 5.8[a]	1.3 ± 1.9[a]	ND	ND
2-furaldehyde	44.3 ± 38.7[a]	ND	ND	85.3 ± 16.0	67.2 ± 8.0	71.9 ± 10.4	71.2 ± 8.3
glyoxal	8540 ± 3300	9910 ± 597	9250 ± 3310	8870 ± 575	9260 ± 574	4230 ± 86.3	4910 ± 120
methylglyoxal	1660 ± 489	2190 ± 134	2020 ± 18.9	1740 ± 36.6	1400 ± 17	1090 ± 50.1	1250 ± 28.3
2,3-butanedione	81.6 ± 24.9	258 ± 30.5	123 ± 61.0	115 ± 44.3	72.4 ± 1.4	168 ± 50.8	193 ± 22.6
2,3-pentanedione	3.3 ± 3.7[a]	29.4 ± 2.6	16.0 ± 4.7	22.3 ± 11.4	10.0 ± 6.8	18.2 ± 3.7	24.7 ± 7.6
2,4-pentanedione	57.9 ± 34.0	136 ± 12.3	78.2 ± 6.9	60.2 ± 8.2	14.5 ± 20.5[a]	41.4 ± 1.7	48.1 ± 3.3
2,3-hexanedione	8.4 ± 3.1	24.1 ± 3.7	10.4 ± 6.1	9.4 ± 0.2	10.6 ± 1.6	6.1 ± 0.6	8.8 ± 3.2

[a] Average contains one replicate that was not detected. The non-detected sample was treated as having a value of zero for both the average and standard deviatio

Table 10-9. Cruise emission (mean ± SD) results in μg/mile for the 2000 Caterpillar C-15 Vehicle. Values rounded to three significant digits. The three CARB tests were intermixed with the other biofuel tests and hence they may have greater variability as a result of "carryover effects" from the most recent biofuel tested. Hexanal and heptanal are not reported due to high reagent blanks. No samples of the Soy 50 cruise were collected

	CARB (n=3)	Soy 100 (n=2)	Animal 50 (n=2)	Animal 100 (n=2)	Renew. 50 (n=2)	Renew. 100 (n=2)
Saturated aldehydes						
butanal	ND	ND	ND	ND	ND	ND
pentanal	5.6 ± 4.9[a]	11.8 ± 1.0	16.1 ± 8.4	13.6 ± 0.2	12.9 ± 6.3	15.0 ± 1.9
hexanal	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported
heptanal	Not reported	Not reported	Not reported	Not reported	Not reported	Not reported
octanal	11.8 ± 0.9	10.6 ± 1.0	12.6 ± 0.4	15.0 ± 1.6	25.1 ± 0.8	17.0 ± 8.0
nonanal	23.1 ± 21.2[a]	30.1 ± 8.6	ND	ND	64.0 ± 55.5	30.3 ± 2.2
decanal	ND	ND	ND	ND	8.7 ± 12.3 [a]	28.5 ± 40.3[a]
Unsaturated aldehydes						
acrolein	99.8 ± 35.9	160 ± 24.6	164 ± 37.8	125 ± 18.6	81.9 ± 2.8	114 ± 9.9
methacrolein	7.1 ± 2.4	6.9 ± 2.3	9.9 ± 1.2	5.4 ± 0.7	6.4 ± 0.8	6.8 ± 0.9
crotonaldehyde	39.0 ± 9.4	55.2 ± 4.0	59.8 ± 5.2	41.7 ± 4.3	46.2 ± 3.2	50.9 ± 5.1
2-methyl-2-butenal	6.5 ± 3.6	6.2 ± 1.2	6.9 ± 0.7	5.7 ± 0.1	4.2 ± 1.3	5.6 ± 1.3
3-methyl-2-butenal	12.1 ± 2.5	9.2 ± 0.9	13.2 ± 1.9	9.4 ± 0.5	17.6 ± 6.1	21.5 ± 1.8
2-hexenal	5.7 ± 1.7	2.5 ± 3.6 [a]	6.7 ± 0.8	7.2 ± 1.3	4.1 ± 1.2	7.2 ± 1.0
2,4-hexadienal	19.7 ± 10.2	48.3 ± 0.8	25.5 ± 0.6	24.0 ± 0.5	12.5 ± 6.1	13.9 ± 0.4
2-heptenal	5.0 ± 2.8	8.8 ± 0.2	7.2 ± 0.2	8.2 ± 0.3	2.5 ± 1.9	4.0 ± 0.5
2,4-heptadienal	5.2 ± 4.9	ND	11.5 ± 1.2	11.9 ± 0.6	2.2 ± 0.6	2.9 ± 0.2
4-decenal	ND	ND	10.4 ± 14.7	9.2 ± 13[a]	1.7 ± 0.5	4.1 ± 1.3
Aromatic aldehydes						
benzaldehyde	55.2 ± 10.7	39.4 ± 9.8	92.5 ± 10.3	49.5 ± 6.8	29.6 ± 1.8	35.8 ± 13.2
o,*m*-tolualdehyde	16.0 ± 4.1	10.5 ± 0.4	17.6 ± 0.8	8.6 ± 0.4	9.4 ± 3.3	8.3 ± 1.2
p-tolualdehyde	14.0 ± 3.4	9.8 ± 0.4	15.8 ± 0.4	9.2 ± 0.1	8.8 ± 3.2	8.8 ± 2.1
2-ethylbenzaldehyde	3.4 ± 2.3	1.8 ± 0.6	6.5 ± 0.6	6.3 ± 0.1	1.1 ± 0.3	1.7 ± 0.6
3,4-dimethylbenzaldehyde	9.2 ± 4.0	7.0 ± 2.2	10.3 ± 0.6	7.5 ± 0.1	4.2 ± 1.6	3.2 ± 0.9
4-methoxybenzaldehyde	3.5 ± 1.2	2.1 ± 0.4	2.1 ± 3.0[a]	4.7 ± 0.1	1.6 ± 0.4	2.9 ± 1.2
1-naphthaldehyde	22.9 ± 1.7	19.2 ± 7.5	15.4 ± 3.8	13.5 ± 2.8	22.9 ± 8.1	12.5 ± 5.5
Misc. carbonyls						
2-methyl-1-propanal	ND	ND	15.4 ± 0.1	4.2 ± 1.5	8.1 ± 11.5 [a]	3.5 ± 4.9 [a]
3-methylbutanal	ND	ND	ND	ND	3.6 ± 5.1 [a]	ND
2-furaldehyde	24.6 ± 21.9 [a]	ND	48.6 ± 2.5	45.8 ± 4.6	36.6 ± 13.0	37.7 ± 10.6
glyoxal	2960 ± 910	4730 ± 2380	714 ± 57.7	1790 ± 1400	824 ± 440	1180 ± 501
methylglyoxal	744 ± 240	791 ± 331	379 ± 5.9	446 ± 276	359 ± 8.8	419 ± 75.6
2,3-butanedione	64.1 ± 26.4	48.8 ± 5.3	73.0 ± 40.1	49.6 ± 7.5	63.5 ± 27.0	127 ± 19.3
2,3-pentanedione	6.5 ± 7.0	3.1 ± 4.4 [a]	13.4 ± 3.2	5.6 ± 7.9[a]	7.6 ± 3.0	15.0 ± 0.7
2,4-pentanedione	20.8 ± 13.8	33.9 ± 9.0	21.0 ± 0.5	15.3 ± 0.1	13.3 ± 4.4	14.7 ± 2.2
2,3-hexanedione	6.8 ± 2.9	2.0 ± 0.4	6.7 ± 1.5	6.9 ± 0.2	3.7 ± 2.5	6.4 ± 1.9

[a] Average contains one replicate that was not detected. The non-detected sample was treated as having a value of zero for both the average and standard deviation.

10.3.1 MBE4000 Vehicle Results

The results from the 2007 MBE 4000 vehicle equipped with a DPF showed lower carbonyl emissions across the board (see Figure 10-20). Only a few compounds were detected at concentrations greater than the concentrations present in the dilution (background) air. Compounds that were detected were present at much lower concentrations than for the 2000 Caterpillar C-15 vehicle. For example, acrolein emissions were between 3 and 8-fold lower in the 2007 MBE 4000 vehicle compared to the 2000 Caterpillar C-15 vehicle. The DPF appears very effective at lowering carbonyl emissions in vapor phase. One peculiar result was that the intermediate fuel blend had slightly lower emissions of acrolein compared to either the CARB or soy 100 fuels (Figure 10-20). This is the opposite of the results from the 2000 Caterpillar C-15 vehicle. However, the sample size is too small to determine if this is a repeatable pattern, or just a statistical outlier.

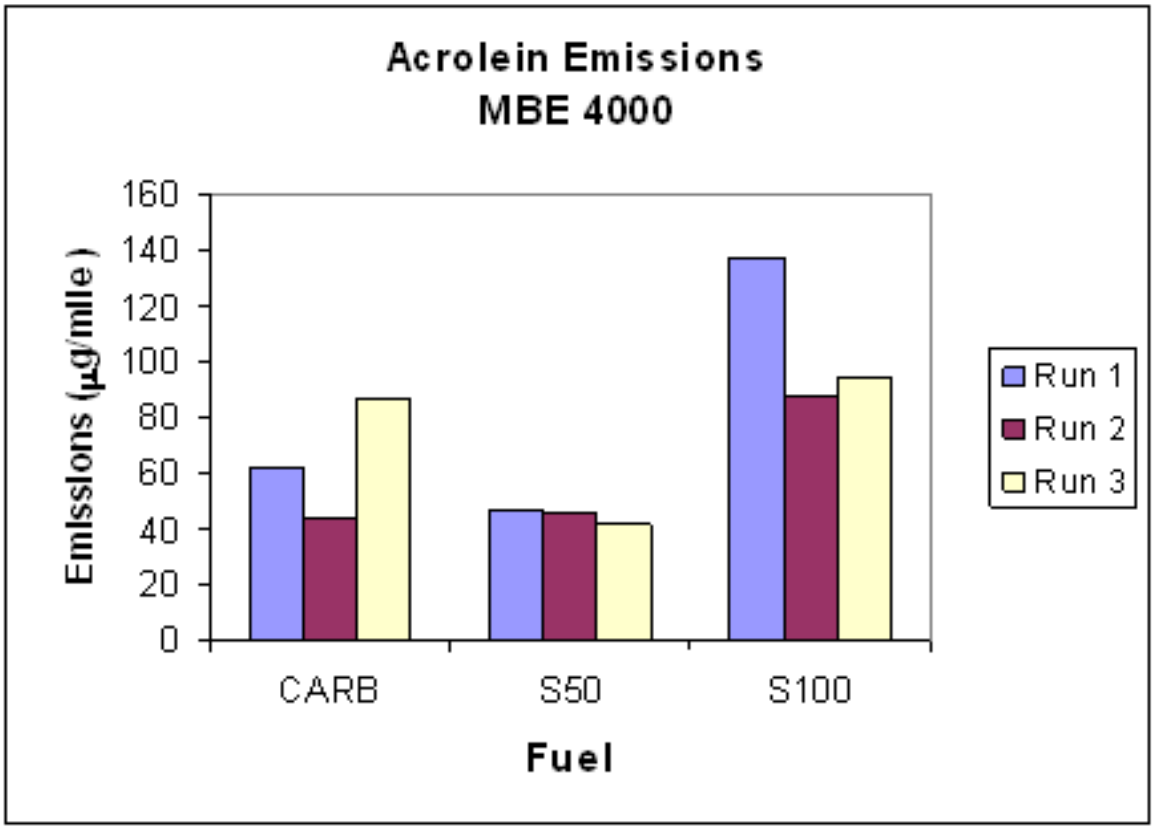


Figure 10-20. Acrolein Emissions for the 2007 MBE4000. Each bar represents a separate UDDS test run of individual samples.

Table 10-10.UDDS emission (mean ± SD) from the 2007 MBE4000 vehicle in μg/mile. "---" indicates that the chemical was not detected in emission sample. Values rounded to three significant digits. Hexanal and heptanal are not reported due to high reagent blanks.

	CARB (n=3)	Soy 50 (n=3)	Soy 100 (n=3)
Saturated aldehydes			
butanal	---	---	---
pentanal	---	---	---
hexanal	Not reported	Not reported	Not reported
heptanal	Not reported	Not reported	Not reported
octanal	---	11.2 ± 9.71[a]	13.1 ± 11.7
nonanal	---	14.3 ± 13.9[a]	14.0 ± 8.42[a]
decanal	27.9 ± 26.7[a]	54.3 ± 56.8[a]	141 ± 95.4
Unsaturated aldehydes			
acrolein	63.9 ± 21.6	44.9 ± 2.83	106 ± 27.0
methacrolein	0.52 ± 0.26	---	---
crotonaldehyde	2.32 ± 0.48	---	2.72 ± 1.61
2-methyl-2-butenal	0.23 ± 0.15	---	0.12 ± 0.11[a]
3-methyl-2-butenal	---	---	---
2-hexenal	---	---	---
2,4-hexadienal	---	---	---
2-heptenal	---	---	---
2,4-heptadienal	---	0.20 ± 0.30[a]	0.22 ± 0.24[a]
4-decenal	---	---	0.71 ± 0.66[a]
Aromatic aldehydes			
benzaldehyde	4.12 ± 2.62	2.11 ± 0.99	2.25 ± 0.91
o,m-tolualdehyde	0.36 ± 0.13	0.19 ± 0.13	---
p-tolualdehyde	---	---	---
2-ethylbenzaldehyde	---	---	---
3,4-dimethylbenzaldehyde	0.14 ± 0.06	0.12 ± 0.16	0.05 ± 0.06[a]
4-methoxybenzaldehyde	0.23 ± 0.15	0.05 ± 0.04[a]	---
1-naphthaldehyde	0.57 ± 0.71[a]	---	---
Misc. carbonyls			
2-methyl-1-propanal	---	---	---
3-methylbutanal	---	---	---
2-furaldehyde	1.98 ± 2.49[a]	1.62 ± 1.93[a]	4.53 ± 3.24
glyoxal	---	---	---
methylglyoxal	---	---	---
2,3-butanedione	12.4 ± 4.1	---	6.81 ± 2.11
2,3-pentanedione	---	---	---
2,4-pentanedione	0.27 ± 0.23	---	0.16 ± 0.18[a]
2,3-hexanedione	---	---	---

[a] Average contains one replicate that was not detected. The non-detected sample was treated as having a value of zero for both the average and standard deviation.

10.4 OC/EC Emissions

The OC/EC emission results for the testing with the soy-based and animal-based biodiesel blends and the renewable diesel blends are presented in Figure 10-21 and Figure 10-22 for the 2000 Caterpillar C-15 and the 2007 MBE4000, respectively. PM speciation was only conducted for the emissions tests with the UDDS cycle and, for the 2007 MBE4000, only for the soy-based biodiesel. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination. The error bars represent one standard deviation on the average value. The percentage differences relative to the CARB diesel for the different biodiesel and renewable diesel blends are provided in Table 10-11, along with the associated t-test values from the statistical analyses.

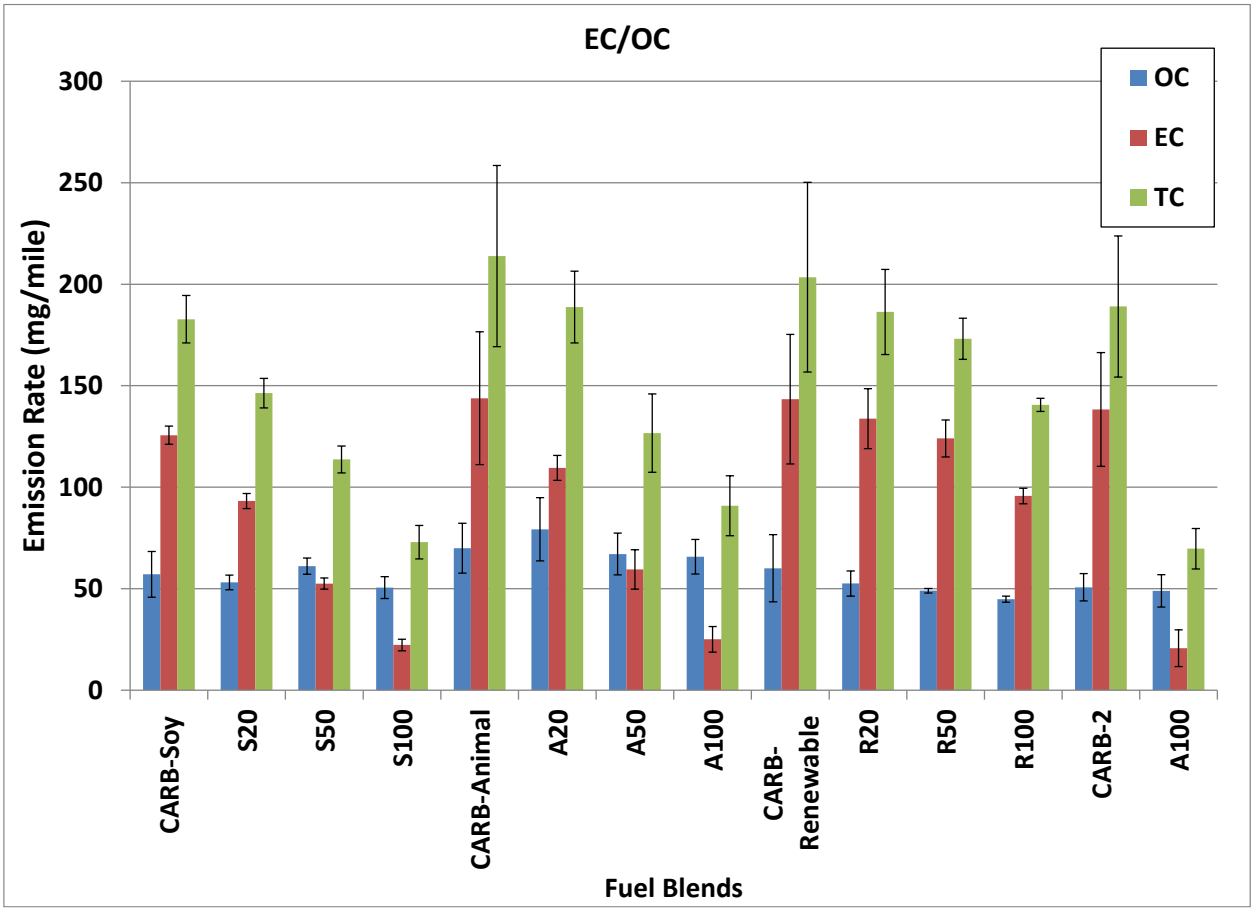


Figure 10-21. Average OC/EC Emission Results for the Biodiesel and Renewable Blends for the 2000 Caterpillar C-15

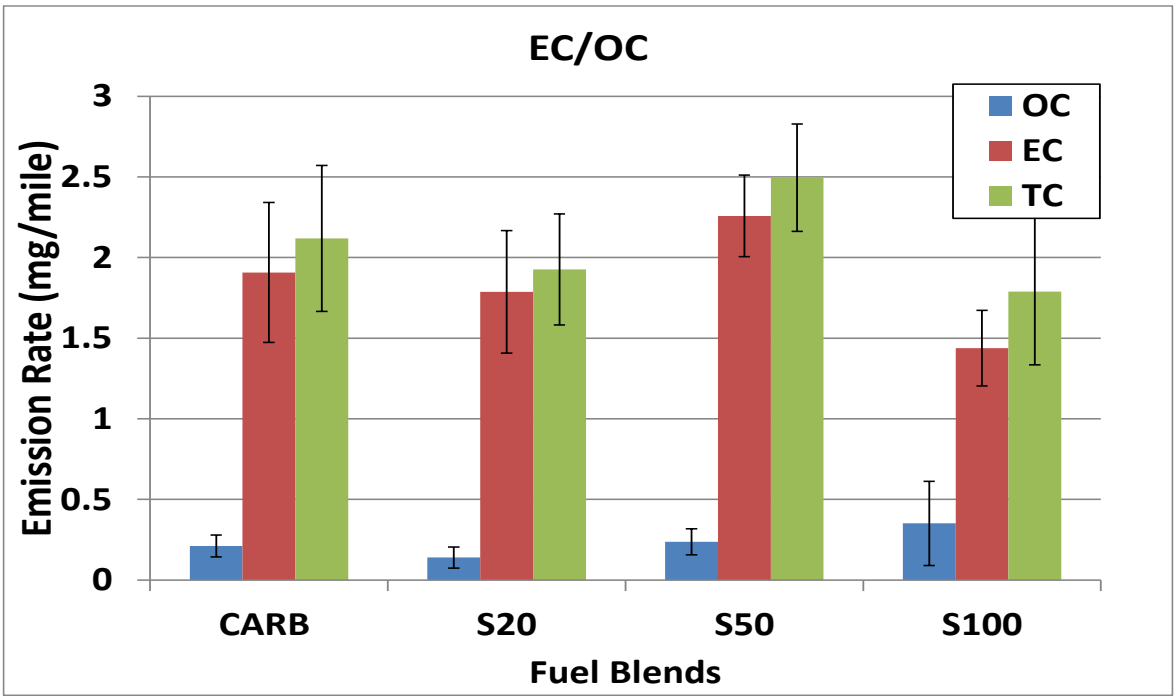


Figure 10-22. Average OC/EC Emission Results for the Biodiesel and Renewable Blends for the 2007 MBE4000.

The total carbon and the elemental carbon components of the PM both showed reductions that increased in magnitude at progressively higher biodiesel blends. Both of these trends are consistent with the overall reduction in PM mass with higher biodiesel levels that is discussed in earlier sections. The organic carbon levels did not show significant differences between the different fuel blends, and in fact were relatively flat as a function of blend level. As a result, the organic carbon fraction of the total PM mass increases as a function of biodiesel blend level. This trend is consistent with the results from other previous studies. The renewable diesel blends showed trends of decreasing elemental and total carbon emissions as a function of blend level, but this was only statistically significant for the R100 fuel.

The total carbon PM mass can be compared with the total PM mass, as measured gravimetrically and described in section 9.2. The results of this comparison are shown in Figure 10-23 for the 2000 Caterpillar C-15 and Figure 10-24 for the 2007 MBE4000 vehicle. The results show a relatively good comparison between the carbonaceous PM and the total PM. This is not unexpected, given that other constituents, such as ions and elements represent less than 1% of the PM mass. There are some cases for the 2000 Caterpillar C-15, where the PM mass for the elemental and organic analysis is higher than that of the total gravimetric mass. This trend was more prevalent for the higher biodiesel blends, which have higher fractions of organic carbon compared to the CARB and low blend fuels. The differences between the total carbonaceous PM mass and the total gravimetric PM mass could be related to differences in organic sampling artifacts between the quartz and Teflon filters (Watson et al., 2008; Chase et al., 2004; Khalek 2005). Although the total carbonaceous PM and total PM mass for the 2007 MBE4000 do not show any statistically significant differences, it is known that artifact formation has a significant impact on filter-based mass measurements conducted at the tailpipe emission levels seen for DPF-equipped engines and vehicles.

Table 10-11. Organic, Elemental, and Total Carbon Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for UDDS Cycle

	CARB vs.	2000 C-15 Caterpillar						2007 MBE 4000	
		Soy-based		Animal-based		Renewable		Soy-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
Organic Carbon	B20	-7%	0.592	13%	0.465	-12%	0.497	-6.31%	0.736
	B50	7%	0.590	-4%	0.770	-18%	0.311	18.38%	0.293
	B100	-11%	0.418	-6%	0.650	-25%	0.181	-24.60%	0.174
	B20-2								
	B100-2			-3%					
Elemental Carbon	B20	-26%	0.001	-24%	0.148	-7%	0.654	-33.94%	0.258
	B50	-58%	0.000	-59%	0.013	-13%	0.366	12.35%	0.691
	B100	-82%	0.000	-83%	0.003	-33%	0.054	66.45%	0.420
	B20-2								
	B100-2			-85%					
Total Carbon	B20	-20%	0.010	-12%	0.416	-8%	0.586	-9.06%	0.590
	B50	-38%	0.001	-41%	0.036	-15%	0.329	17.78%	0.310
	B100	-60%	0.000	-57%	0.011	-31%	0.072	-15.54%	0.425
	B20-2								
	B100-2			-63%					

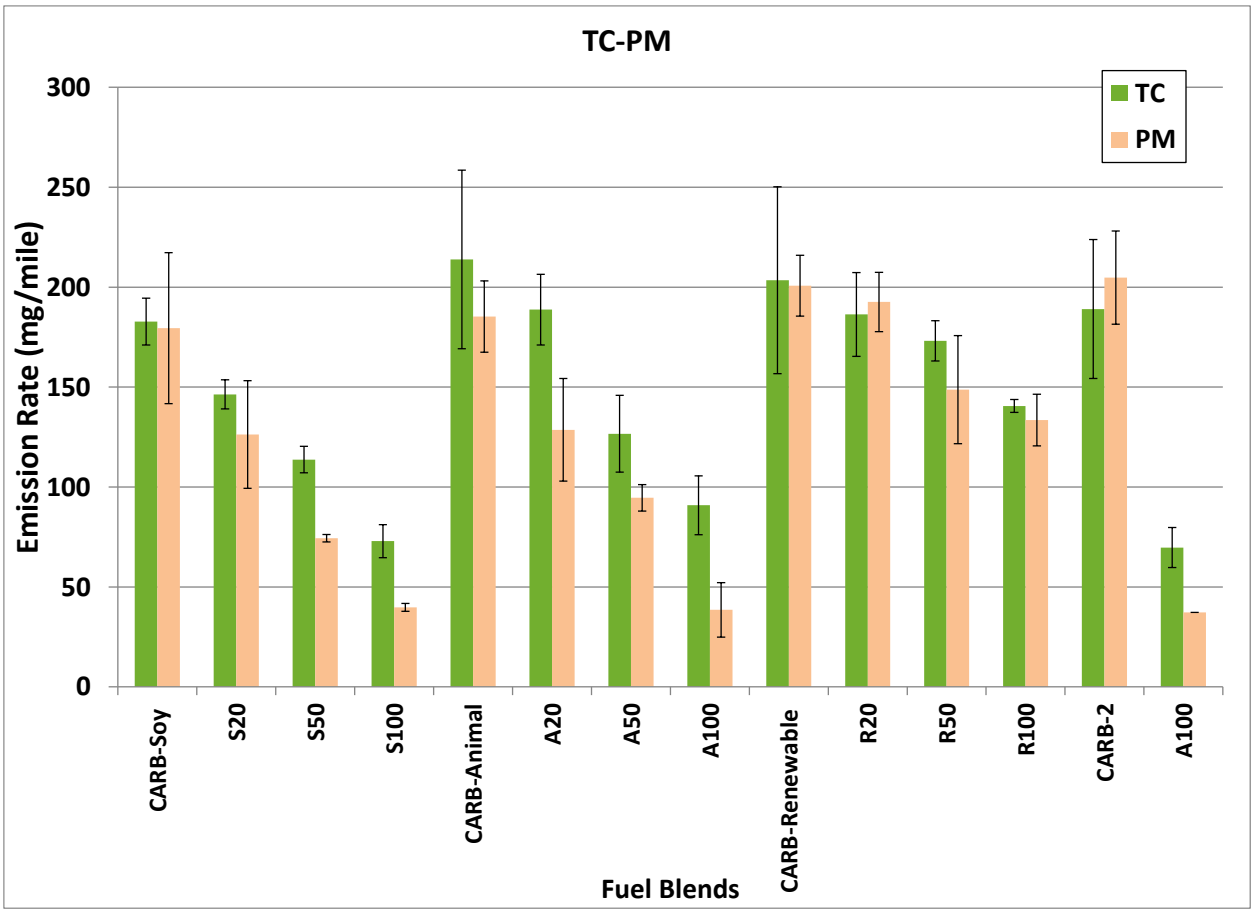


Figure 10-23. Average TC/PM Emission Results for the Biodiesel and Renewable Blends for the 2000 Caterpillar C-15

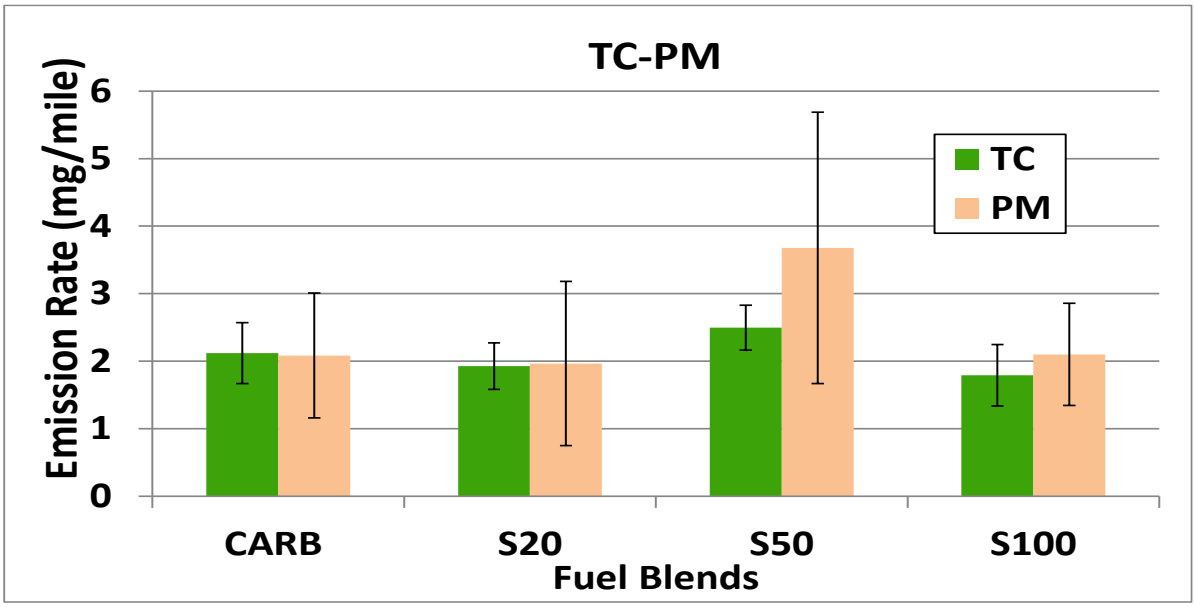


Figure 10-24. Average TC/PM Emission Results for the Biodiesel and Renewable Blends for the 2007 MBE4000

10.5 Ion Emissions

The ion emission results for the testing with the soy-based and animal-based biodiesel blends and the renewable diesel blends are presented in Figure 10-25 and Figure 10-26 for the 2000 Caterpillar C-15 and the 2007 MBE4000, respectively. Ion analysis was only conducted for the emissions tests with the UDDS cycle and, for the 2007 MBE4000, only for the soy-based biodiesel. The corresponding percentage differences relative to the CARB diesel, and associated t-test values are provided in Table 10-12.

The ion emissions were generally very low, comprising less than 1% of the total PM mass for the 2000 Caterpillar C-15. Chloride, potassium, and magnesium emissions were below the laboratory detection limit for most tests, and these data have been labeled NA in Table 10-12. Additionally percentage differences are marked as NA when the emissions for the CARB fuel are below the detection limit and hence there is a division by zero in the percentage differences. There are also cases when the emission level of the biodiesel blend is below the detection limit, and hence the percentage differences are automatically -100%, as listed in the table. It should be noted that in some of these cases a t-test value can still be obtained, which then indicates whether the values of the other emissions component are above the detection limit.

Overall, there are no consistent trends in the ion emissions between the different fuels. In some cases, there are statistically significant differences for specific fuel blends with respect to CARB, but in most cases, these trends are not consistent over the range of blend levels tested with a particular fuel. Calcium emissions were higher for the soy-based biodiesel for all blend levels for the 2000 Caterpillar C-15, which could be related to trace amounts of calcium in the soy-biodiesel. There is not an increase in calcium emissions with increasing blend level as would be expected if this were the case, however, and this same trend is not seen for the 2007 MBE4000. Ammonium emissions showed reductions in emissions for the B50 and B100 biodiesel blends for the 2000 Caterpillar C-15. No changes in ammonium emissions were found for the 2007 MBE4000.

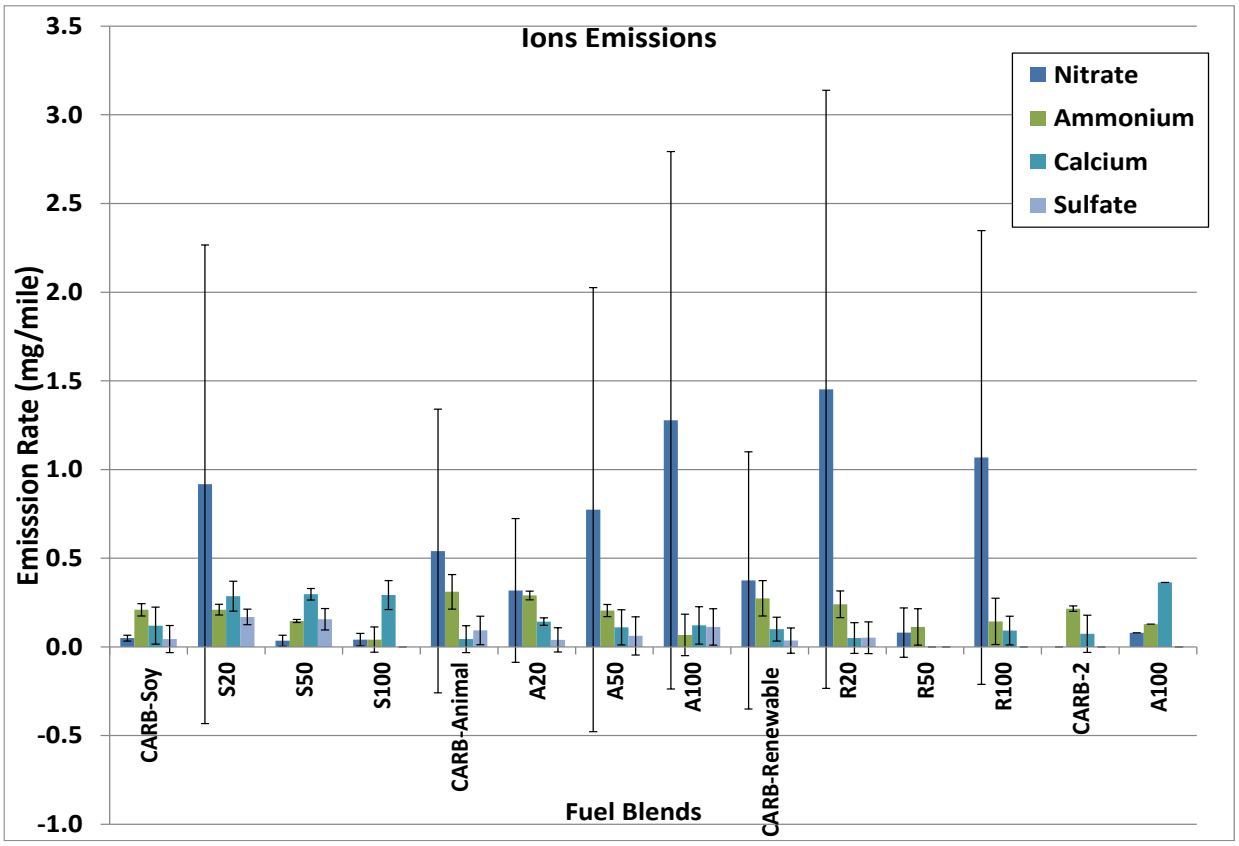


Figure 10-25. Average Ion Emission Results for the Biodiesel and Renewable Blends for the 2000 Caterpillar C-15

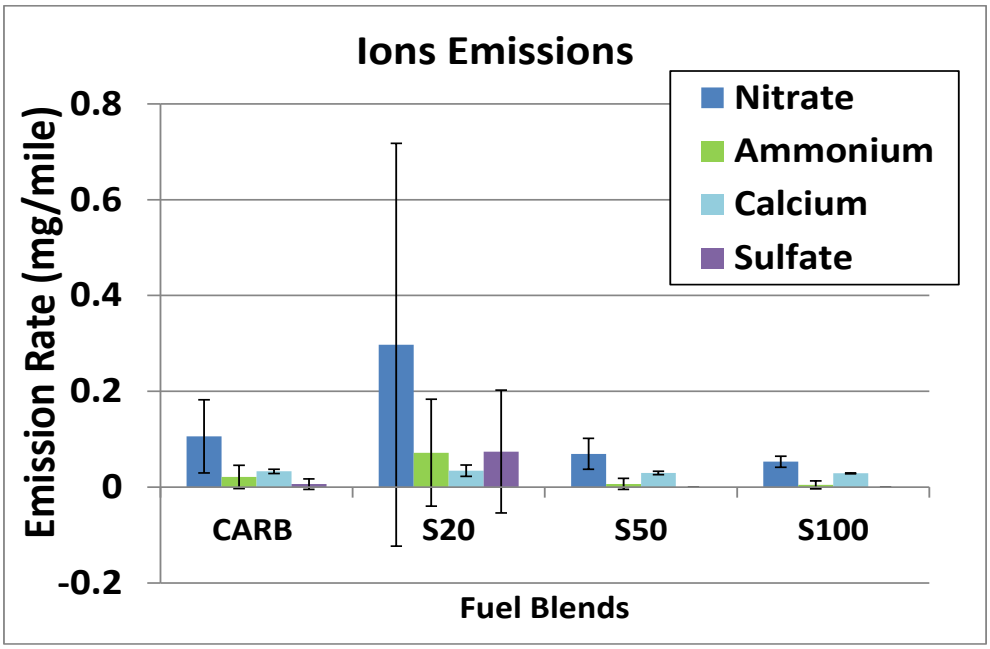


Figure 10-26. Average Ion Emission Results for the Biodiesel and Renewable Blends for the 2007 MBE4000

Table 10-12. Different Ion Percentage Differences Between the Biodiesel and Renewable Blends and the CARB ULSD base fuel for UDDS Cycle

	CARB vs.	2000 C-15 Caterpillar						2007 MBE 4000	
		Soy-based		Animal-based		Renewable		Soy-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values	% Difference	P-values
Nitrate	B20	1741%	0.328	-41%	0.689	133%	0.295	180.25%	0.482
	B50	-31%	0.497	43%	0.799	-79%	0.527	-34.68%	0.485
	B100	-19%	0.698	136%	0.498	185%	0.399	-49.92%	0.301
	B20-2								
	B100-2			NA					
Ammonium	B20	0%	0.975	-7%	0.740	-25%	0.645	238.66%	0.487
	B50	-30%	0.039	-7%	0.150	-59%	0.090	-68.21%	0.408
	B100	-80%	0.022	-78%	0.050	-48%	0.192	-77.91%	0.329
	B20-2								
	B100-2			-40%					
Calcium	B20	139%	0.099	227%	0.094	28%	0.429	4.20%	0.859
	B50	148%	0.049	152%	0.407	-100%	0.055	-10.10%	0.368
	B100	144%	0.087	177%	0.358	-8%	0.892	-12.72%	0.192
	B20-2								
	B100-2			390%					
Sulfate	B20	282%	0.070	-57%	0.434	25%	0.802	1087.36%	0.413
	B50	253%	0.118	-33%	0.715	-100%	0.437	-100.00%	0.374
	B100	-100%	0.374	21%	0.808	-100%	0.437	-100.00%	0.374
	B20-2								
	B100-2			NA					
Chloride	B20	NA	NA	NA	NA	NA	NA	NA	NA
	B50	NA	0.374	NA	NA	NA	NA	NA	NA
	B100	NA	NA	NA	NA	NA	NA	NA	NA
	B20-2	NA		NA		NA			
	B100-2	NA		NA		NA			
Sodium	B20	NA	0.374	NA	NA	-100%	0.437	88.67%	0.400
	B50	NA	0.059	NA	NA	-100%	0.437	2.83%	0.784
	B100	NA	0.123	NA	0.374	-100%	0.437	-6.31%	0.468
	B20-2	NA		NA		NA			
	B100-2	NA		NA		NA			
Potassium	B20	NA	NA	NA	NA	NA	NA	8.05%	0.508
	B50	NA	0.144	NA	NA	NA	NA	-1.54%	0.718
	B100	NA	NA	NA	0.374	NA	NA	-65.25%	0.135
	B20-2	NA		NA		NA			
	B100-2	NA		NA		NA			
Magnesium	B20	NA	NA	NA	NA	NA	NA	59.16%	0.309
	B50	NA	NA	NA	NA	NA	NA	-49.44%	0.525
	B100	NA	NA	NA	NA	NA	NA	-0.39%	0.996
	B20-2	NA		NA		NA			
	B100-2	NA		NA		NA			

NA: Percentage Difference is Not Available

10.6 Emissions of Elements

The emission results for elements for the soy-based, animal-based biodiesel blends, and the renewable diesel blends are presented in Figure 10-27 and Figure 10-28, for the 2000 Caterpillar C-15 and the 2007 MBE4000, respectively. Elemental analysis was only conducted for the emissions tests with the UDDS cycle and, for the 2007 MBE4000, only for the soy-based biodiesel. These figures show only the 10 elements with the highest emission rates for the 2000 Caterpillar C-15 and only elements that were measured above the detection limit for all the fuels for the 2007 MBE4000. The corresponding percentage differences relative to the CARB diesel and associated t-test values for these two vehicles/engines are provided in Appendix K, along with charts of other elements not included in this section.

The emissions of the trace elements were relatively low, comprising on average 1.65% of the total PM mass for the 2000 Caterpillar C-15 and 1.48% of the total PM mass for the 2007 MBE4000. Additionally, there were essentially no statistically significant trends between fuels for the elements, as shown in Appendix K. Overall, it does not appear that biodiesel or renewable blends will have a significant impact on element emissions, based on the results of this study.

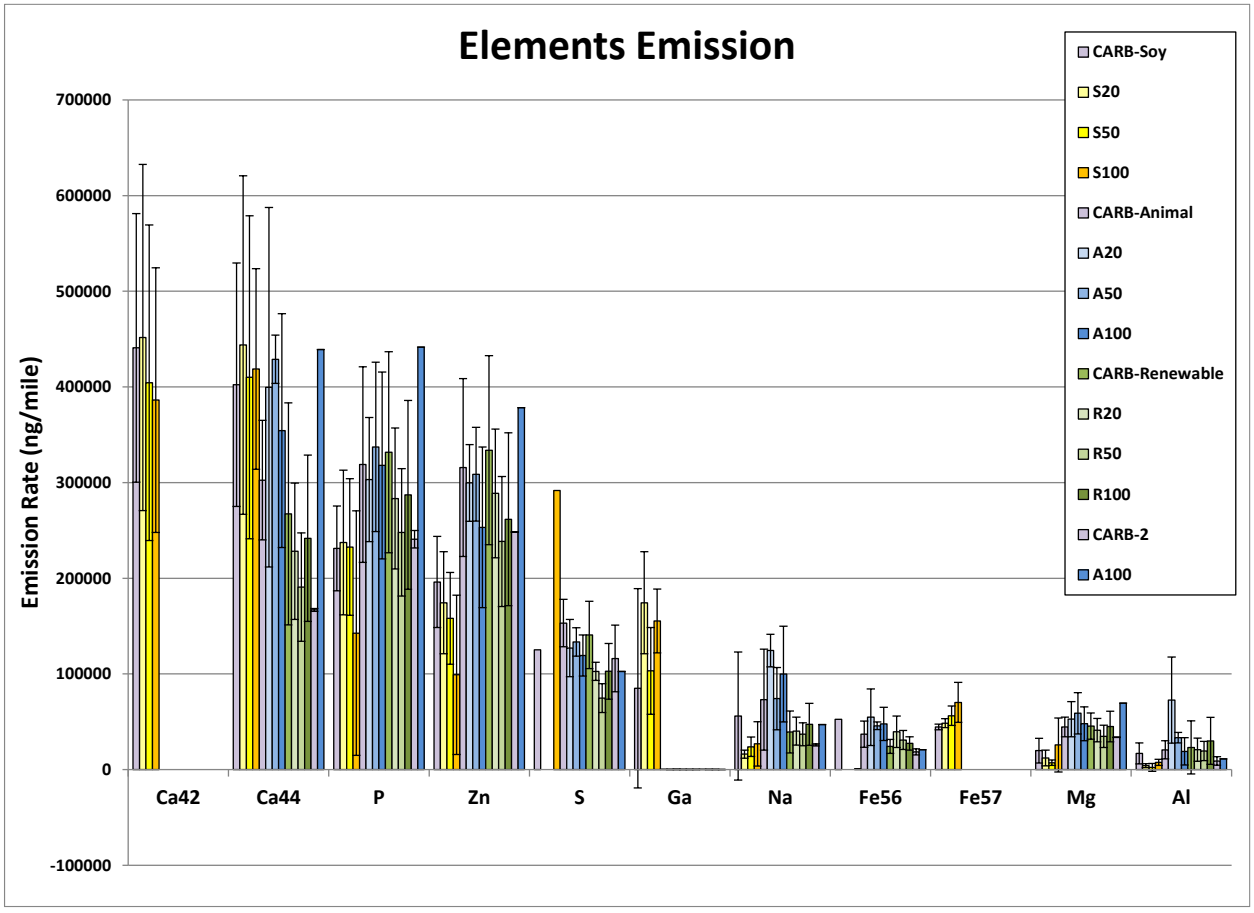


Figure 10-27. Average Element Emission Results for the Biodiesel and Renewable Blends for the 2000 Caterpillar

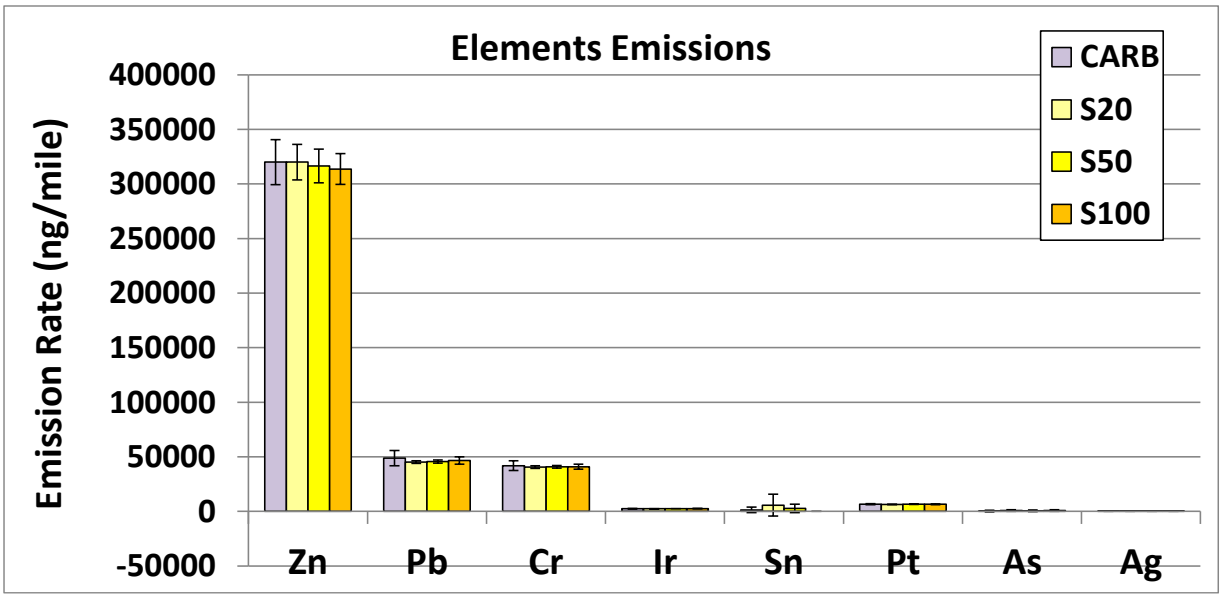


Figure 10-28. Average Element Emission Results for the Soy-based Biodiesel Blends for the 2007 MBE4000

10.7 Real-Time PM Emissions

The total particle number (PN) counts for each of the test vehicles and for the UDDS and Cruise cycles are presented in Figure 10-29, as a function of the different test fuels. The results show that particle number was a function of the engine technology. The 2000 Caterpillar C-15 had the highest PN counts, followed closely by the 2006 Cummins ISM. The PN counts for the 2007 MBE4000 were considerably lower than those of the other two vehicles due to the removal of a significant fraction of the particles by the DPF. For the 2000 Caterpillar C-15-equipped vehicle, the PN varied between 1.4 x 10^{13} and 4.2 x 10^{15} #/mile over the different test cycles and fuels. For the 2006 Cummins ISM-equipped vehicle, the PN varied between 6.52 x 10^{14} and 1.19 x 10^{15} #/mile for the UDDS cycle and between 4.8 x10^{14} and 1.65 x 10^{15} #/mile for the 50-mph cruise cycle. The PN counts for the 2007 MBE4000 showed a stronger dependence on test cycles, with the 50-mph cruise having the higher PN count. For the 2007 MBE4000-equipped vehicle, the PN varied between 1.76 x 10^{12} and 6.41 x 10^{12} #/mile for the UDDS cycle and between 1.76 x10^{13} and 1.31 x 10^{14} #/mile for the 50-mph cruise cycle. The cruise cycles were generally associated with higher exhaust temperatures than UDDS cycles. In the case of the 2007 MBE4000 vehicle, this may have led to some conversion of fuel sulfur to sulfate in the presence of the DOC of the aftertreatment system, generating more nucleation mode particles during the cruise cycle. Since the 2000 Caterpillar C-15 and the 2006 Cummins ISM were not equipped with aftertreatment system, the higher exhaust temperatures would not have generated significant levels of nucleation mode particles, so the differences between the PN for the two cycles for these vehicles are not as great.

PN showed some differences between fuels, but in general, the differences in PN were not as consistent as those found for PM mass, and they did not follow the same trends that were observed for the PM mass. For the 2000 Caterpillar C-15 equipped vehicle, PN showed some increases for the higher blends of animal-based biodiesel. The highest PN counts were found for the animal-based B100 at 4.2 to 4.4 x 10^{15} #/mile.

For 2006 Cummins ISM, on average there is a slight decrease (22-28%) in PN for the 20% blend fuels (Soy B20 & Animal B20) compared with CARB for the cruise cycle. Similar reductions were achieved for B20 (Both Animal and Soy) and B50 (Both Animal and Soy) for the UDDS cycle. PN increased, in general, for pure animal and soy based biodiesel (B100) for the 2006 Cummins ISM (except for Soy B100 in cruise cycle) with respect to B20 and B50 blends.

For the 2007 MBE4000 equipped vehicle, PN showed some decreases for the higher animal-based biodiesel blends compared with the CARB diesel, but for the 50-mph cruise, the soy- and animal-based B100 fuels showed the highest counts.

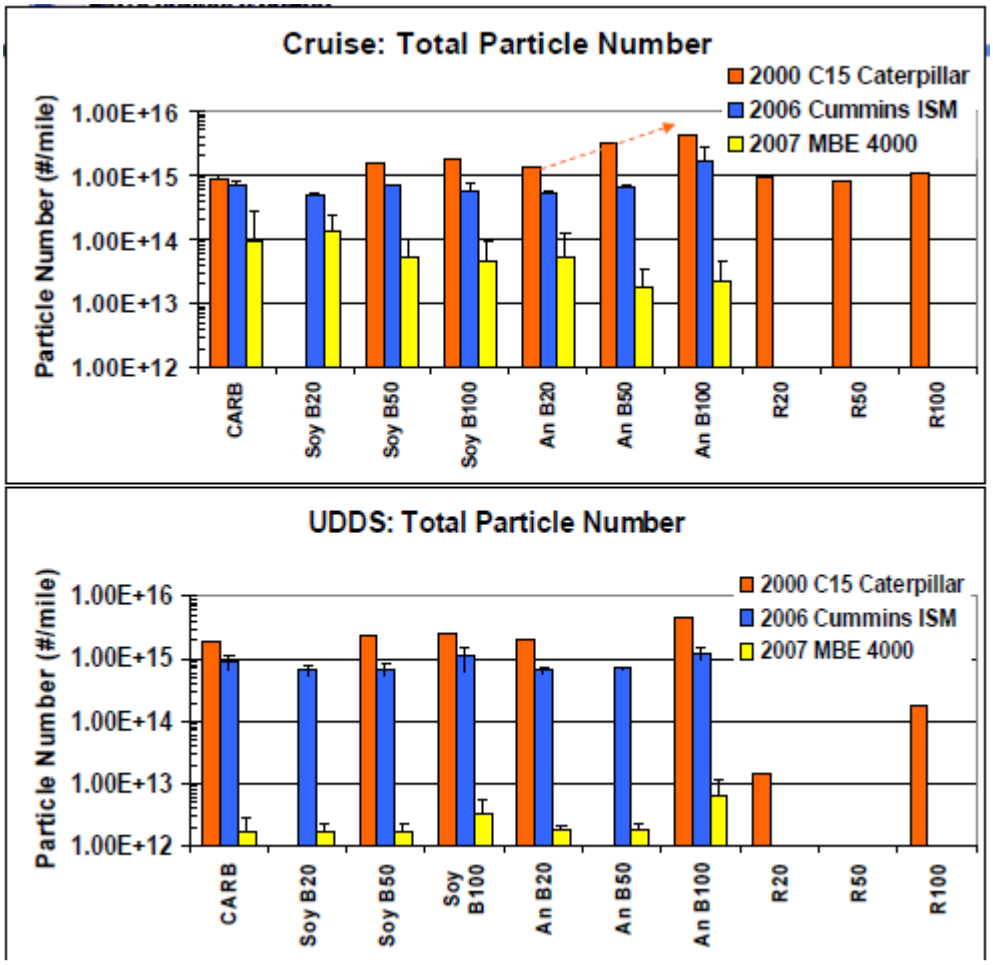


Figure 10-29. Total Particle Number Counts for the 50-mph Cruise cycle (upper panel) and the UDDS cycle (lower panel)

The particle size distributions are presented in Figure 10-30, Figure 10-31, and Figure 10-32, respectively, for the 2000 Caterpillar C-15 vehicle, the 2006 Cummins ISM vehicle, and the

2007 MBE4000 vehicle. The size distributions differed for different vehicle/fuel/cycle combinations, showing a range of mono-, bi-, and tri-modal distributions.

The 2000 Caterpillar C-15 showed the most significant changes across the different fuel types. The 2000 Caterpillar C-15 showed the highest concentrations of smaller particles (<20nm), with a distinct peak ~10nm for all fuel types and cycles. Nucleation ~<10 to 30 nm increased while the accumulation mode between ~80 to 300 nm decreased with increasing blend levels for Animal and Soy biodiesel. For the renewable diesel, tri-modal distributions were observed with peaks at ~10, 60, 230nm. The largest particles (230nm) increased with increasing blends for Renewable fuels.

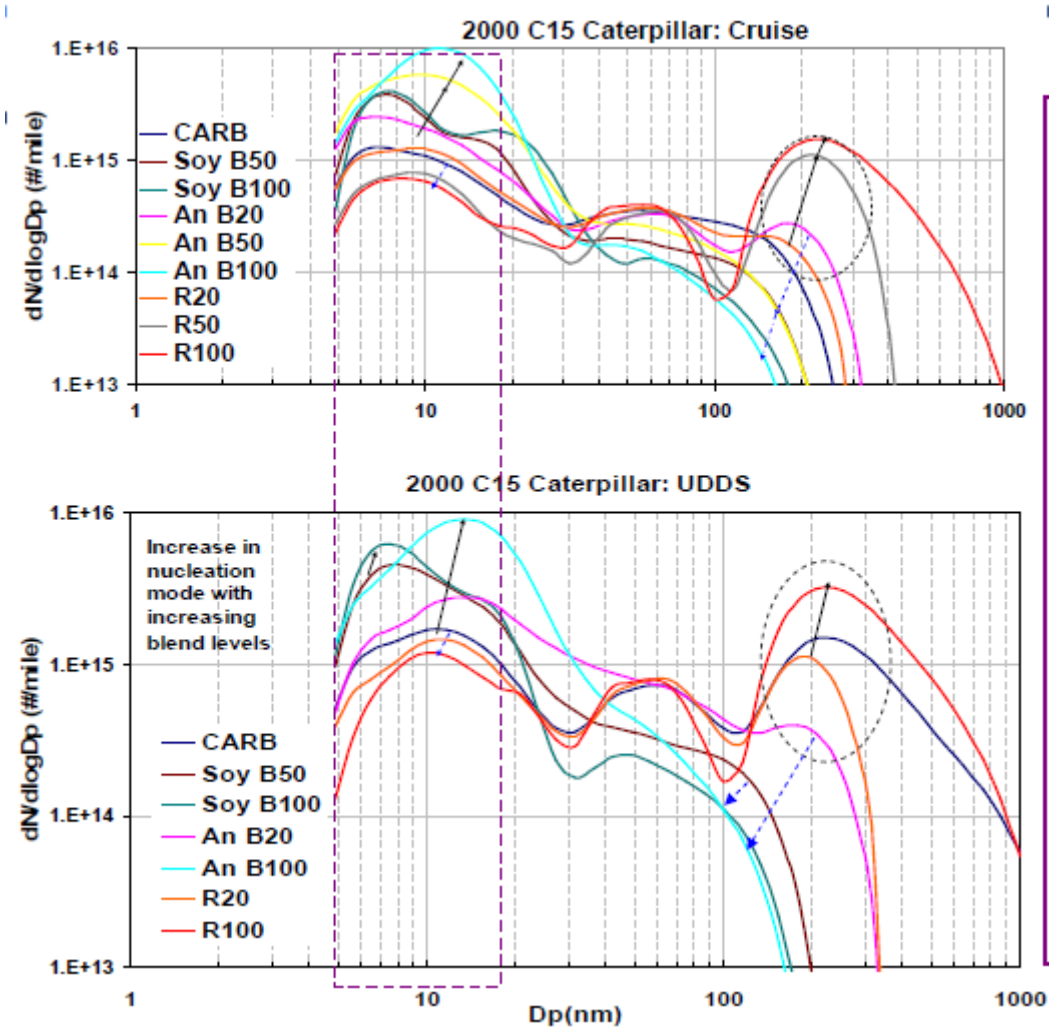


Figure 10-30. Size Distributions for the 2000 Caterpillar C-15 for the 50-mph Cruise cycle (upper panel) and the UDDS cycle (lower panel)

The 2006 Cummins ISM showed a distinct peak at ~10 nm and a broader peak at ~50-60 nm. For the biodiesel blends (B50, B100) the size of larger mode (~50nm) decreased and shifted towards smaller modes, while the small nucleation mode (10-20nm) increased, especially for B100. Since this vehicle does not have a DPF, the second mode (~50 nm) is likely generated from elemental carbon emissions.

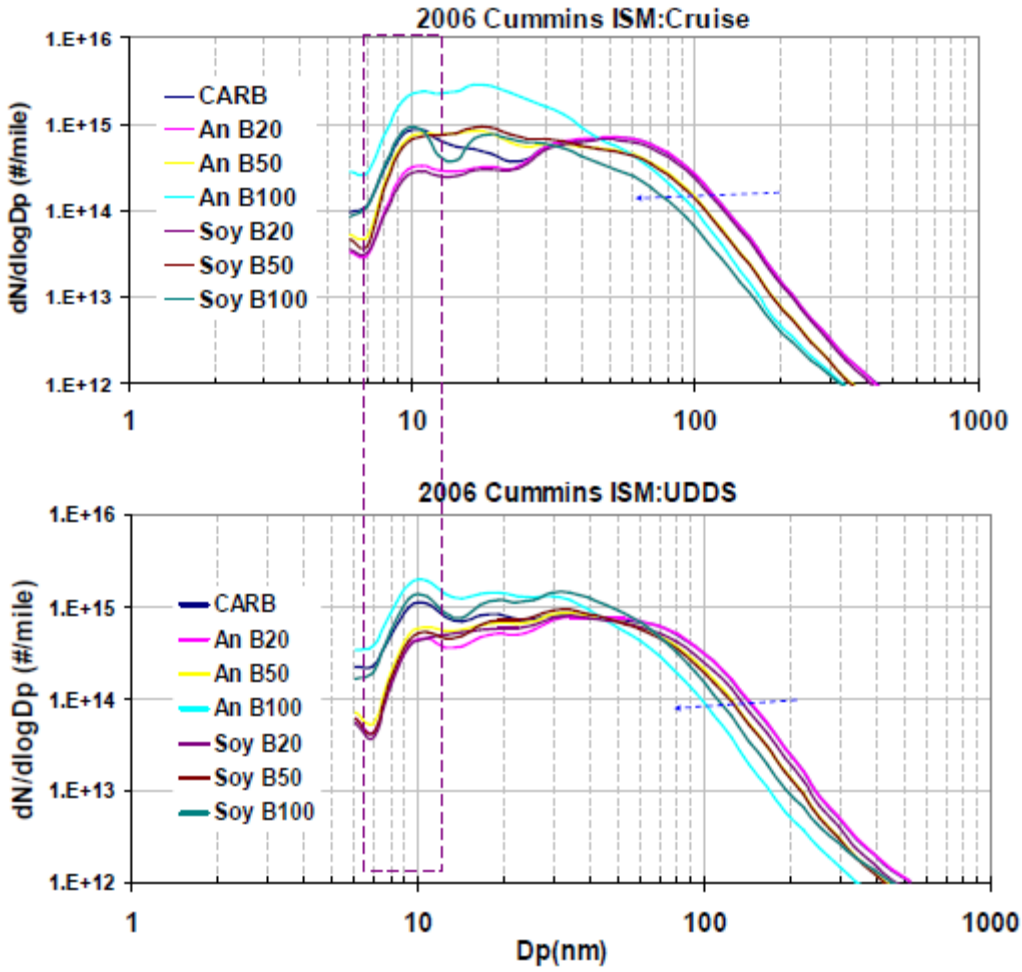


Figure 10-31. Size Distributions for the 2006 Cummins ISM for the 50-mph Cruise cycle (upper panel) and the UDDS cycle (lower panel)

The size distributions for the 2007 MBE4000 vehicle showed predominantly two modes and <10nm and ~50-70 nm. The concentration of the nucleation mode particles (<10 nm) increased significantly for the 50 mph cruise cycle in comparison with the UDDS cycle for this vehicle. This vehicle showed a dramatic increase in particles between ~50-70 nm for the soy-based and animal-based B100, along with a corresponding decrease in nucleation mode particles (<10 nm). The decrease in nucleation mode particles was observed only for the cruise cycle, where nucleation is predominant. This is in contrast to the trends seen for the other two non-DPF equipped vehicles.

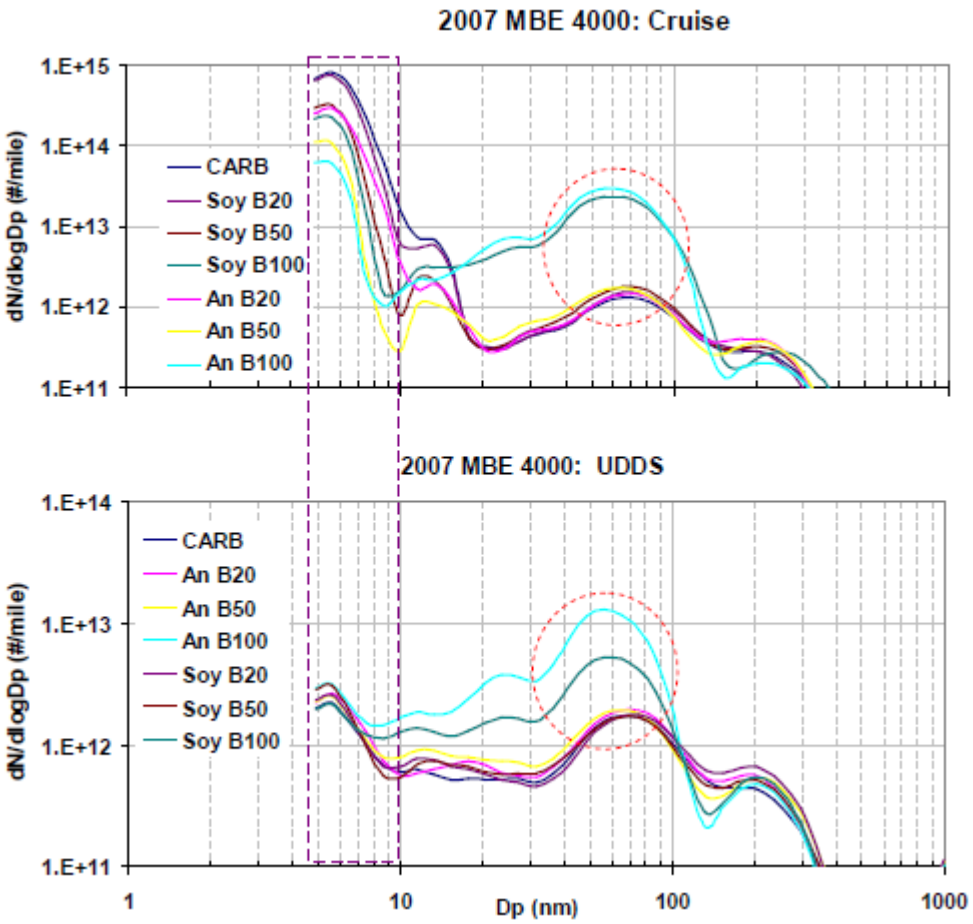


Figure 10-32. Size Distributions for the 2007 MBE4000 for the 50-mph Cruise cycle (upper panel) and the UDDS cycle (lower panel)

The particle length measurements from the EAD are shown in Figure 10-33 for the testing on the 2006 Cummins ISM and the 2007 MBE4000 equipped vehicles. A study by Wilson et al. (2006) demonstrated good correlation between EAD signal and the estimated particle surface area deposited in the lungs, indicating that EAD signals are useful tool for inferring human exposure to ultrafine particles. The 2006 Cummins ISM showed about a factor of one or two higher particle length measurements than the 2007 MBE4000 for both the cruise and UDDS cycles. For the 2006 Cummins ISM, the particle length was in the range of ~10^{10} mm/mile, and was relatively constant at that level over the whole spectrum of fuel types and driving conditions. For the 2007 MBE4000, the particle length did not show any significant differences between the soy-based biodiesel bends and the CARB diesel for the 50-mph cruise cycle. The animal-based B100 did show higher emissions than the lower blends of the animal-based biodiesel for the cruise, however, and the soy- and animal-based B100 fuel had the highest signals for the UDDS for the 2007 MBE4000.

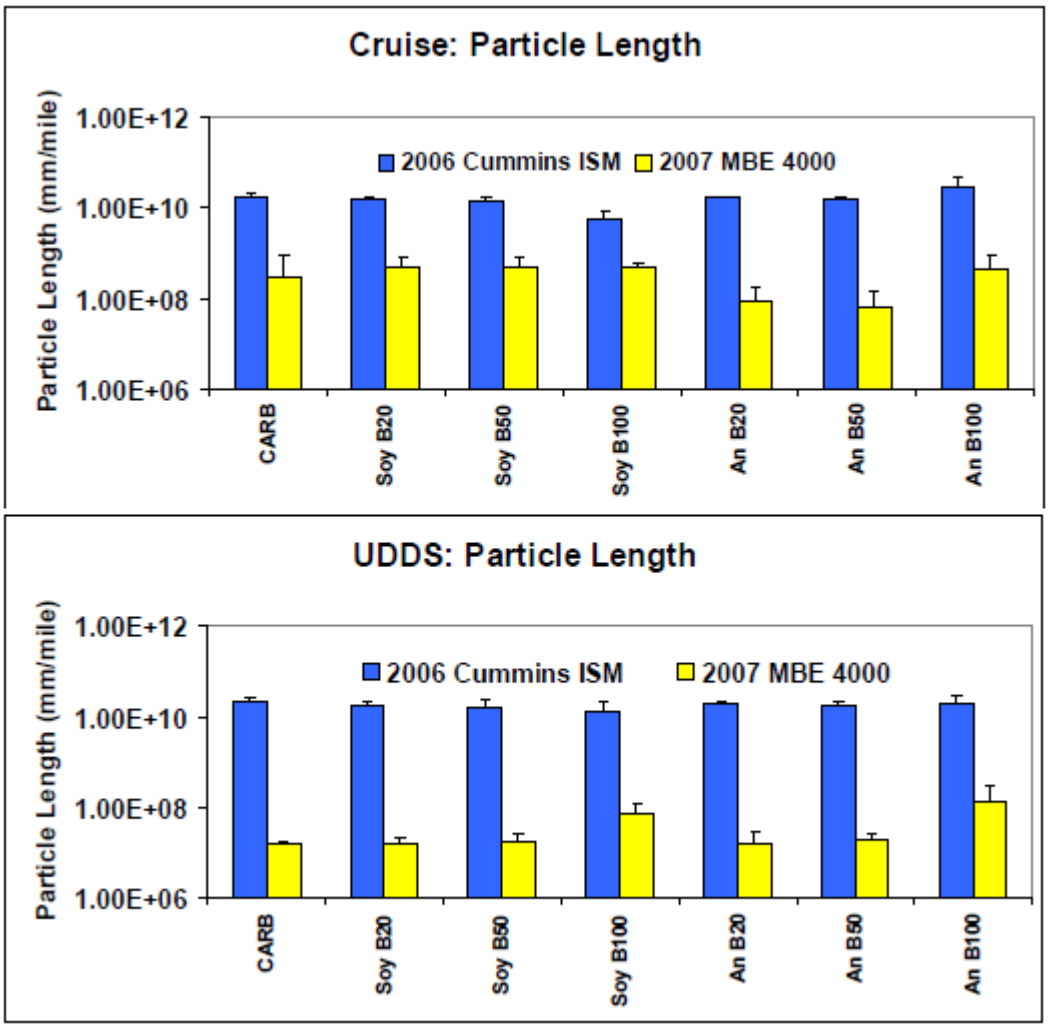


Figure 10-33. Particle Length Measurements for the 2006 Cummins ISM and the 2007 MBE4000 for the 50-mph Cruise cycle (upper panel) and the UDDS cycle (lower panel)

The particle-bound PAH (pPAH) measurements from the PAS are shown in Figure 10-34 for the testing on the 2006 Cummins ISM and the 2007 MBE4000 equipped vehicles. The pPAH levels measured by the PAS were considerably higher for the 2006 Cummins ISM than the 2007 MBE4000, as would be expected. For the 2006 Cummins ISM, pPAHs were higher for the UDDS cycle (39-235 μg/mile) than for the Cruise (7.4-160 μg/mile) cycle. The pPAH emissions for the 2007 MBE4000 were low, varying between 1.7-24.4 μg/mile. The 2006 Cummins ISM also showed a consistent trend of decreasing pPAHs with increasing biodiesel level for both the soy-based and animal-based biodiesels. The 2007 MBE4000 showed an opposite trend, however, with significant increases in pPAHs for the soy- and animal-based B100 fuels. This increase in pPAHs for the B100 fuels for the 2007 MBE4000 corresponded with an increase in accumulation mode particles, as seen in Figure 10-32. Complete chemical analysis results of filter based PAHs might shed some light on the plausible cause of the relatively higher pPAH emissions for B100 fuels.

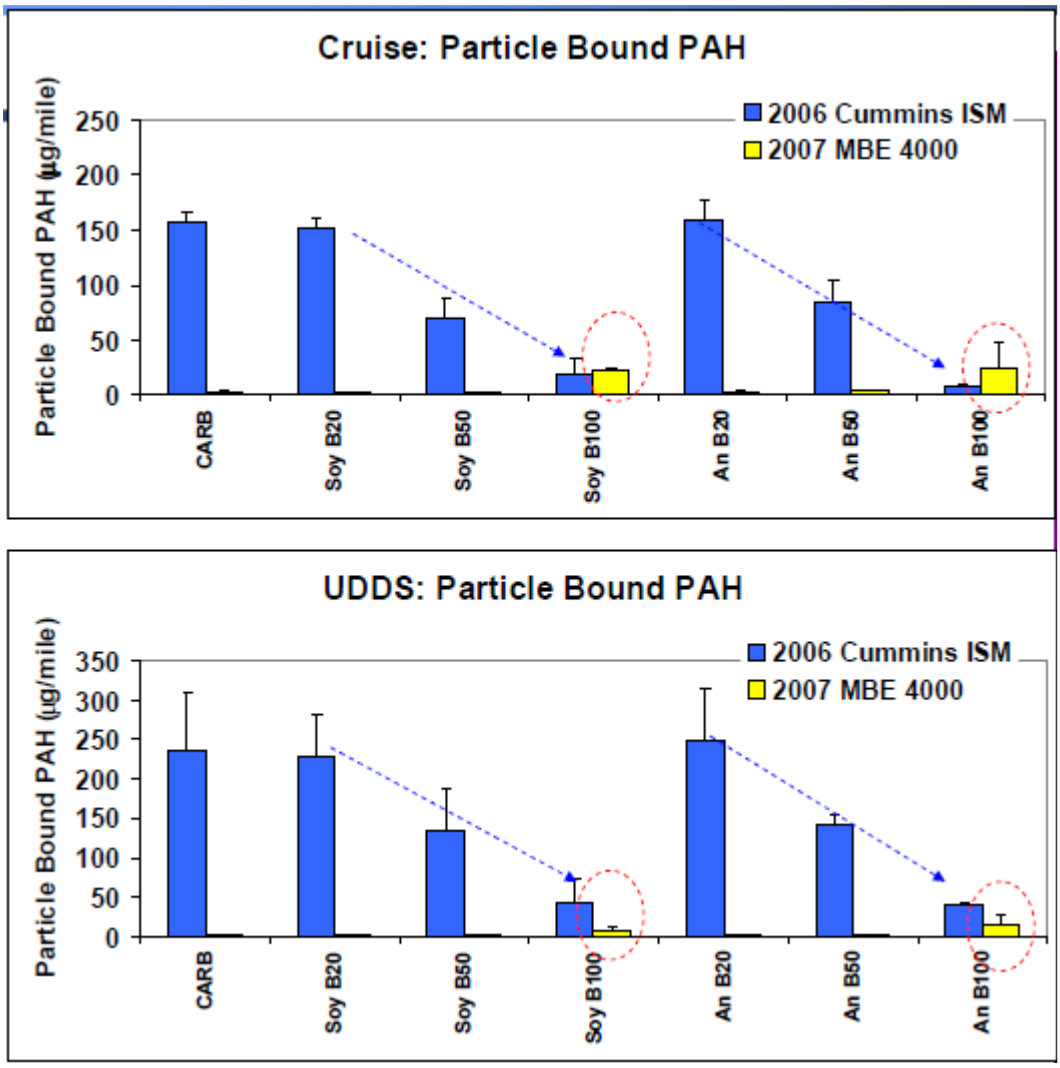


Figure 10-34. Particle-Bound PAH Measurements for the 2006 Cummins ISM and the 2007 MBE400 for the 50-mph Cruise cycle (upper panel) and the UDDS cycle (lower panel)

10.8 PAH Emissions

The PAH emissions in the particulate and vapor phase were measured for the CARB diesel, soy biodiesel, animal biodiesel, renewable diesel, and their respective blends with the CARB diesel (20% and 50%) on the UDDS driving cycle for the 2000 Caterpillar C-15 vehicle. Triplicate samples were obtained for each fuel and the blend level, except for the CARB and animal 100% fuels. For CARB diesel and the animal 100% fuels, eight and four replicates were taken, respectively. Replicate samples were analyzed separately, and the statistical comparisons between fuels were conducted for the 2000 Caterpillar C-15 vehicle. For the 2007 MBE4000 vehicle, measurements were made for the CARB diesel, the soy biodiesel and the blends (20% and 50%) with the UDDS driving cycle. Triplicate samples were taken, but they were combined for analyses due to low concentrations of PAHs, and therefore, variability in the samples is not reported for the 2007 MBE4000 vehicle. Also, the statistical comparisons between fuels were not conducted for this vehicle. For the C-15 vehicle, some PAHs showed decreasing trends over time in the CARB diesel samples that were taken eight times intermittently throughout the study.

Therefore, CARB samples were matched to the corresponding time period when the biodiesel and/or renewable diesel samples were taken. In addition to the emission samples, triplicate samples were taken for the tunnel blank for both vehicles.

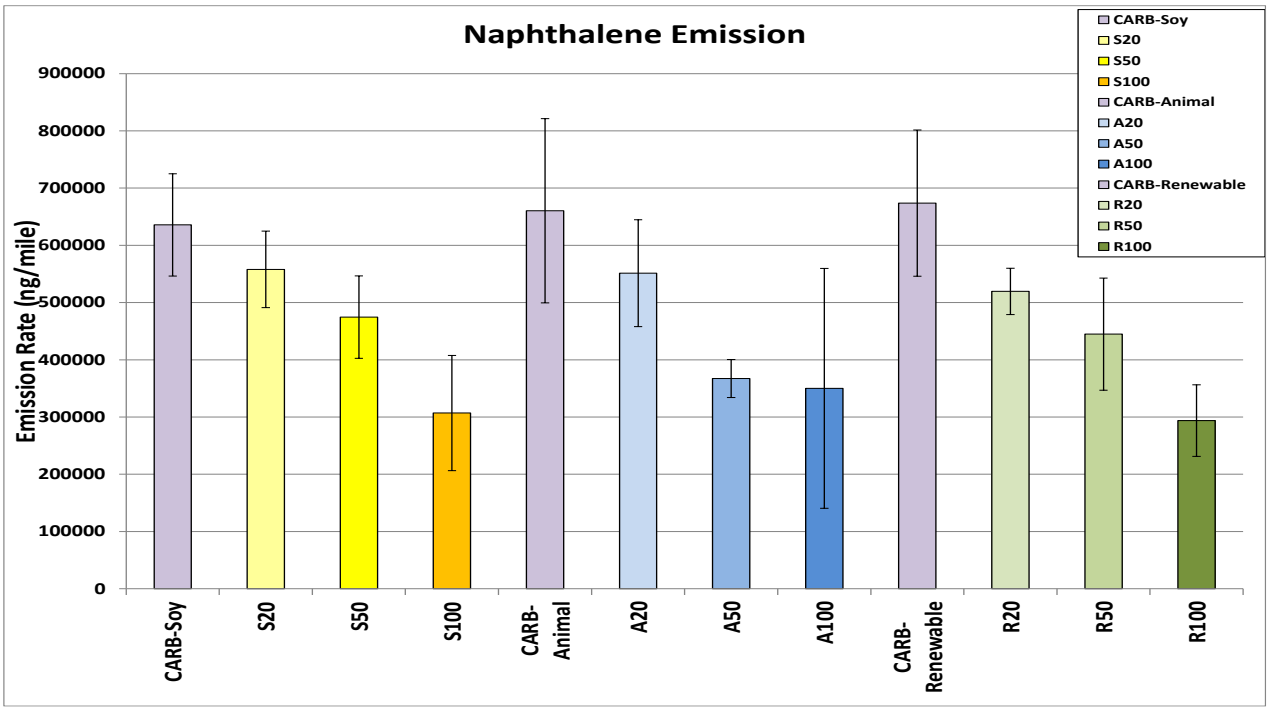
The most abundant PAHs measured were naphthalene, 2-methylnaphthalene, and 1-methylnaphthalene. In all fuels and blends for both vehicles, the emissions of these three compounds accounted for approximately 70 to 80% of all PAHs measured. Emissions of all PAHs were lower for the 2007 MBE4000 compared to the 2000 Caterpillar C-15 vehicle. Many particle-associated PAHs were not detected in the 2007 MBE4000 vehicle. The vapor phase PAHs decreased by over 95% in the 2007 MBE4000 vehicle compared to the 2000 Caterpillar C-15 vehicle. The results show that the DPF for the 2007 MBE4000 was effective in reducing PAHs, not only in the particle phase, but also in the vapor phase. The results also show that PAH emissions decrease with increasing blend levels of biodiesel and renewable diesel fuel for the 2000 Caterpillar C-15 vehicle. These trends are discussed in greater detail below for each of the selected species.

10.8.1 Naphthalene

Naphthalene is a 2-ring PAH mainly present in the vapor phase. The US EPA classifies naphthalene as a "possible human carcinogen". In the sampling train consisting of a filter, PUF, and XAD, approximately 95% of naphthalene was found in XAD in all fuels and blends for the both vehicles tested. The total naphthalene emission results are presented in Figure 10-35 for the 2000 Caterpillar C-15 and the 2007 MBE4000 vehicles. The results show that the emissions for the 2000 Caterpillar C-15 vehicle are considerably higher than those for the 2007 MBE4000 vehicle. Naphthalene emissions decreased by approximately 97% for the 2007 MBE4000 vehicle compared to the 2000 Caterpillar C-15 vehicle for the CARB diesel, soy biodiesel, and the blends. The DPF for the 2007 MBE4000 vehicle was effective in reducing naphthalene emissions. The results for the 2000 Caterpillar C-15 vehicle show statistically significant reductions in naphthalene as a function of increasing biodiesel and renewable blend level. For example, the reductions in 100% soy biodiesel, 100% animal biodiesel, and 100% renewable diesel relative to the CARB diesel were 52%, 44%, and 56%, respectively. For the 2000 Caterpillar C-15 vehicle, no statistically significant differences were observed in emission reductions between the soy, or animal-based biodiesel, or renewable diesel. The same trend was observed also for the 2007 MBE4000, however, statistical comparisons were not conducted for this vehicle. Also, the concentrations measured in the emission samples were very low, where emissions in soy 100% biodiesel was only 10% elevated over the corresponding tunnel blank for the 2007 MBE4000. Therefore, the trends for the 2007 MBE4000 vehicle may not be significant.

10.8.2 Phenanthrene

Phenanthrene is a 3-ring PAH mostly present in the vapor phase. For the 2000 Caterpillar C-15 vehicle, more than 70% of phenanthrene was in the PUF, 29% or less was in the filters, and only 1% or less was found in XAD for all fuels and blends. For the 2007 MBE4000 vehicle, it was mostly in the PUF, and only 2% or less was found in the filters. The shift in the phase distribution observed in the 2007 MBE4000 vehicle may partly be attributed to the lower concentration of particles in the exhaust from this vehicle.



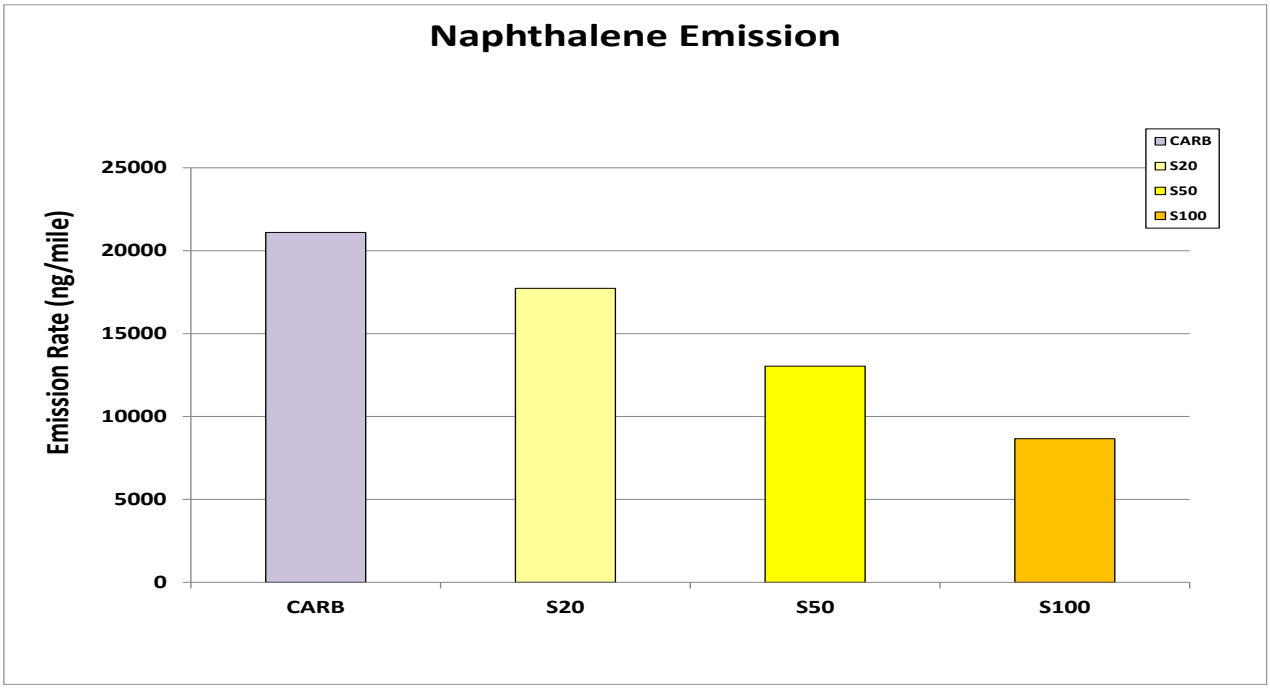


Figure 10-35. Average Naphthalene Emissions in particle and the vapor phase for the CARB diesel, Soy-Biodiesel (S-100) , Animal-biodiesel (A-100), and Renewable diesel (R100) and their blends (20% and 50%).Testing for the 2000 Caterpillar C-15 (upper panel) and for the Soy-Biodiesel for the 2007 MBE4000 (lower panel) were taken over the UDDS driving cycle. Error bars for the 2000 Caterpillar C-15 vehicle represent one standard deviation from the replicate samples. For the 2007 MBE4000, the replicates were combined for analyses.

Total phenanthrene emissions are shown in Figure 10-36 for the 2000 Caterpillar C-15 and the 2007 MBE4000 vehicles. The results show that the emissions for the 2000 Caterpillar C-15 vehicle are considerably higher than those for the 2007 MBE4000 vehicle. Phenanthrene emissions decreased by 97 to 98% for the 2007 MBE4000 compared to the 2000 Caterpillar C-15 vehicle for both diesel and soy biodiesel and their blends. The results show statistically significant reductions in phenanthrene as a function of increasing biodiesel and renewable blend level for the 2000 Caterpillar C-15. The 2007 MBE4000 did not show any trends as a function of fuel for phenanthrene. Overall, concentrations of phenanthrene measured in the emission samples were low for the 2007 MBE4000 vehicle, and were similar to the concentration in the corresponding tunnel blank. The reductions observed in the 100% soy and animal biodiesel and renewable diesel for the 2000 Caterpillar C-15 vehicle compared to the corresponding CARB diesel were 36%, 70%, and 62% for the soy and animal based biodiesel, and renewable diesel, respectively. The differences in the feedstock were statistically significant, with the largest reductions in phenanthrene emissions for the animal based biodiesel, followed by the renewable diesel and the soy biodiesel for the 2000 Caterpillar C-15 vehicle.

10.8.3 Fluoranthene

Fluoranthene is a 4-ring semivolatile PAH. For the 2000 Caterpillar C-15 vehicle, it was found in filters and the PUF. More than 70% was found in the filters for CARB diesel, renewable diesel and its blends, approximately 20% was found in the filters for the soy biodiesel, and 40% for the animal based biodiesel. The difference in the phase distribution may partly be due to the higher PM emissions for CARB diesel and renewable diesel compared to soy and animal based biodiesel. For the 2007 MBE4000 vehicle, only 10% or less was found in the filters due to low PM emissions from this vehicle. Total fluoranthrene emissions are shown in Figure 10-37 for the 2000 Caterpillar C-15 and the 2007 MBE4000 vehicles. The results show that the emissions for the Caterpillar C-15 vehicle are considerably higher than those for the 2007 MBE4000 vehicle. Fluoranthene emissions for the 2007 MBE4000 decreased by 97% in the CARB diesel and 94% in the soy biodiesel compared to the 2000 Caterpillar C-15 vehicle. The results show statistically significant reductions in fluoranthene as a function of increasing biodiesel and renewable blend level for the 2000 Caterpillar C-15. Concentrations of fluoranthene measured in the emission samples for the 2007 MBE4000 vehicle were not significantly elevated over the corresponding tunnel blank. The 2007 MBE4000 did not show any trends as a function of fuel for fluroanthene. For the 2000 Caterpillar C-15 vehicle, the reductions observed in the 100% biodiesel or renewable diesel compared to the corresponding CARB diesel were 66%, 69%, and 60% for the soy- and animal-based biodiesel, and renewable diesel, respectively. There were no significant differences observed between different feedstocks in reducing fluoranthene emissions for the 2000 Caterpillar C-15 vehicle.

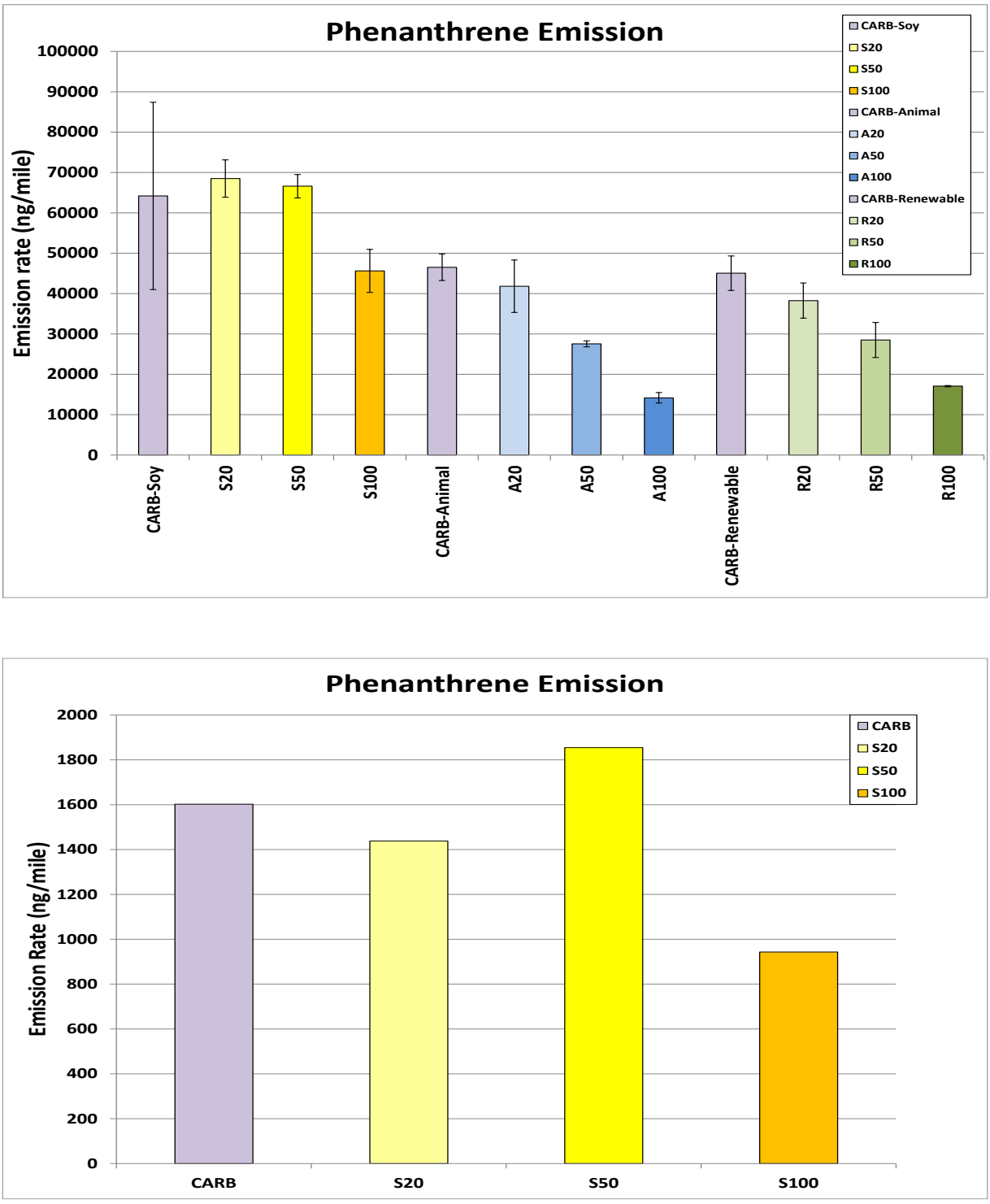
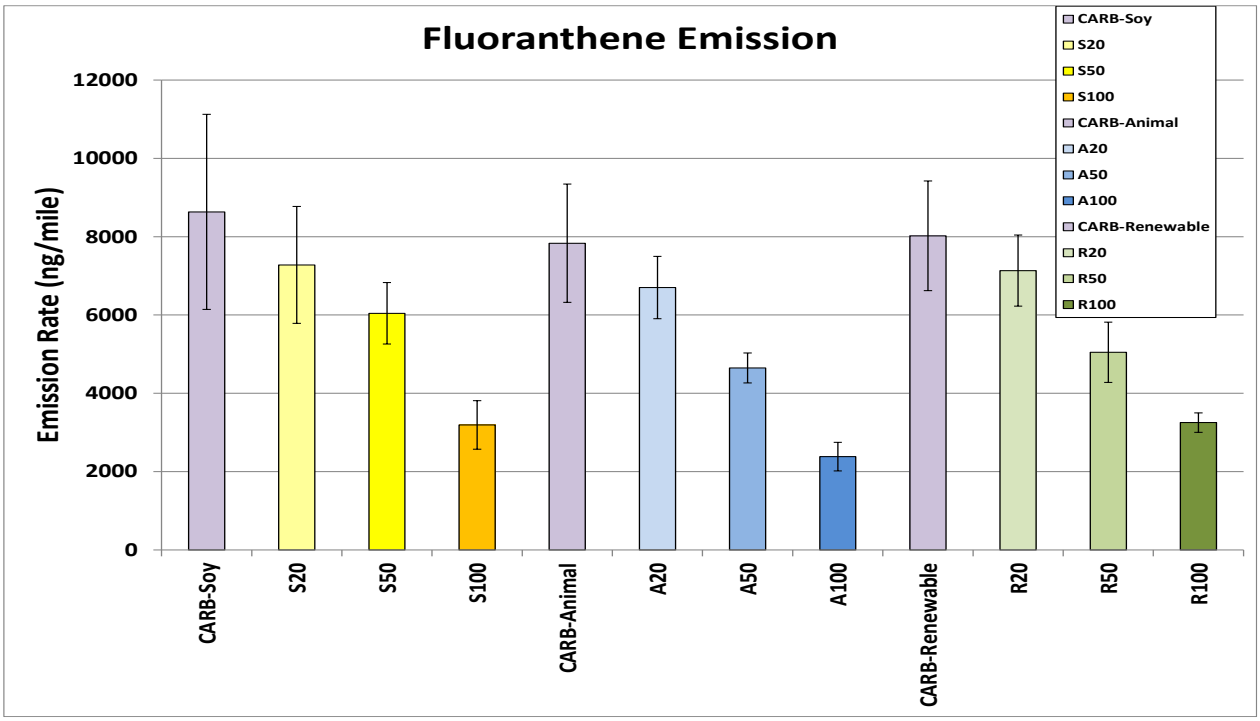


Figure 10-36. Average Phenanthrene Emission Results in particle and the vapor phase for the CARB diesel, Soy-Biodiesel (S-100), Animal biodiesel (A-100), and Renewable diesel (R-100) and their blends (20% and 50%). Testing for the 2000 Caterpillar C-15 (upper panel) and for the Soy-Biodiesel for the 2007 MBE4000 (lower panel) over the UDDS driving cycle. Error bars for the 2000 Caterpillar C-15 vehicle represent one standard deviation from the replicate samples. For the 2007 MBE4000, the replicates were combined for analyses.



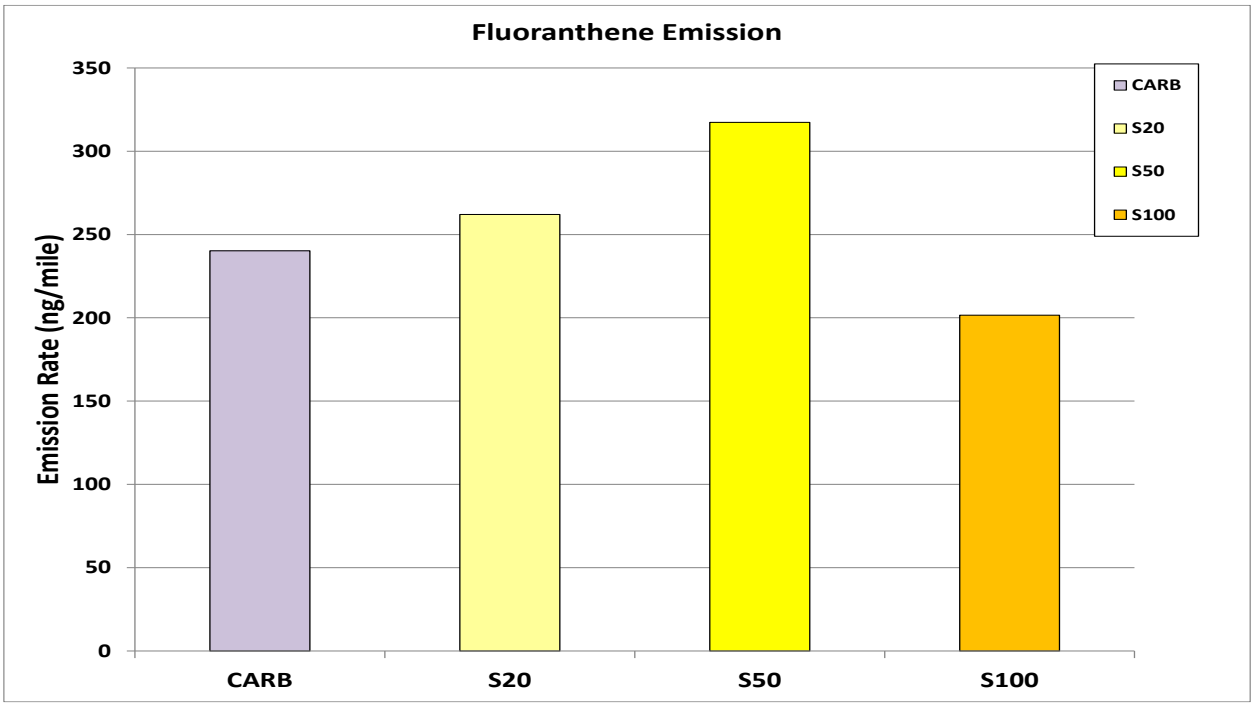


Figure 10-37. Average Fluoranthene Emission Results in Particle and the Vapor phase for the CARB diesel, Soy-Biodiesel (S100), Animal-Biodiesel (A100), and Renewable Diesel (R100) and their blends (20% and 50%) for the 2000 Caterpillar C-15 (upper panel) and for the Soy-Biodiesel for the 2007 MBE4000 (lower panel) over the UDDS driving cycle. Error bars for the 2000 Caterpillar C-15 vehicle represent one standard deviation from the replicate samples. For the 2007 MBE4000, the replicates were combined for analyses.

10.8.4 Benz(a)anthracene

Benz(a)anthracene is a 4-ring PAH mostly associated with the particle phase. The US EPA classifies it as “probable human carcinogen”. Benz(a)anthracene was found only in the filters for both 2000 Caterpillar C-15 and 2007 MBE4000 vehicles. Total benz(a)anthracene emissions are shown in Figure 10-38 for the 2000 Caterpillar C-15 and the 2007 MBE4000 vehicles. The results show that the emissions for the 2000 Caterpillar C-15 vehicle are considerably higher than those for the 2007 MBE4000 vehicle. Benz(a)anthracene emissions decreased for the 2007 MBE4000 vehicle by more than 99% for CARB and approximately 98% for the soy biodiesel compared to the 2000 Caterpillar C-15 vehicle. The results show statistically significant reductions in benz(a)anthracene as a function of increasing biodiesel and renewable blend levels for the 2000 Caterpillar C-15. The concentrations observed for the 2007 MBE4000 vehicle were barely quantifiable, and no statistically significant trends were observed for this vehicle. For the 2000 Caterpillar C-15 vehicle, the reductions observed in the 100% soy- and animal-based biodiesel, and renewable diesel compared to the corresponding CARB diesel were 78%, 78%, and 55%, respectively. The reduction observed in the renewable diesel was statistically different from the reductions in the soy- or animal-based biodiesel. There was no significant difference observed between the soy- and animal-based biodiesels.

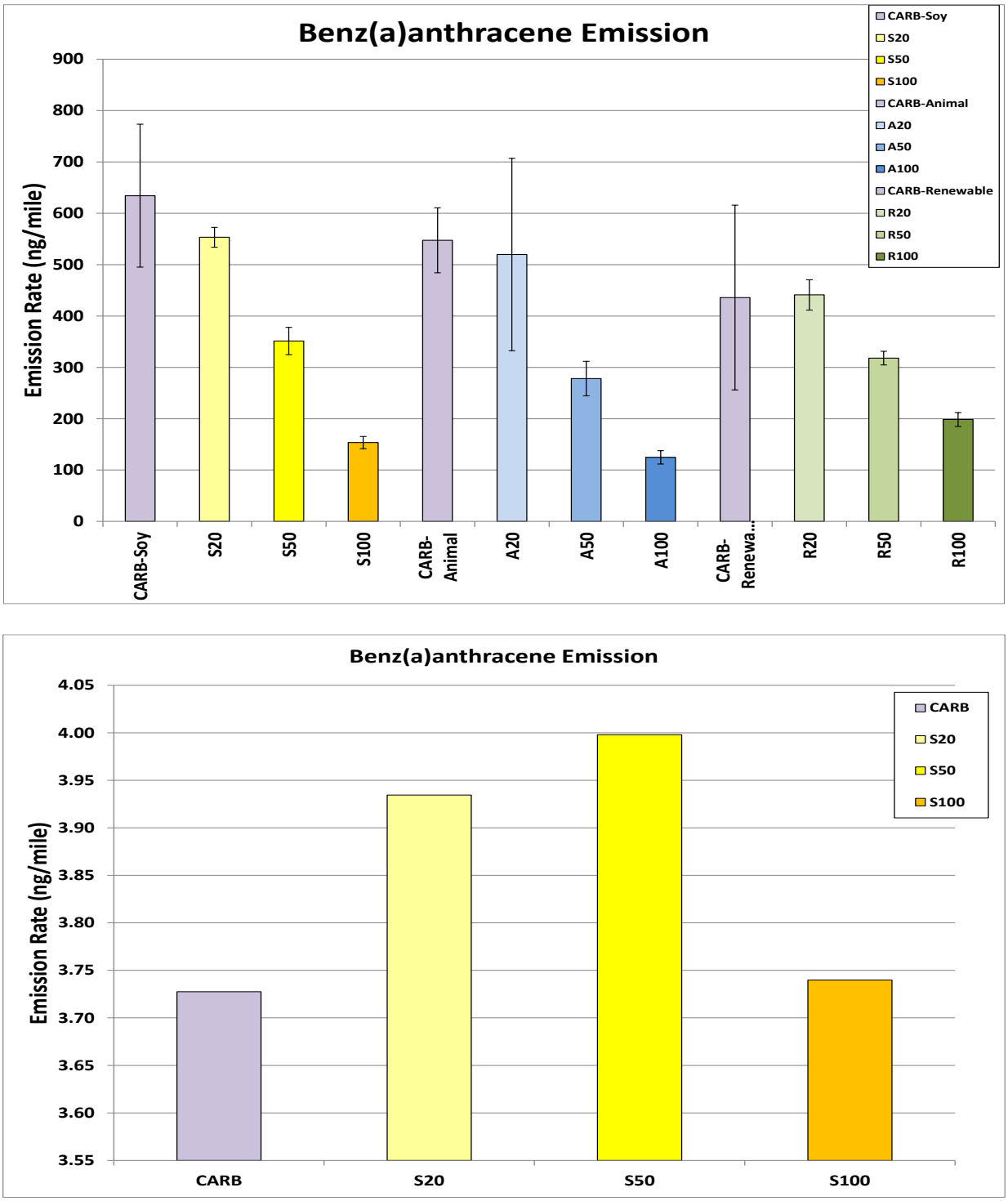


Figure 10-38. Average Benz(a)anthracene Emission Results in particles for the CARB diesel, Soy-Biodiesel (S100), Animal-Biodiesel (A100), and Renewable Diesel (R100) and their blends (20% and 50%) for the 2000 Caterpillar C-15 (upper panel) and for the Soy-Biodiesel for the 2007 MBE4000 (lower panel) with the UDDS driving cycle. It was not detected in the vapor phase. Error bars for the 2000 Caterpillar C-15 vehicle represent one standard deviation from the replicate samples. For the 2007 MBE4000, the replicates were combined for analyses.

10.8.5 Benzo(a)pyrene

Benzo(a)pyrene is a 5-ring particle associated PAH. The US EPA classifies benzo(a)pyrene as a "probable human carcinogen". Benzo(a)pyrene was detected only in the filter samples for the 2000 Caterpillar C-15 vehicle. It was not detected for the 2007 MBE4000 vehicle in any fuels or blend levels tested. Benzo(a)pyrene emissions are shown in Figure 10-39 for the 2000 Caterpillar C-15 vehicle. The results show statistically significant reductions in benzo(a)pyrene as a function of increasing biodiesel blend level for the 2000 Caterpillar C-15 for soy- and animal-based biodiesel. For the renewable diesel, the same trend also was seen in Figure 10-39, although the reduction was not statistically significant due to higher variability in the corresponding CARB diesel samples. For the 2000 Caterpillar C-15 vehicle, the reductions observed in the 100% soy- and animal-based biodiesel, and renewable diesel compared to the corresponding CARB diesel were 74%, 69%, and 33%, respectively. The benzo(a)pyrene decreased more for soy and animal based biodiesel than for renewable diesel from the corresponding CARB diesel.

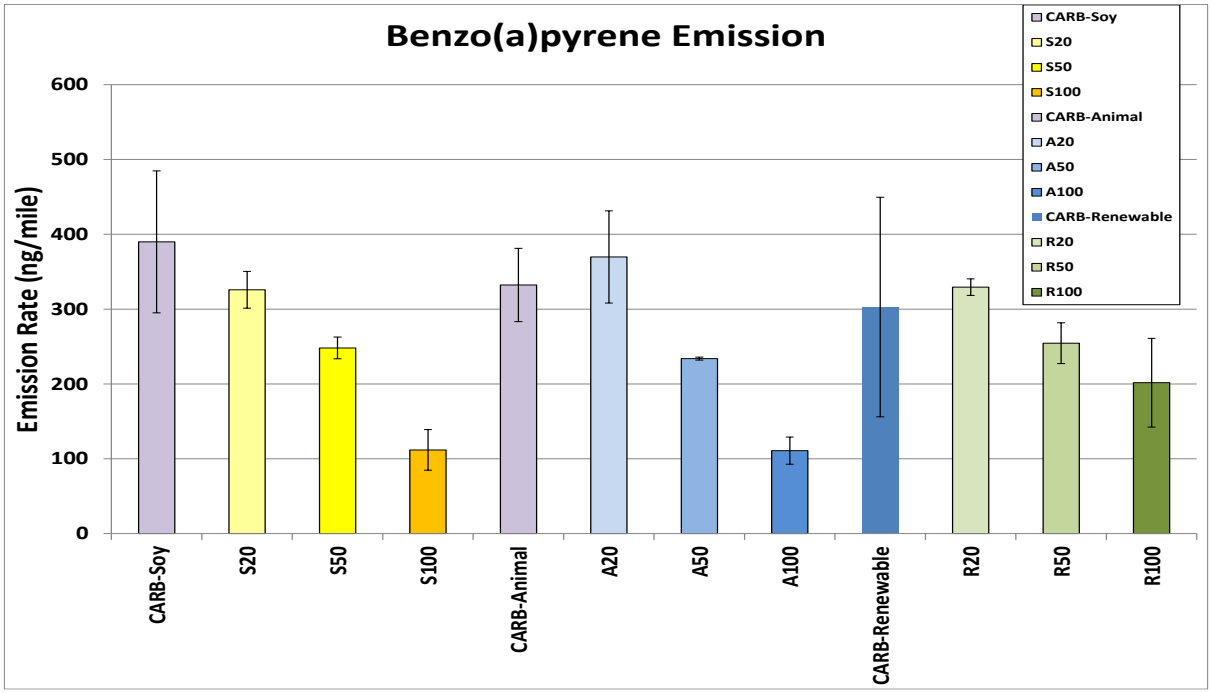


Figure 10-39. Average Benzo(a)pyrene Emission Results in Particle Phase for the CARB diesel, Soy-Biodiesel (S100), Animal-Biodiesel (A100), and Renewable Diesel (R100) and their blends (20% and 50%) for the 2000 Caterpillar C-15 over the UDDS Driving Cycle. It was not detected in the vapor phase. Error bars represent one standard deviation from the replicate samples

10.8.6 Indeno(1,2,3-c,d)pyrene

Indeno(1,2,3-c,d)pyrene is a 6-ring particle associated PAH. The US EPA classifies indeno(1,2,3-c,d)pyrene as "probable human carcinogen". Indeno(1,2,3-c,d)pyrene was found only in the filter samples for the 2000 Caterpillar C-15 vehicle. It was not detected for the 2007 MBE4000 vehicle for any fuels or blend levels tested. Indeno(1,2,3-c,d)pyrene emissions are shown in Figure 10-40 for the 2000 Caterpillar C-15 vehicle. The results show statistically

significant reductions in indeno(1,2,3-c,d)pyrene as a function of increasing soy biodiesel blend level for the 2000 Caterpillar C-15. For the animal based biodiesel a statistically significant reduction was observed in the biodiesel 100% fuel. The reduction for the renewable diesel was not significant partly because of relatively higher variability in the corresponding CARB samples. For the 2000 Caterpillar C-15 vehicle, the reductions observed in the 100% soy- and animal-based biodiesel and renewable diesel compared to the corresponding CARB diesel were 53%, 49%, and 21% for the soy and animal based biodiesel, and the renewable diesel, respectively. However, differences in reduction levels for different feedstocks were not statistically significant.

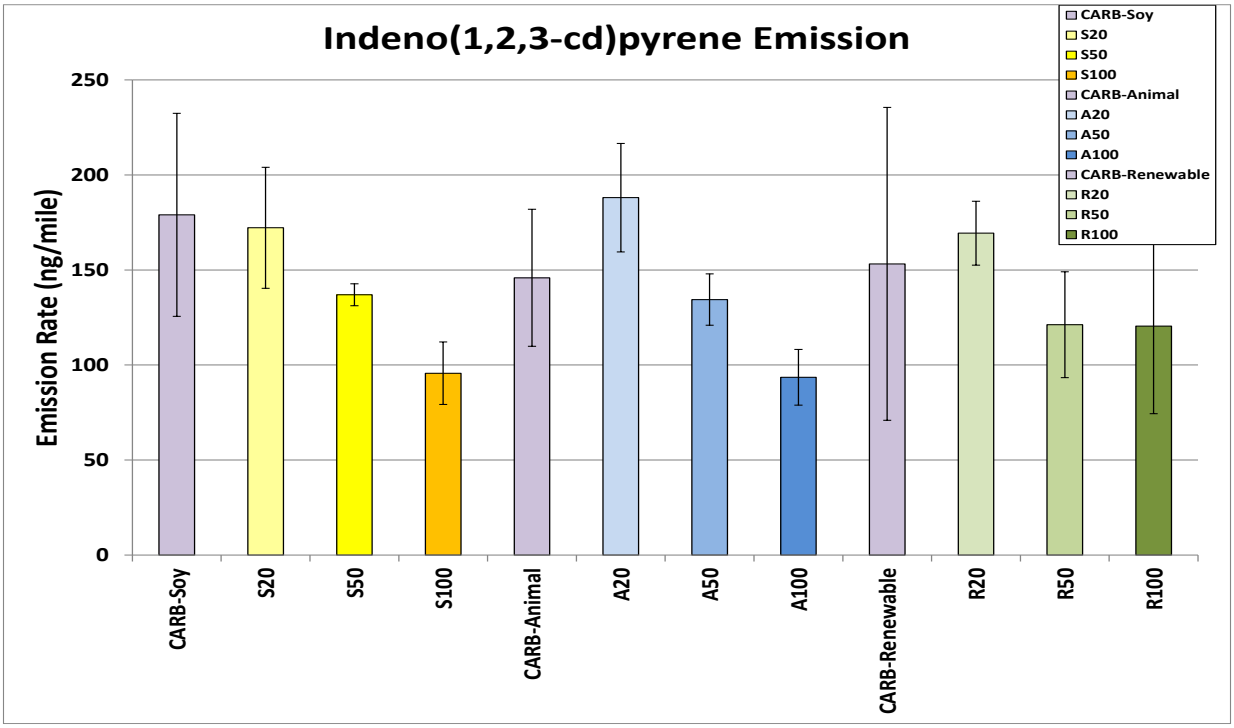


Figure 10-40. Average Indeno(1,2,3-c,d)pyrene Emission Results in Particles for the CARB diesel, Soy-Biodiesel (S100), Animal-Biodiesel (A100), and Renewable Diesel (R100) and their blends (20% and 50%) for the 2000 Caterpillar C-15. It was not detected in the vapor phase. Error bars represent one standard deviation from the replicate samples.

10.8.7 1-Methylnaphthalene

1-Methylnaphthalene is a methylsubsituted naphthalene that is volatile. Approximately 80% or more was found in the XAD and the rest was in the PUF for both vehicles and all fuels. The 1-methylnaphthalene emissions are shown in Figure 10-41 for the 2000 Caterpillar C-15 and the 2007 MBE4000 vehicles. The results show that the emissions for the 2000 Caterpillar C-15 vehicle are considerably higher than those for the 2007 MBE4000 vehicle. 1-Methylnaphthalene emissions decreased for the 2007 MBE4000 vehicle by more than 99% for CARB diesel, the soy biodiesel, and the blends compared to the 2000 Caterpillar C-15 vehicle. The results show statistically significant reductions in 1-methylnaphthalene as a function of increasing biodiesel and renewable blend level for the 2000 Caterpillar C-15, except for the 20% and 50% soy

biodiesel blends due to the relatively high variability observed in the measurements for the corresponding CARB samples. The same trend was also generally observed for the 2007 MBE4000. However, the concentrations measured in the emission samples were very low and were similar to the concentrations in the corresponding tunnel blank sample. Therefore, the trend for the 2007 MBE4000 vehicle may not be significant. For the 2000 Caterpillar C-15 vehicle, the reductions in 100% soy biodiesel, 100% animal biodiesel, and 100% renewable diesel relative to the CARB diesel were 46%, 67%, and 72%, respectively. Animal-based biodiesel and renewable diesel were more effective in reducing emissions compared to the CARB diesel. The reductions observed for animal-biodiesel and renewable diesel were similar.

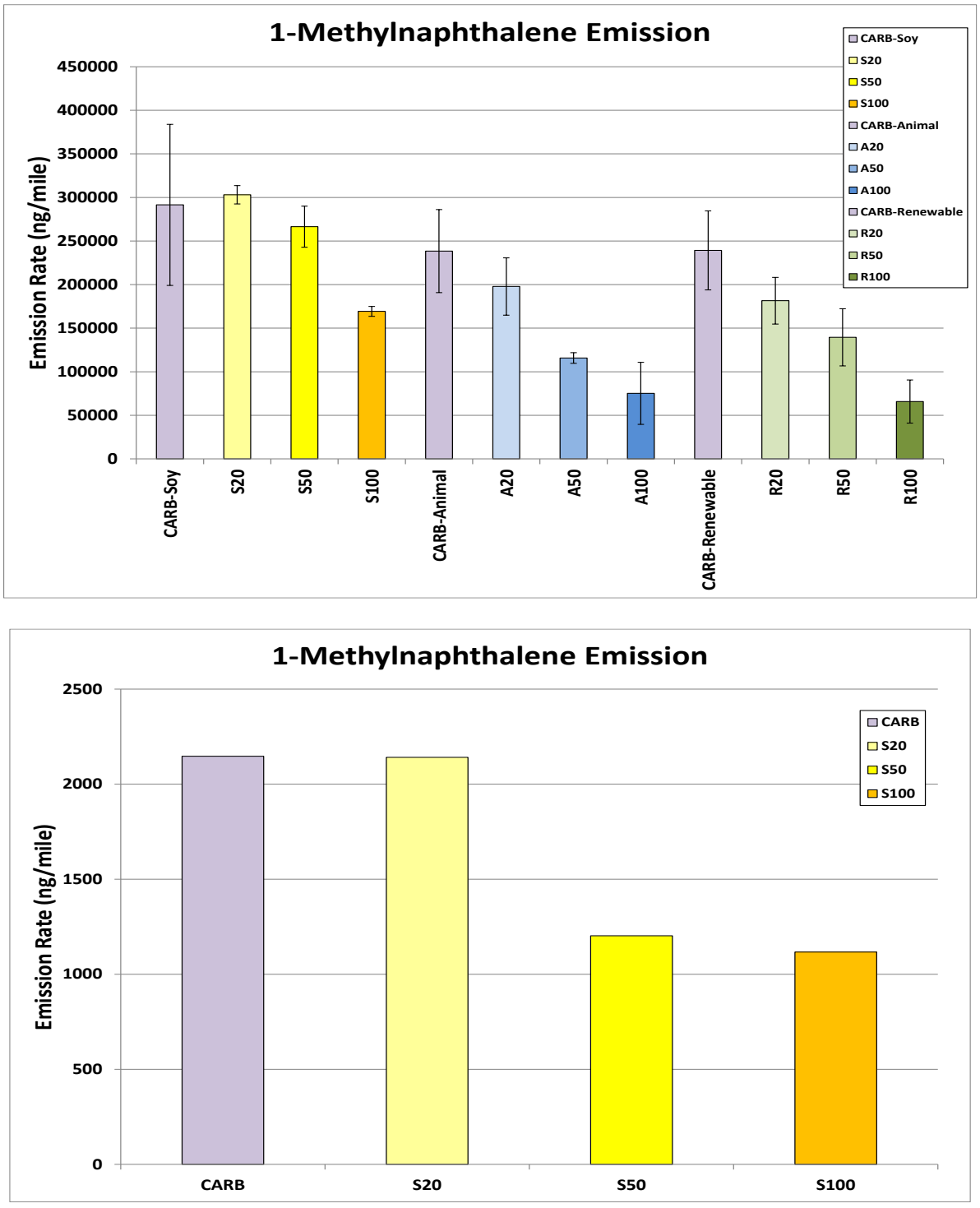


Figure 10-41. Average 1-Methylnaphthalene Emission Results in Particle and the Vapor Phase for the CARB diesel, Soy-Biodiesel (S100), Animal-Biodiesel (A100), and Renewable Diesel (R100) and their blends (20% and 50%) for the 2000 Caterpillar C-15 (upper panel) and for the Soy-Biodiesel for the 2007 MBE4000 (lower panel) over the UDDS Driving Cycle. Error bars for the 2000 Caterpillar C-15 vehicle represent one standard deviation from the replicate samples. For the 2007 MBE4000, the replicates were combined for analyses.

10.9 Nitrated PAHs

Nitrated PAHs or nitro-PAHs are potent mutagens (WHO 2003). The emissions of nitro-PAHs were measured in the particulate and vapor phases for the same samples as for PAHs for the CARB diesel, soy biodiesel, animal biodiesel, renewable diesel, and their respective blends for the 2000 Caterpillar C-15, and the CARB diesel, soy biodiesel, and the respective blends for the 2007 MBE4000 vehicle. One CARB sample and one animal 100% sample for the 2000 Caterpillar C-15 vehicle were lost during the sample preparation; hence, there were seven replicates for the CARB and triplicate samples for the rest of the fuels for nitro-PAH analyses for the 2000 Caterpillar C-15 vehicle. For the MBE4000 vehicle, triplicate samples were taken for all fuels, but they were combined for analyses due to very low concentrations.

Compounds detected were 1-nitronaphthalene, 2-nitronaphthalene, 5-nitroacenaphthene, 9-nitroanthracene, 3-nitrophenanthrene, 2-nitrophenanthrene and 1-nitropyrene for the 2000 Caterpillar C-15 vehicle. 2-Nitrofluorene, 3-nitrofluoranthene, 7-nitrobenz(a)anthracene, 6-nitrochrysene, 6-nitrobenzo(a)pyrene were analyzed for, but were not detected in any samples. For the 2007 MBE4000 vehicle, only 1-nitronaphthalene, 2-nitronaphthalene, 3-nitrophenanthrene, 9-nitroanthracene and 1-nitropyrene were detected at very low concentrations. The most prominent nitro-PAHs measured were 1-nitronaphthalene and the 2-nitronaphthalene in all fuels and blends for both vehicles. More than 70% of all nitro-PAHs measured consisted of these two compounds for the 2000 Caterpillar C-15 vehicle, and it was more than 90% for the 2007 MBE4000 vehicle. For the 2000 Caterpillar C-15 vehicle, 2-nitronaphthalene dominated over 1-nitronaphthalene, whereas for the 2007 MBE4000 1-nitronaphthalene was the dominant species. Emissions of all nitro-PAHs decreased in 2007 MBE4000 compared to the 2000 Caterpillar C-15 vehicle. The total emission of 1-nitronaphthalene and 2-nitronaphthalene decreased by approximately 90% in the 2007 MBE4000 vehicle compared to the 2000 Caterpillar C-15 vehicle. The rest of the compounds in the MBE4000 samples were found only at barely quantifiable levels. The results show that the DPF for the 2007 MBE4000 was effective in reducing nitro-PAHs, not only in the particle phase, but also in the vapor phase, which is different from a previous study on DPF equipped engines/vehicles (Heebet.al., 2008). The results also show that nitro-PAH emissions decreased with increasing blend levels of biodiesel and renewable diesel fuel for the 2000 Caterpillar C-15 vehicle. These trends are discussed in greater detail below for each of the selected species.

10.9.1 1-Nitronaphthalene

1-Nitronaphthalene is a semivolatile, nitro-substituted naphthalene. For the 2000 Caterpillar C-15 vehicle, 1-nitronaphthalene was found mostly in the PUF, with 4 to 10% of the total amount in the filters, and 0 to 14% present in the XAD, depending on the fuel type. For the 2007 MBE4000 vehicle, it distributed between the PUF and the XAD. Although the concentrations in the PUF were much lower for the 2007 MBE4000 than for the 2000 Caterpillar C-15, the XAD concentrations were higher for the 2007 MBE4000 than for the 2000 Caterpillar C-15 for 1-nitronaphthalene for all the fuels. This may possibly be an artifact caused by the nitration of naphthalene that was collected on the XAD during sampling. Since the sample duration was 1.5 times longer, and the nitrogen dioxide (NO_2) levels were higher due to its use as an oxidizer of PM for the DPF equipped 2007 MBE4000, there was a greater likelihood of nitration and the

formation of nitronaphthalene in the 2007 MBE4000 than the 2000 Caterpillar C-15. Another possibility is that 1-nitronaphthalene initially captured by the PUF may have migrated downstream to XAD during the longer sampling time for the 2007 MBE4000 than for the 2000 Caterpillar C-15. The 1-nitronaphthalene emissions are shown in Figure 10-42 for the 2000 Caterpillar C-15 and the 2007 MBE4000 vehicles. The results show that the emissions for the 2000 Caterpillar C-15 vehicle are considerably higher than those for the 2007 MBE4000 vehicle. 1-Nitronaphthalene emissions decreased for the 2007 MBE4000 vehicle by approximately 90% in CARB, soy biodiesel, and the blends compared to the 2000 Caterpillar C-15 vehicle. The results show statistically significant reductions in 1-nitronaphthalene as a function of increasing animal biodiesel and renewable blend level for the 2000 Caterpillar C-15. For soy biodiesel, although the same trend was generally observed, the reduction was statistically significant only in the soy 100% biodiesel. For the 2000 Caterpillar C-15 vehicle, the reductions in 100% soy biodiesel, 100% animal biodiesel, and 100% renewable diesel relative to the CARB diesel were 34%, 57% and 62%, respectively. The renewable diesel was most effective in reducing the emissions, followed by animal biodiesel, and then soy biodiesel. The 2007 MBE4000 showed reductions in 1-nitronaphthalene for the B50 and B100 fuels, however, no statistical evaluations were obtained.

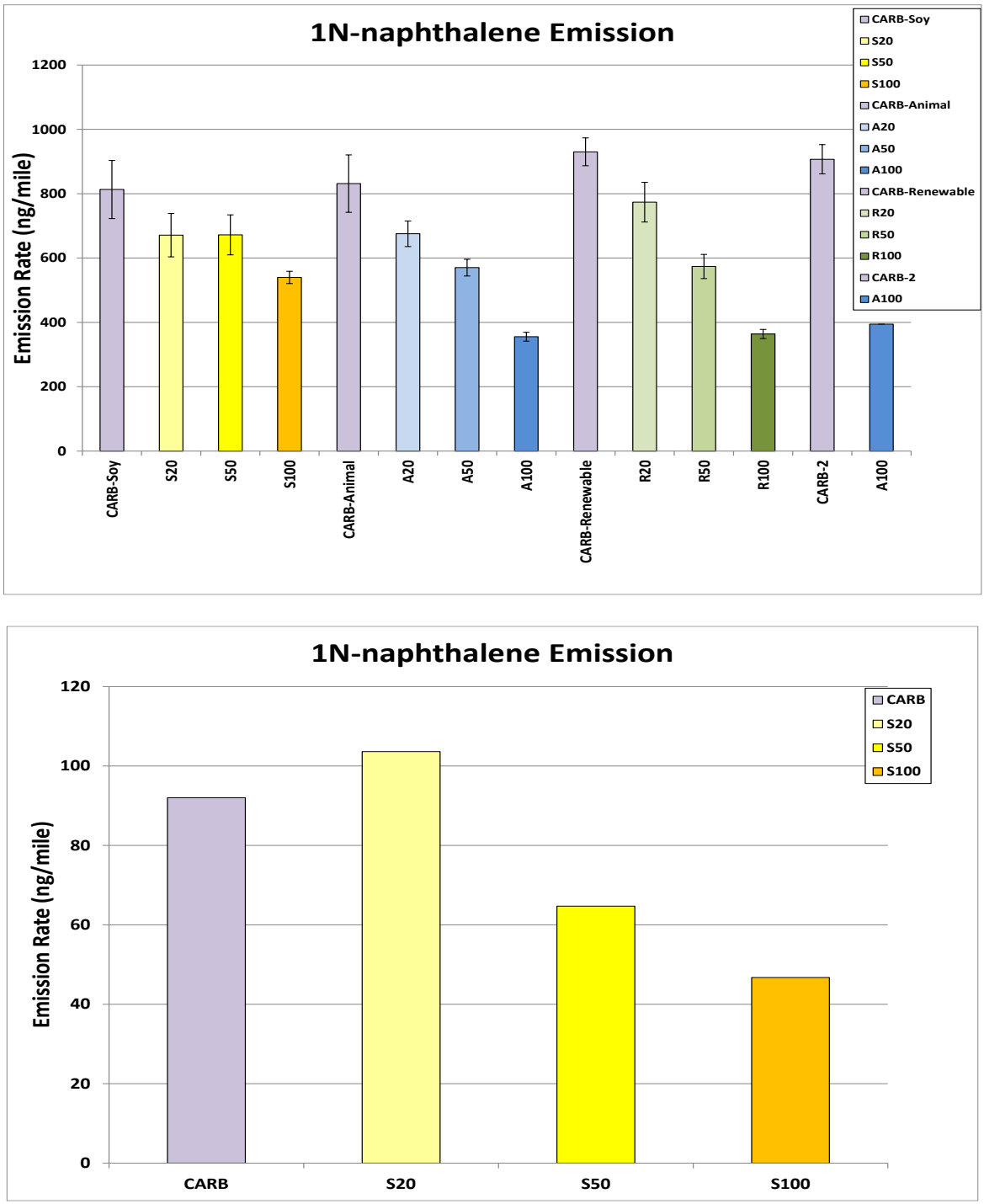


Figure 10-42. Average 1-Nitronaphthalene Emission Results in Particle and the Vapor Phase for the CARB diesel, Soy-Biodiesel (S100), Animal-Biodiesel (A100), and Renewable Diesel (R100) and their blends (20% and 50%) for the 2000 Caterpillar C-15 (upper panel) and for the Soy-Biodiesel for the 2007 MBE4000 (lower panel) over the UDDS Driving Cycle. Error bars for the 2000 Caterpillar C-15 vehicle represent one standard deviation from the replicate samples. For the 2007 MBE4000, the replicates were combined for analyses.

10.9.2 9-Nitroanthracene

9-Nitroanthracene is a 3-ring nitro substituted anthracene. For the 2000 Caterpillar C-15 vehicle, approximately 30 to 90% of 9-nitroanthracene was found in filters and the rest in the PUF depending on the fuels. Higher blend levels had higher percentages in the PUF as a result of lower concentrations in the filters. For the 2007 MBE4000 vehicle, 9-nitroanthracene was found only in the PUF in low concentrations, suggesting again the possible contribution from nitration of anthracene that occurred in the PUF. The 9-nitroanthracene emissions are shown in Figure 10-43 for the 2000 Caterpillar C-15 and the 2007 MBE4000 vehicles. The results show that the emissions for the 2000 Caterpillar C-15 vehicle are considerably higher than those for the 2007 MBE4000 vehicle. 9-Nitroanthracene emissions decreased for the 2007 MBE4000 vehicle by more than 98% in CARB diesel, soy biodiesel and the blends compared to the 2000 Caterpillar C-15 vehicle. There were statistically significant reductions in 9-nitroanthracene as a function of increasing biodiesel and renewable blend level for the 2000 Caterpillar C-15 for all the fuels and blend levels tested. For the 2000 Caterpillar C-15 vehicle, the reductions in 100% soy biodiesel, 100% animal biodiesel, and 100% renewable diesel relative to the CARB diesel were 58%, 78% and 82%, respectively. The renewable diesel was most effective in reducing the emissions, followed by animal biodiesel, and then soy biodiesel. The emissions measured for the 2007 MBE4000 vehicle were similar in the CARB diesel and soy biodiesel and the blends, and they were very low.

10.9.3 1-Nitropyrene

1-Nitropyrene is a 4 ring, nitro substituted pyrene associated with the particle phase. 1-Nitropyrene has been known to be a major constituent in diesel exhaust (WHO 1989, WHO 2003). For the 2000 Caterpillar C-15 vehicle, it was found only in the filter samples, whereas for the 2007 MBE4000 it was also in the PUF at low concentrations. Again, the artifact formation from nitration of pyrene absorbed in the PUF is suspected for the 2007 MBE4000 vehicle. The 1-nitropyrene emissions are shown in Figure 10-44 for the 2000 Caterpillar C-15 and the 2007 MBE4000 vehicles. The results show that the emissions for the 2000 Caterpillar C-15 vehicle are considerably higher than those for the 2007 MBE4000 vehicle. The concentrations measured in the 2007 MBE4000 samples were barely quantifiable. The results show reductions in 1-nitropyrene as a function of increasing biodiesel and renewable blend level for the 2000 Caterpillar C-15. The reductions were statistically significant for all the fuels and the blends, except for the animal 20% biodiesel, although the reduction trend was seen clearly for this fuel in the Figure. For the 2000 Caterpillar C-15 vehicle, the reductions in 100% soy biodiesel, 100% animal biodiesel, and 100% renewable diesel relative to the CARB diesel were 88%, 90% and 88%, respectively. Soy biodiesel, animal biodiesel and renewable diesel were equally effective in reducing the emissions of 1-nitropyrene. For the 2007 MBE4000 vehicle, the emissions were barely quantifiable, which masked any differences between the fuels and the blends. The artifact contribution may also have been significant in the measured concentrations.

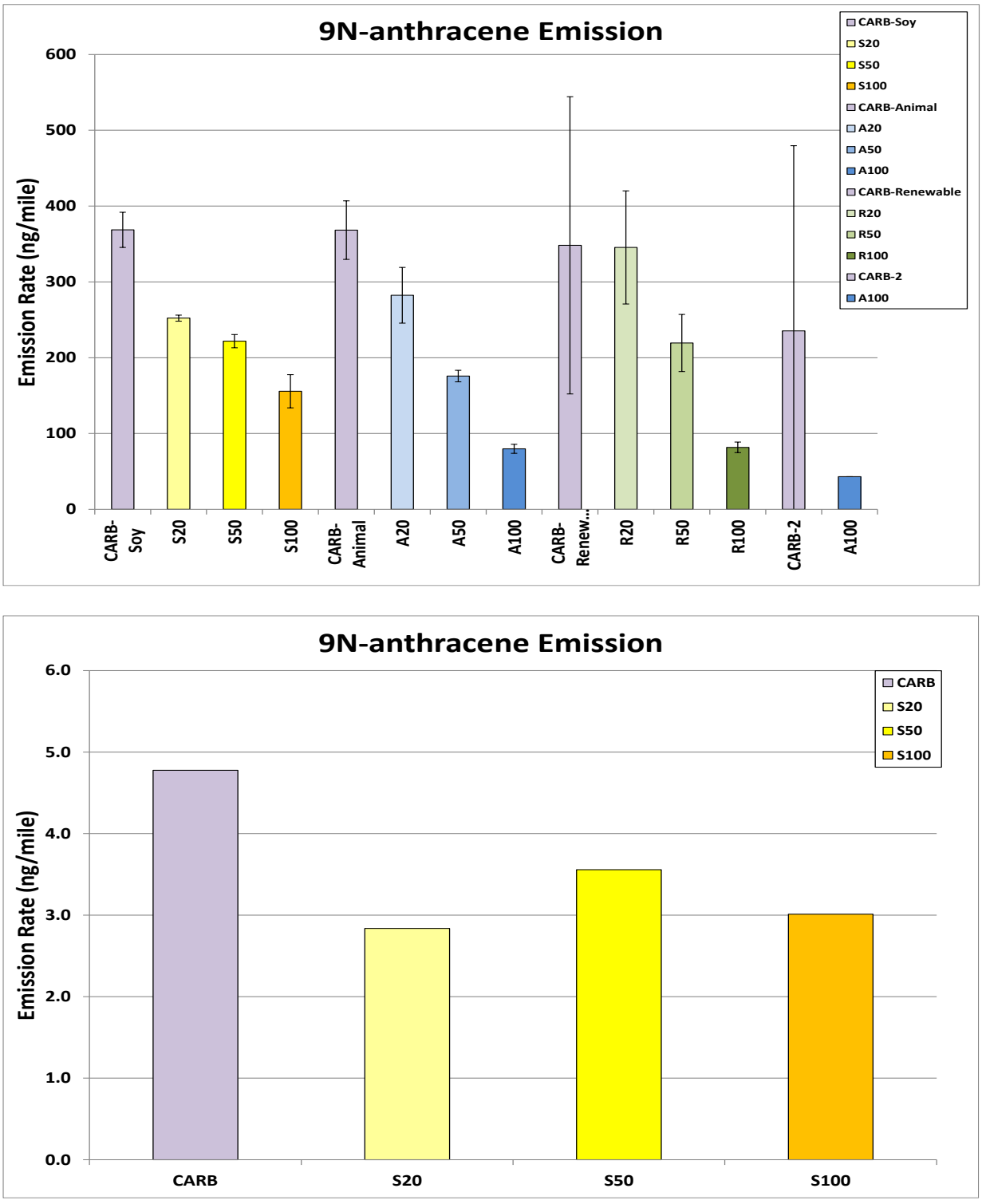


Figure 10-43. Average 9-Nitroanthracene Emission Results in Particle and the Vapor Phase for the CARB diesel, Soy-Biodiesel (S100), Animal-Biodiesel (A100), and Renewable Diesel (R100) and their blends (20% and 50%) for the 2000 Caterpillar C-15 (upper panel) and for the Soy-Biodiesel for the 2007 MBE4000 (lower panel) over the UDDS Driving Cycle. Error bars for the 2000 Caterpillar C-15 vehicle represent one standard deviation from the replicate samples. For the 2007 MBE4000, the replicates were combined for analyses.

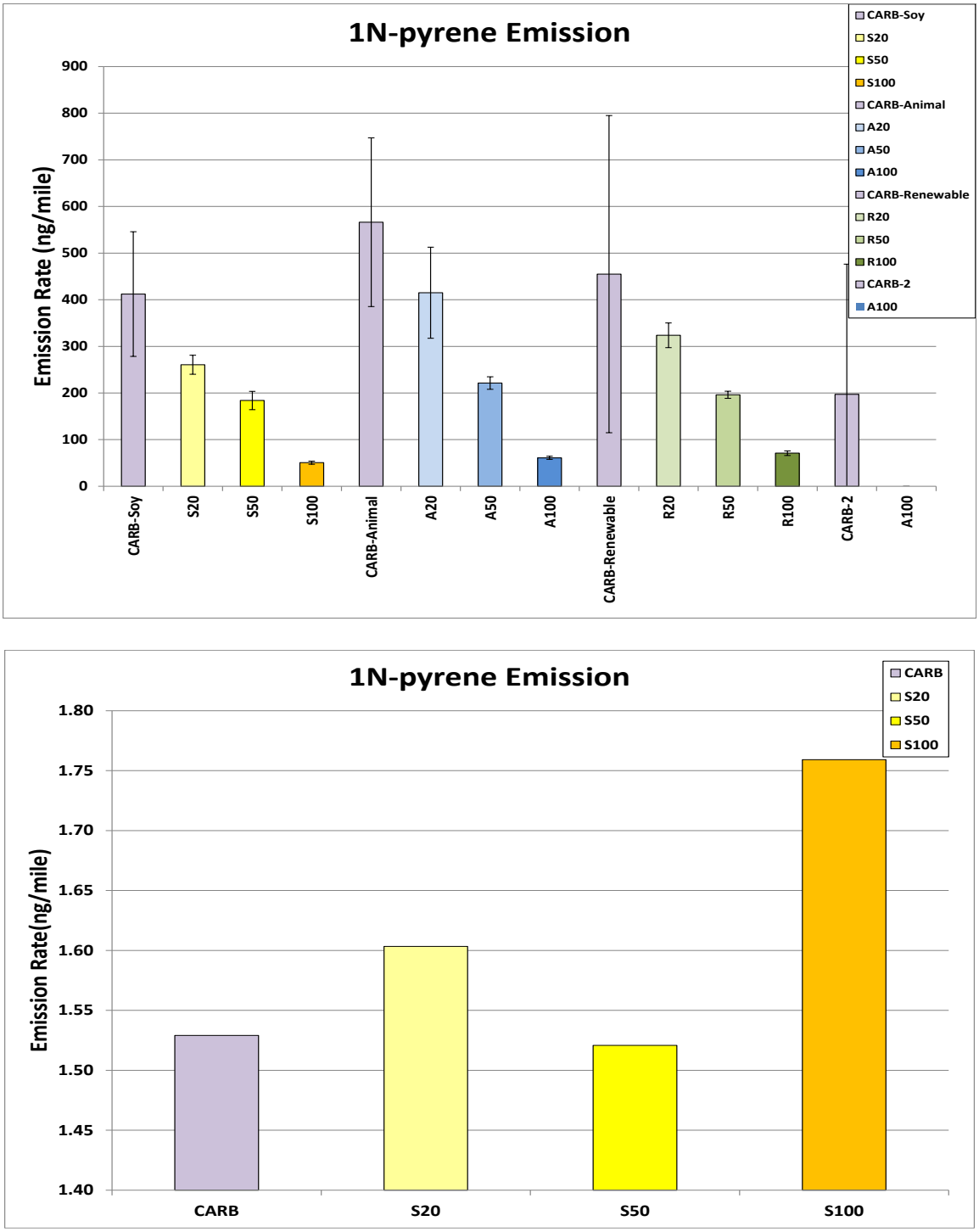


Figure 10-44. Average 1-Nitropyrene Emission Results in Particle and the Vapor Phase for the CARB diesel, Soy-Biodiesel (S100), Animal-Biodiesel (A100), and Renewable Diesel (R100) and their blends (20% and 50%) for the 2000 Caterpillar C-15 (upper panel) and for the Soy-Biodiesel for the 2007 MBE4000 (lower panel) over the UDDS driving cycle. Error bars represent one standard deviation from the replicate samples. For the 2007 MBE4000, the replicates were combined for analyses.

10.10. Oxygenated- PAH

Oxygenated PAHs, or Oxy-PAHs, were analyzed in the biodiesel particle samples for the 2000 Caterpillar C-15 vehicle only. Chemical analyses for these oxy-PAHs were conducted by the Desert Research Institute (Reno, NV), who were provided with portions of the filter samples. The results were obtained for the CARB diesel, soy biodiesel, animal biodiesel and renewable diesel, and the blends (20% and 50%), except that soy 100% biodiesel was not analyzed due to the sample availability. Eight replicates for CARB diesel, duplicates for animal 100% biodiesel and renewable 20% diesel, and triplicate samples for the rest were analyzed separately. Emissions of some oxy-PAHs were as high as volatile PAHs, and much higher than nitro-PAHs. However, the reduction trends in biodiesel and renewable diesel seen in PAHs or nitro-PAHs were not observed for oxy-PAHs. The results for selected species that were present in higher concentrations are discussed below.

10.10.1 9-Fluorenone

9-Fluorenone is a 3-ring aromatic carbonyl, which has been identified in diesel PM (Jakober et al., 2006). 9-Fluorenone emissions measured in the PM are shown in Figure 10-45. The results show decreases in 9-fluorenone as a function of increasing biodiesel and renewable diesel blends. The decreases compared to the CARB for the 20% and 50% soy biodiesel, 50% and 100% animal biodiesel, and 100% renewable diesel were statistically significant.

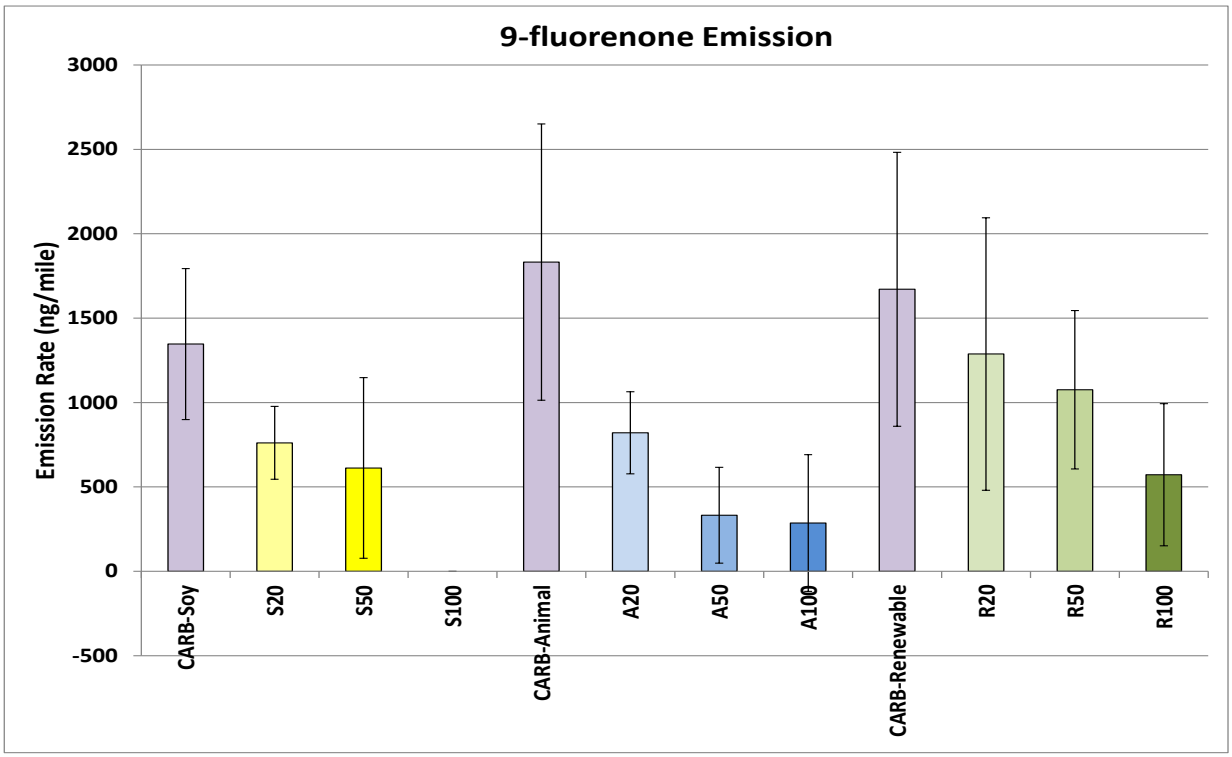


Figure 10-45. Average 9-Fluorenone Emission Results in Particles for the CARB diesel, Soy-Biodiesel, Animal-Based, and Renewable Blend testing for the 2000 Caterpillar C-15 over the UDDS driving cycle. Error bars represent one standard deviation from the replicate samples. Soy 100% biodiesel was not analyzed.

10.10.2 Perinaphthenone

Perinaphthenone is a 3-ring aromatic carbonyl, which has been identified in diesel PM (Jakober et al., 2006). Perinaphthenone emissions measured in the PM are shown in Figure 10-46. The results generally show decreases in perinaphthenone as a function of increasing animal biodiesel and renewable diesel. The decreases seen in 50% and 100%, animal biodiesel and 50% and 100% renewable diesel were statistically significant. The emissions seen for the soy biodiesel blends were not significantly different from the corresponding CARB diesel.

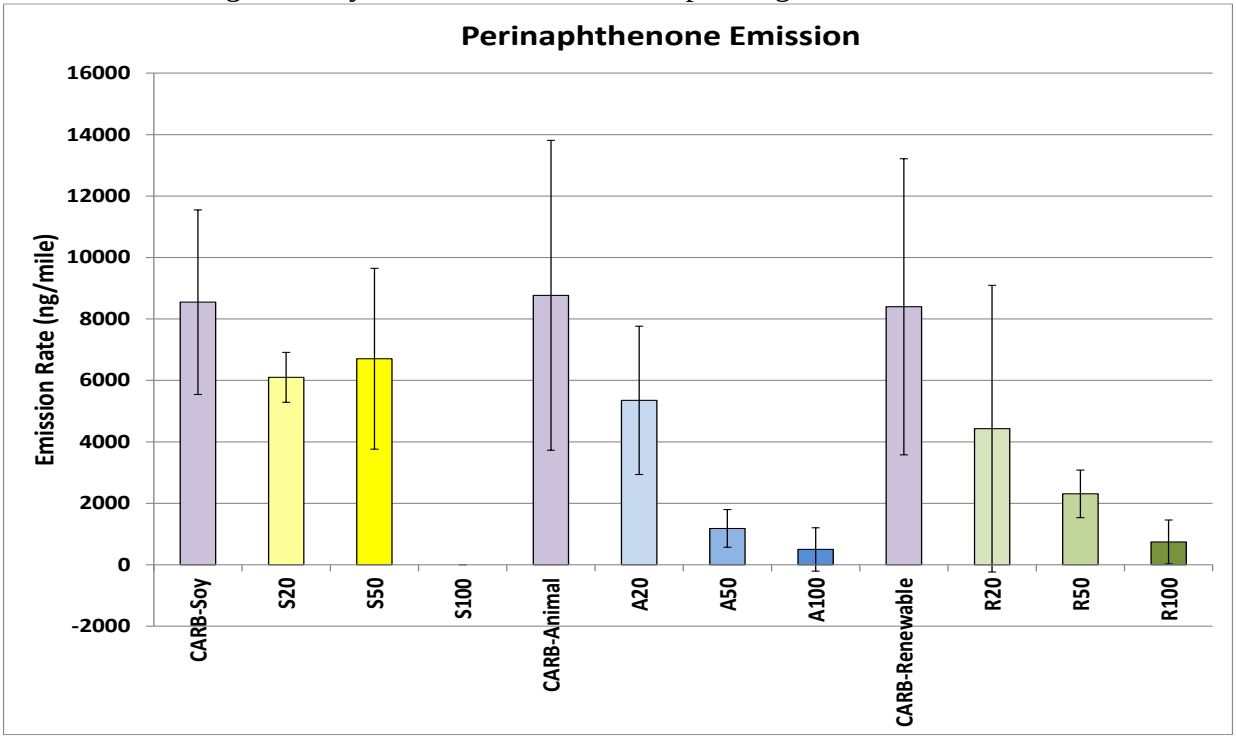


Figure 10-46. Average Perinaphthenone Emission Results in Particles for the CARB diesel, Soy-Biodiesel, Animal-Based, and Renewable blend testing for the 2000 Caterpillar C-15 over the UDDS driving cycle. Error bars represent one standard deviation from the replicate samples. Soy 100% biodiesel was not analyzed.

10.10.3 1,2-Naphthoquinone

1,2-Naphthoquinone is a cyclic dione derived from naphthalene. It has been identified in diesel PM (Cho et al., 2004; Jakober et al., 2007). 1,2-Naphthoquinone emissions measured in the PM are shown in Figure 10-47. There were increases in 1,2-naphthoquinone as a function of increasing soy and animal biodiesels. However, statistical evaluation showed the increases were not deemed significant, except that the statistics were not obtained for animal 100% biodiesel and renewable diesel 20% blend. For the renewable diesel and the blends, the differences with the CARB diesel were not statistically significant.

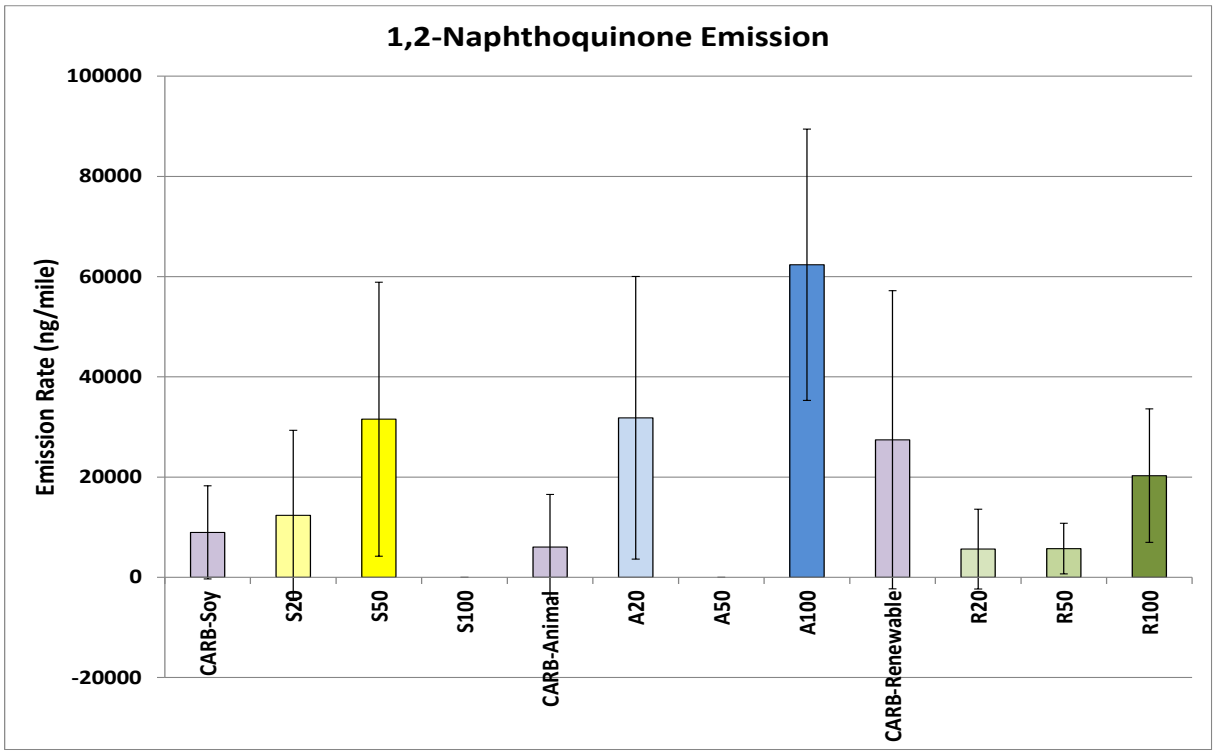


Figure 10-47. Average 1,2-Naphthoquinone Emission Results in Particles for the CARB diesel, Soy-Biodiesel, Animal-Based, and Renewable blend testing for the Caterpillar C-15 over the UDDS driving cycle. Error bars represent one standard deviation from the replicate samples. Soy 100% biodiesel was not analyzed.

10.10.4.1,8-Naphthalic Anhydride

1,8-Naphthalic anhydride is an anhydride of naphthalene dicarboxylic acid. It has been identified in diesel PM (Bayona et al., 1988). 1,8-Naphthalic anhydride emissions measured in the PM are shown in Figure 10-48. The results show decreases in 1,8-naphthalic anhydride as a function of increasing animal biodiesel and renewable diesel blends. The decreases with CARB were statistically significant in 50% blends and 100% for both animal and renewable diesel. The emissions seen in soy biodiesel blends were not significantly different from the emissions in CARB.

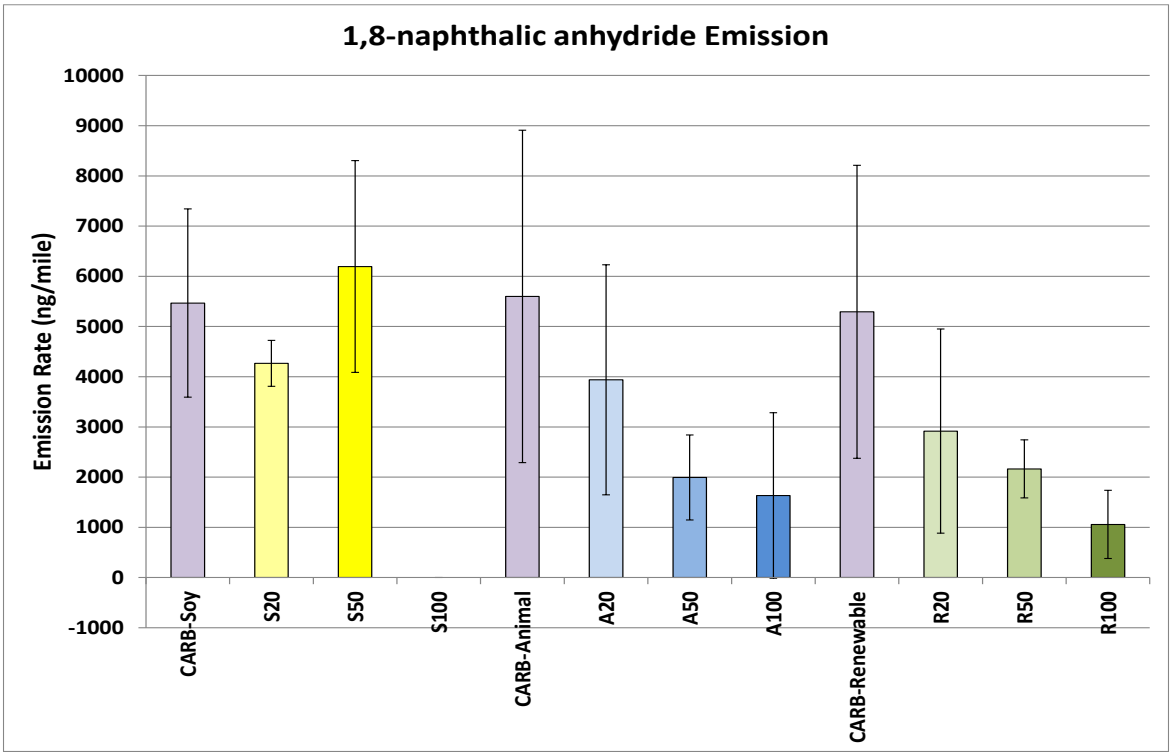


Figure 10-48. Average 1,8-Naphthalic Anhydride Emission Results in Particles for the CARB diesel, Soy-Biodiesel, Animal-Based, and Renewable Blend testing for the 2000 Caterpillar C-15 over the UDDS driving cycle. Error bars represent one standard deviation from the replicate samples. Soy 100% biodiesel was not analyzed.

11.0 Heavy-Duty Chassis Dynamometer Testing – Health Effects

11.1 Genotoxicity Analyses

The mutagen emission results for the 2000 Caterpillar C-15 are illustrated in Figure 11-1 to Figure 11-4 for the particle emissions and in Figure 11-5 through Figure 11-8 for the vapor-phase samples. The mutagen emissions were tested with tester strains TA98 or TA100 with (denoted with a +) and without (denoted with a -) the addition of metabolic enzymes (liver S-9). The results for each test cycle represent the average of all test runs done on that particular combination. The CARB diesel samples were matched to the corresponding time period when the biodiesel and renewable diesel samples were taken. The error bars represent one standard deviation on the average value.

For particle samples tested in TA98, with and without S9, it appears that the mutagen emissions decrease (viewed as decreasing "steps") with increasing levels of soy biodiesel in the blend **(**Fig. 2-1). For the animal biodiesel, there appears to be an increase in the A-20 emissions compared to the CARB sample. With the renewable biodiesel, the pattern of the decreasing steps is similar with CARB>20>50>100 fuels. The emissions for TA98 (+S9) are, overall, slightly higher than for –S9.

For the particle samples tested in TA100, the decreasing pattern with each fuel is again observed with soy and with renewable biodiesel with and without S9. The animal A20 appears to increase once more (as previously seen in tester strain TA98) relative to the CARB fuel. In general, for both tester strains the emissions when tested with S9 are higher than the emissions without S9. Overall, TA98 appears to be more sensitive than TA100 in evaluating the mutagen emissions for particles.

The results of the C-15 vehicle PM for CARB and biodiesel fuels are, in general, consistent to the emissions observed for the CNG vehicles reported previously for the UDDS test cycle (Kado et al., 2005).

The vapor-phase was also tested with tester strains TA98 and TA100, with and without S9 (± S9) as illustrated in Figure 11-5 through Figure 11-8. In TA98, the mutagen emissions were slightly higher when tested with the addition of S9 enzymes than for minus S9. In general, for the emissions with TA98 with S9, there appears a decreasing stair-step pattern for all fuels. However, the S50 fuel appears to have elevated or similar mutagen emissions relative to the CARB fuel emissions collected during the same time period. In TA100, the mutagen emissions were again higher when S9 metabolic enzymes were added compared to when no S9 was added. The S50 blend had the highest mutagen emission rate of all the fuels for the TA100 tester strain.

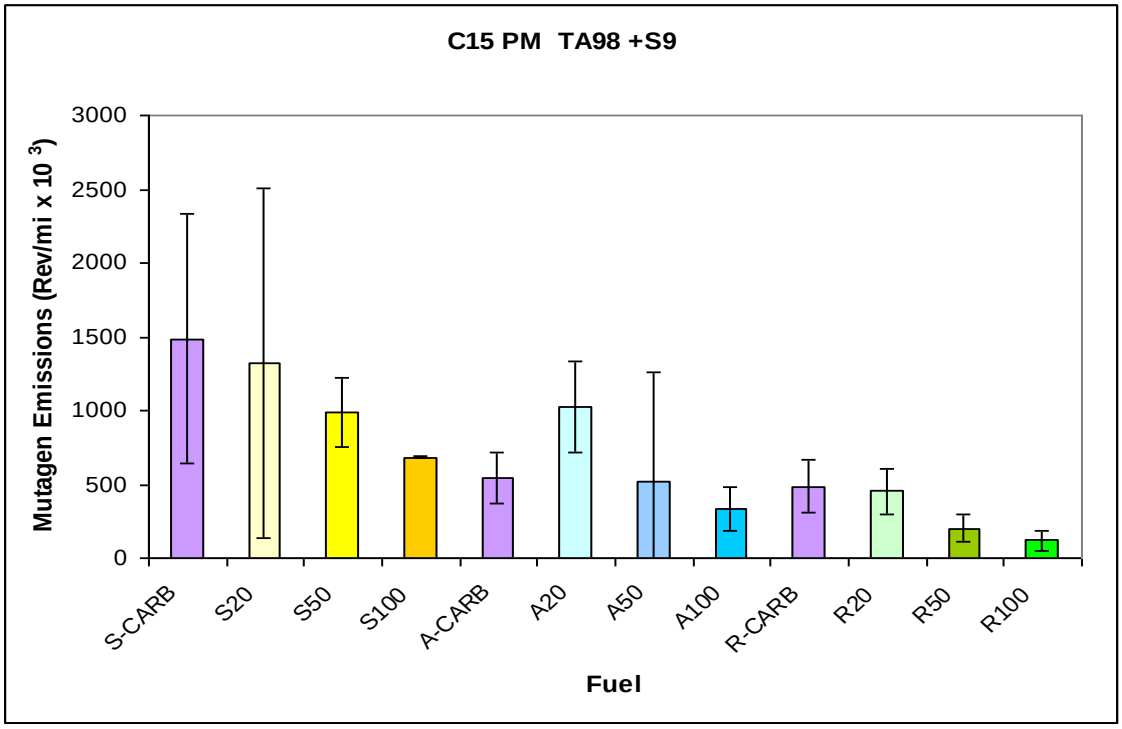


Figure 11-1. Mutagen Emissions for Particle Phase (PM) Samples Tested in TA98 (+S9) and Collected from the 2000 Caterpillar C-15 Vehicle. Bars for Figures 11-1 through 11-4 represent the Mean ± SD of triplicate individual samples collected.

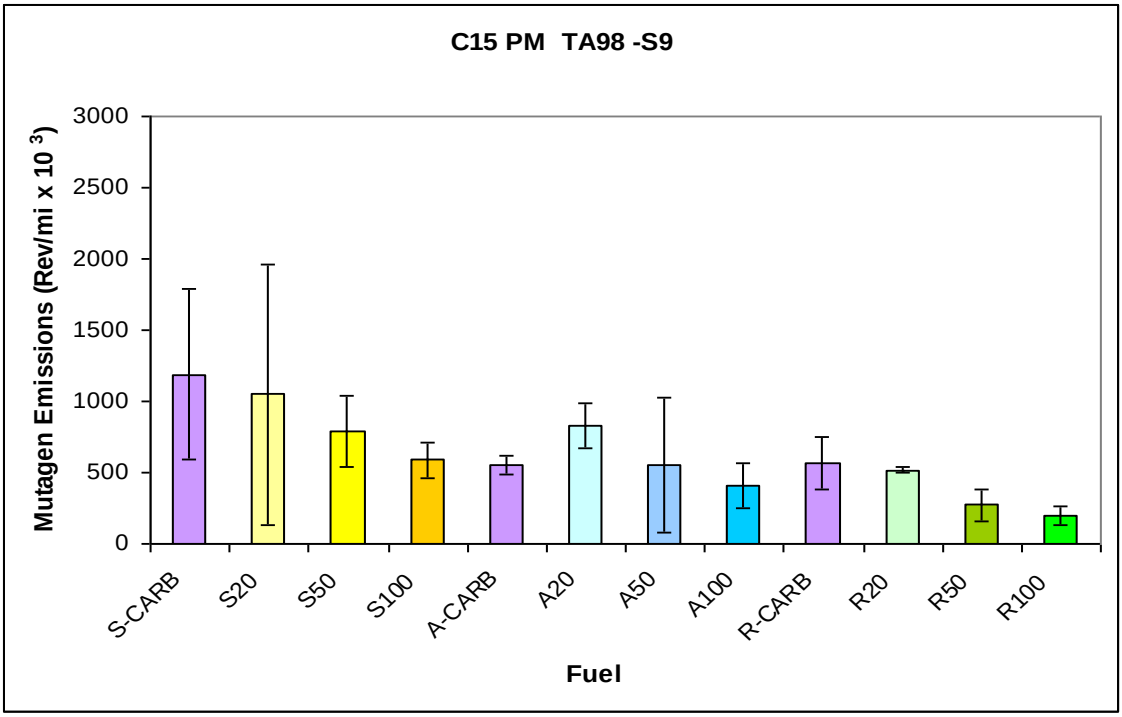


Figure 11-2. Mutagen Emissions for Particle Phase (PM) Samples Tested in TA98 (-S9) and Collected from the 2000 Caterpillar C-15 Vehicle.

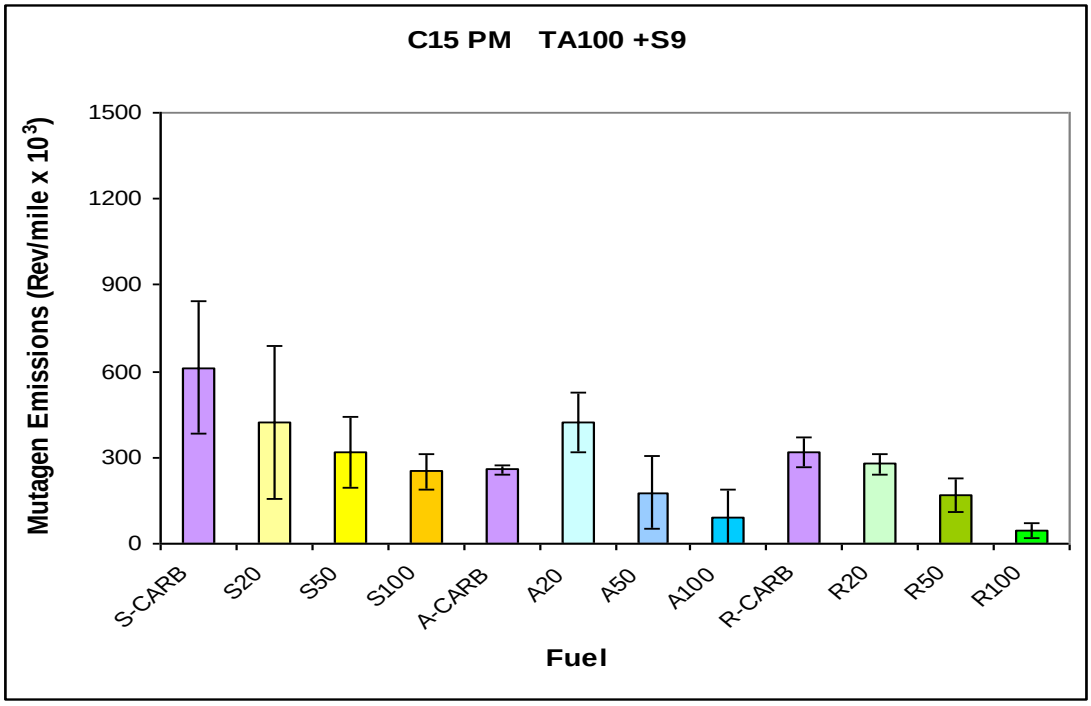


Figure 11-3. Mutagen Emissions for Particle Phase (PM) Samples Tested in TA98 (+S9) and Collected from the 2000 Caterpillar C-15 Vehicle

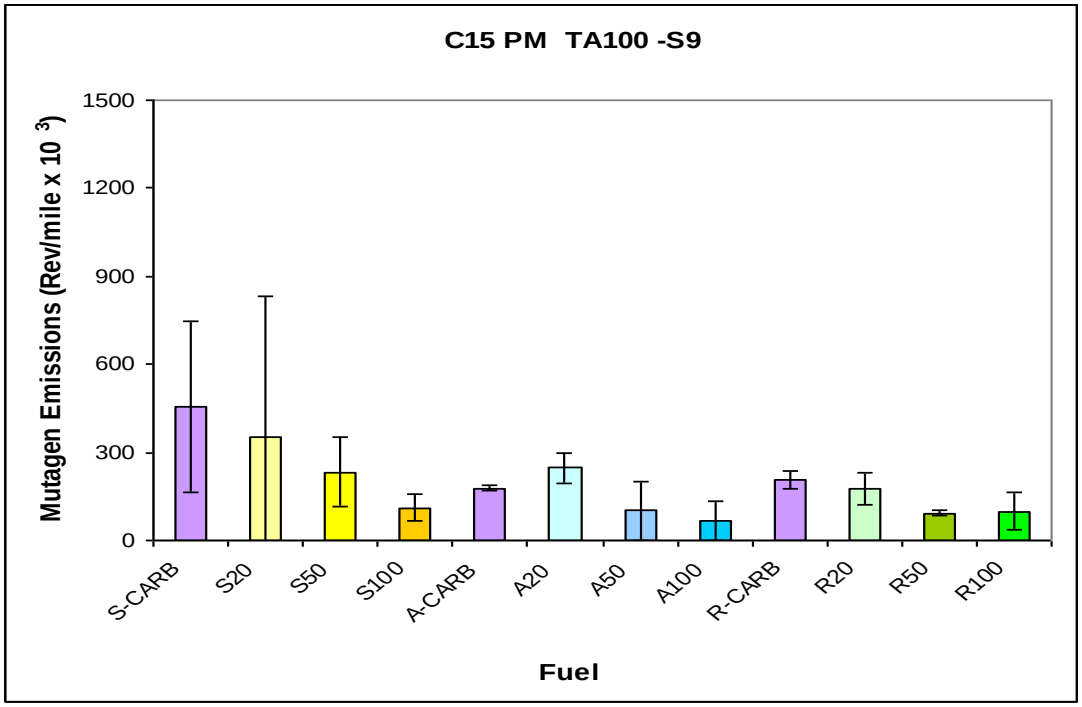


Figure 11-4. Mutagen Emissions for Particle Phase (PM) Samples Tested in TA98 (-S9) and Collected from the 2000 Caterpillar C-15 Vehicle

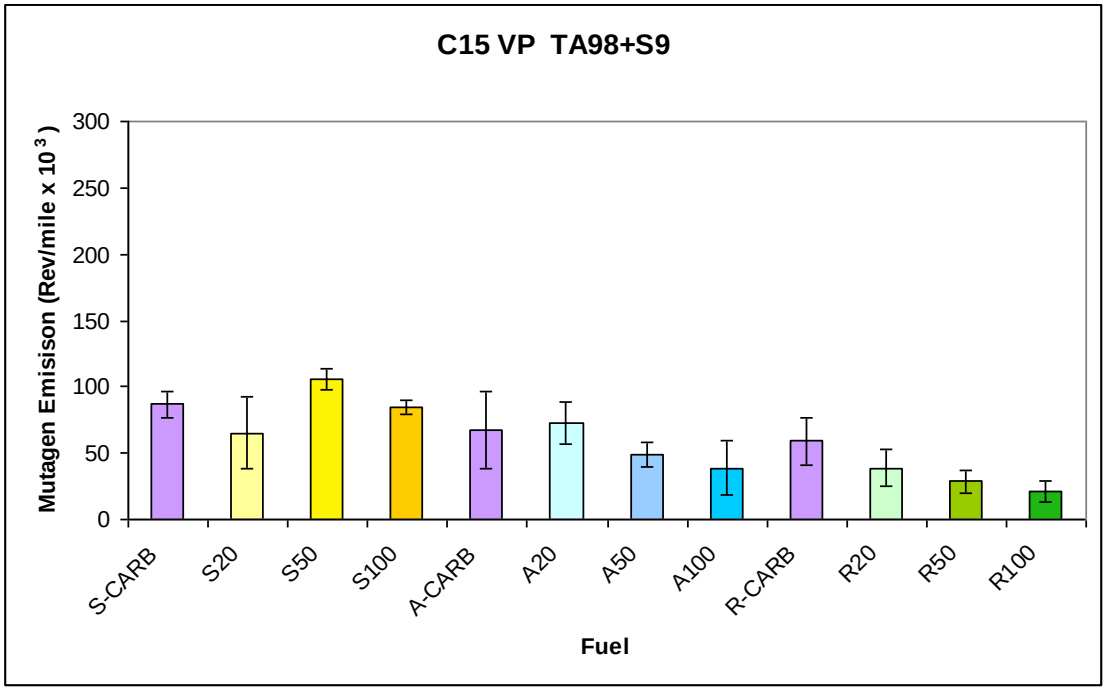


Figure 11-5. Mutagen Emissions for Vapor phase Samples Tested in TA98 (+S9) and collected from the 2000 Caterpillar C-15 Vehicle. Bars for Figures 11-5 through 11-8 represent the Mean ± SD of triplicate individual samples collected.

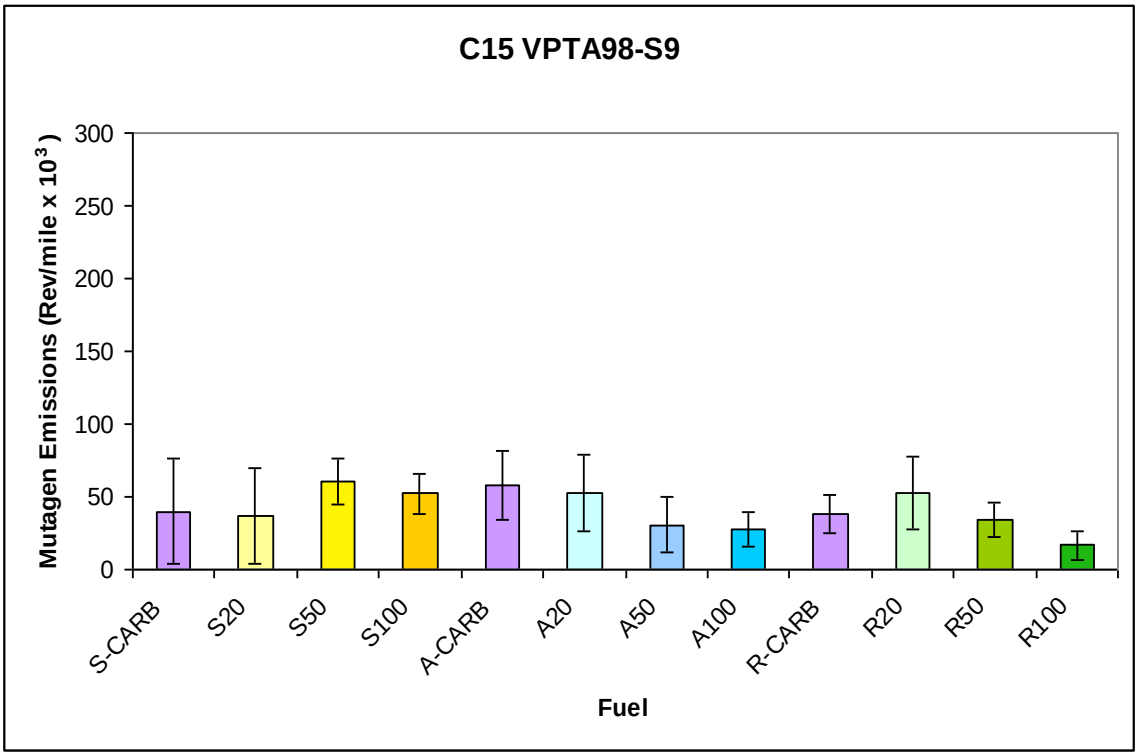


Figure 11-6. Mutagen Emissions for Vapor phase Samples Tested in TA98 (-S9) and Collected from the 2000 Caterpillar C-15 Vehicle.

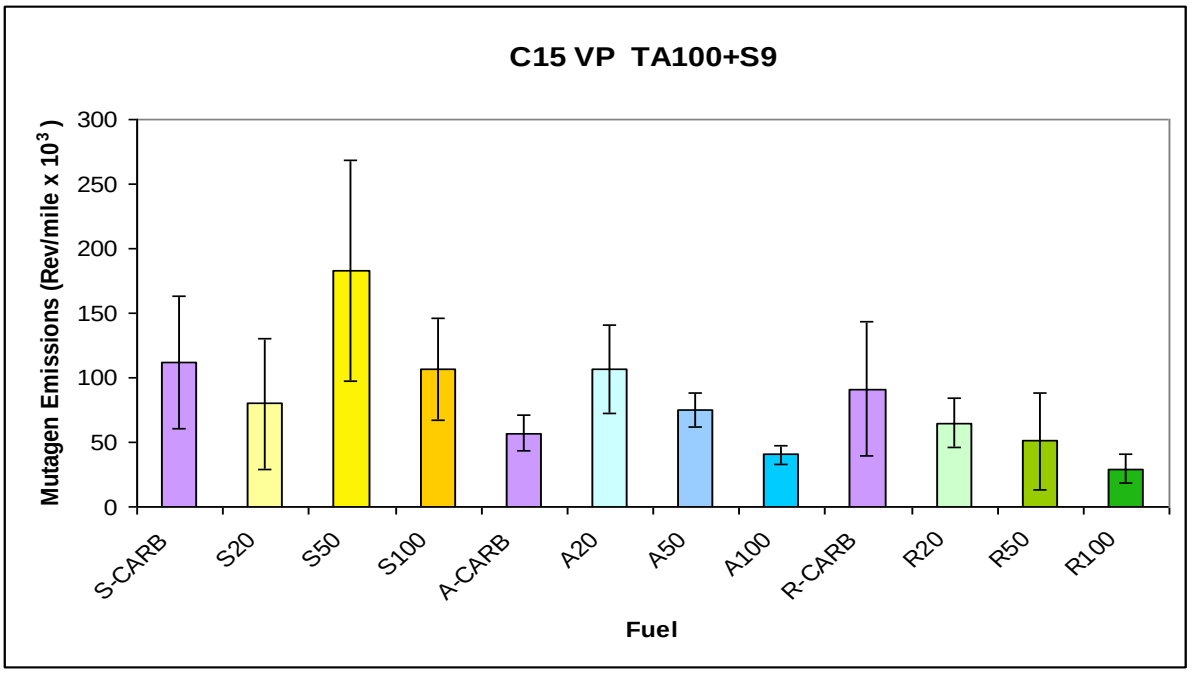


Figure 11-7. Mutagen Emissions for Vapor phase Samples Tested in TA100 (+S9) and Collected from the 2000 Caterpillar C-15 Vehicle.

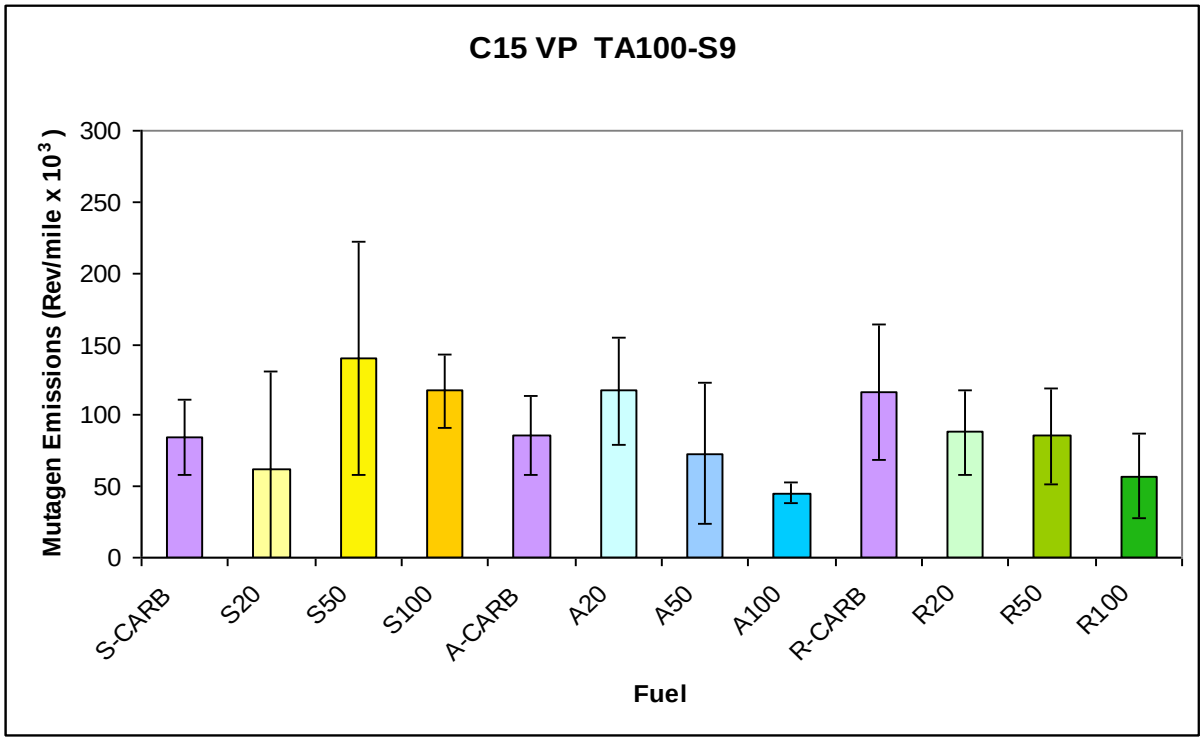


Figure 11-8. Mutagen Emissions for Vapor phase Samples Tested in TA100 (-S9) and Collected from the 2000 Caterpillar C-15 Vehicle.

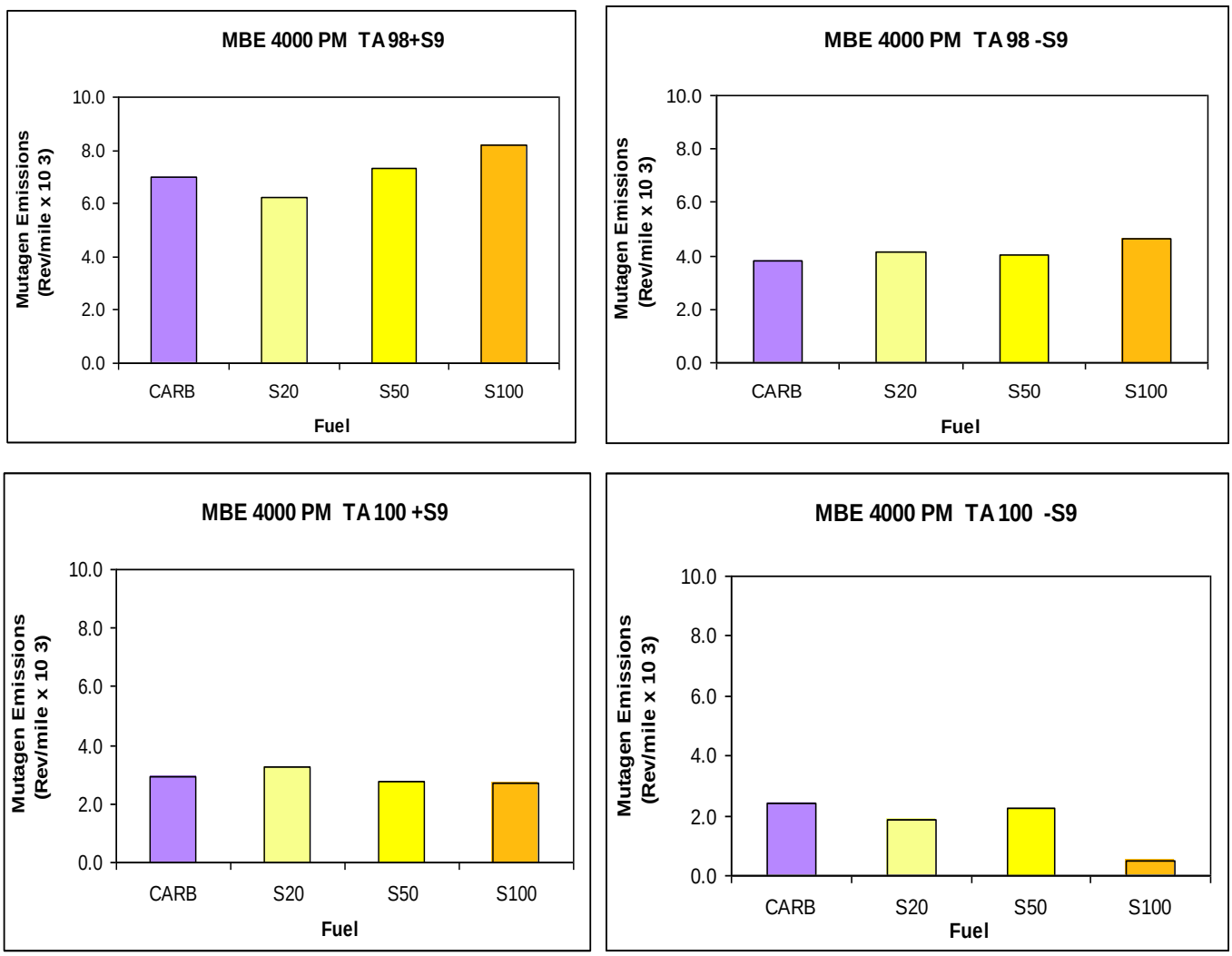


Figure 11-9. Mutagen Emissions of Particulate Matter from an MBE 4000 vehicle. Samples were tested in tester strains TA98 and TA100 with and without S9 for the 2007 the Particle Phase Tested in TA98 and TA100 (± SD) MBE4000 vehicle. Each bar represents a pooled sample from 9 x 3 UDDS runs.

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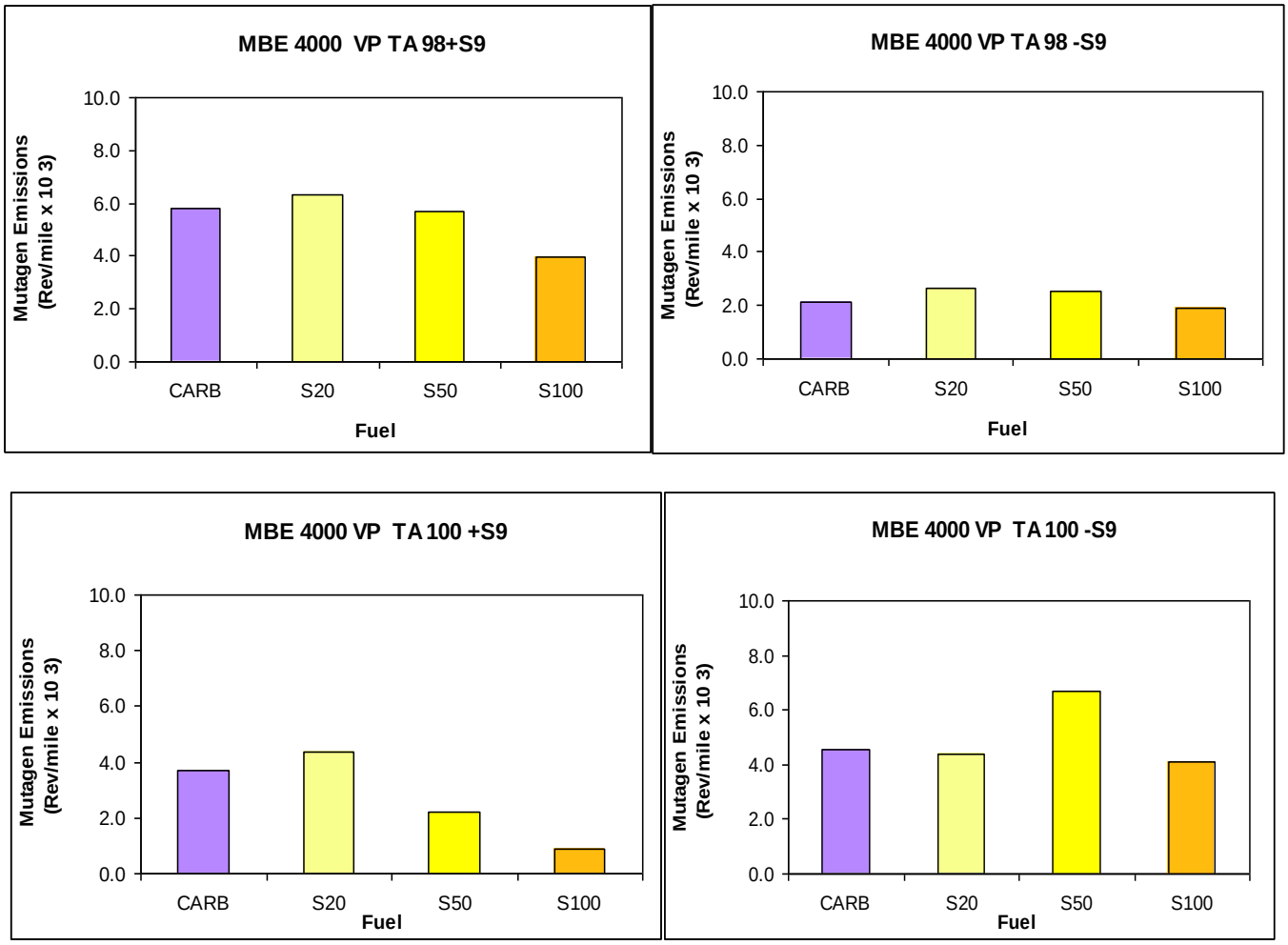


Figure 11-10. Mutagen Emissions of Vapor Phase from an MBE 4000 vehicle. Samples were tested in tester strains TA98 and TA100 with and without S9. Each bar represents a pooled sample from 9 x 3 UDDS runs.

11.2 Inflammatory and oxidative stress response

Results from the inflammatory and oxidative stress response for the 2000 Caterpillar C-15 are shown in Figure 11-11 through Figure 11-16 and the results for the 2007 MBE4000 are shown in Figure 11-17 through Figure 11-19. These Figures show response rates for the CYP1a1, IL-8, COX-2, HO-1, and MUC5AC for the macrophage and the lung Clara cells. The results for the 2000 Caterpillar C-15 vehicle represent the average of triplicate samples taken for each fuel or fuel blend. The error bars represent one standard deviation on the average value from the triplicate samples that were analyzed separately. For the 2007 MBE4000 vehicle, the triplicate samples were combined for analysis due to low responses, hence the variability in the samples is not provided.

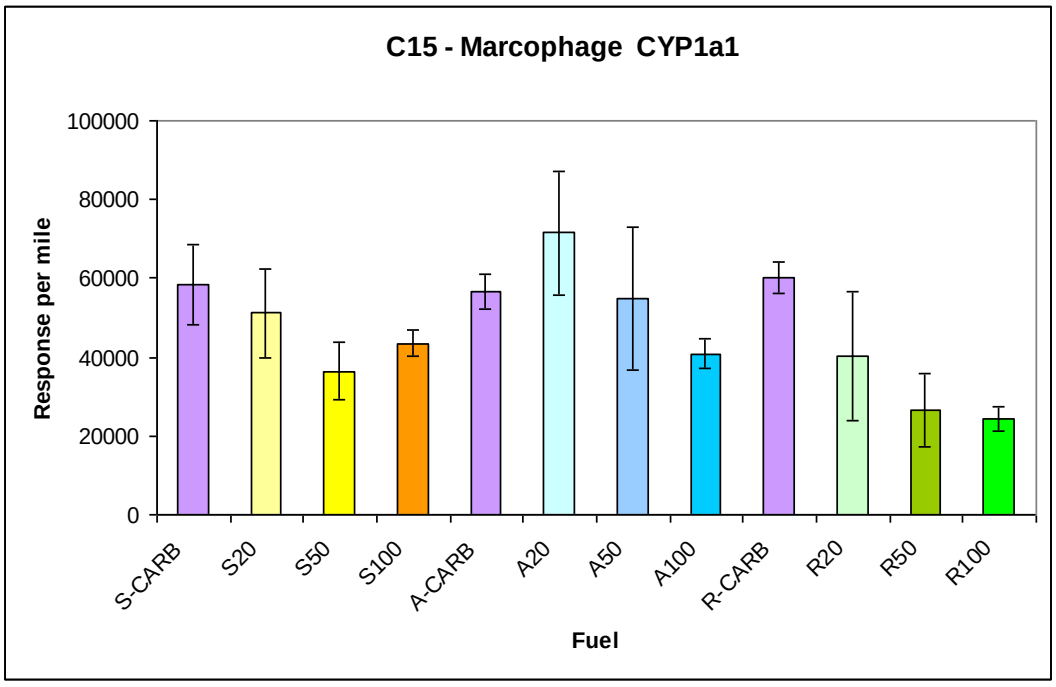


Figure 11-11. Effect of diesel and biodiesel fuels on CYP1a1 expression in the macrophages on a per mile basis for the 2000 Caterpillar C-15 on the UDDS cycle.

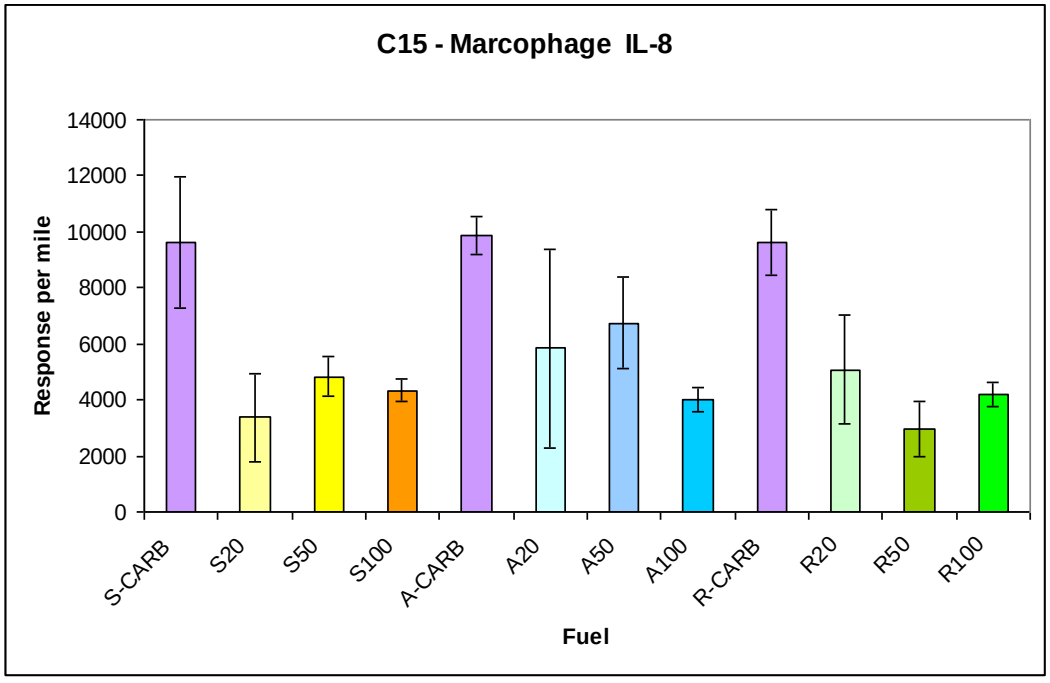


Figure 11-12. Inflammatory Response of IL-8 in the macrophages on a per mile basis for the 2000 Caterpillar C-15 on the UDDS cycle.

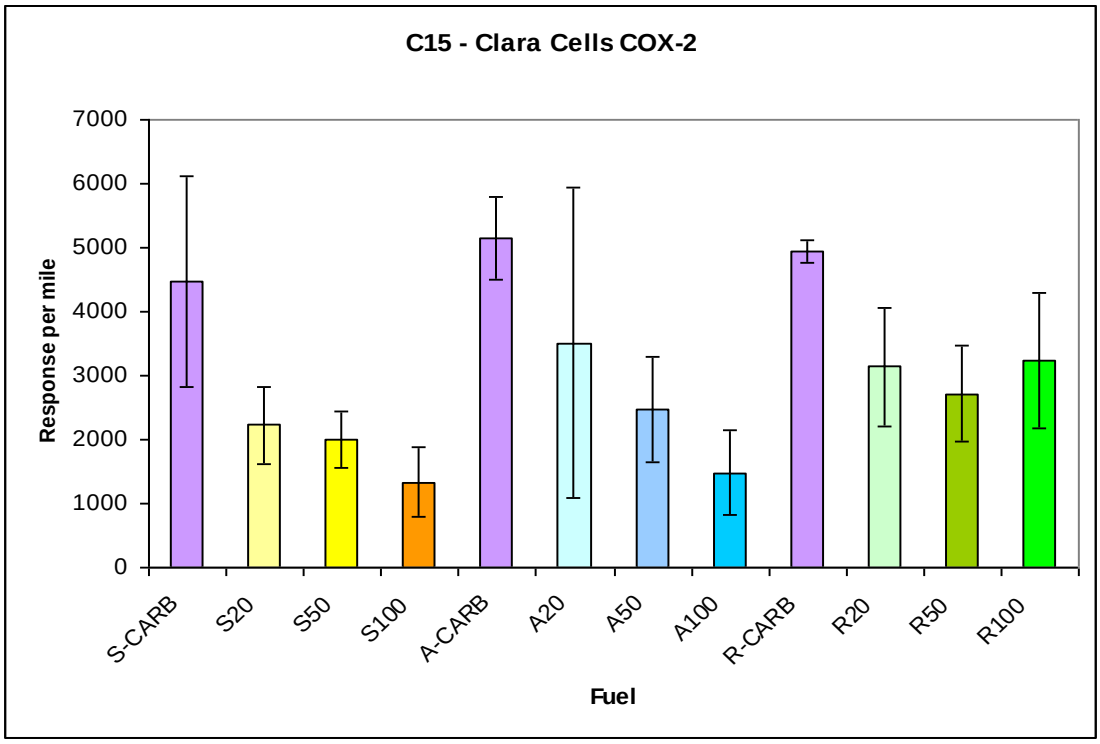


Figure 11-13. Inflammatory Response of COX-2 in the lung Clara cells on a per mile basis for the 2000 Caterpillar C-15 on the UDDS cycle

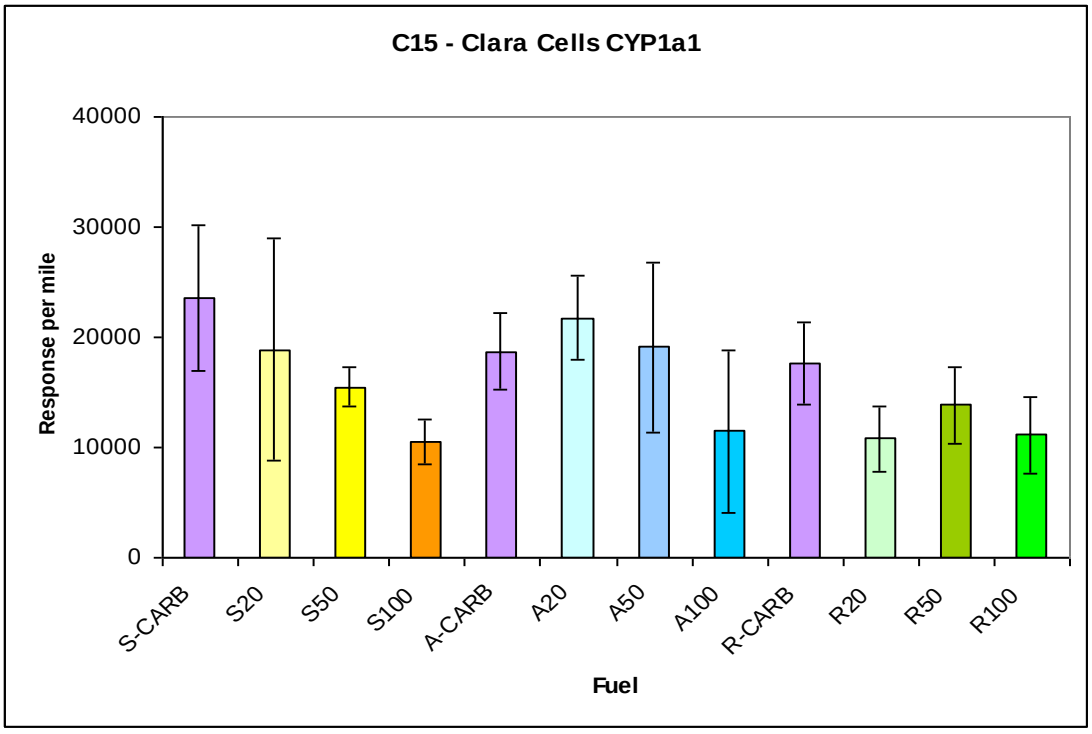


Figure 11-14. Effect of diesel and biodiesel fuels on CYP1a1 expression in the lung Clara cells on a per mile basis for the 2000 Caterpillar C-15 on the UDDS cycle.

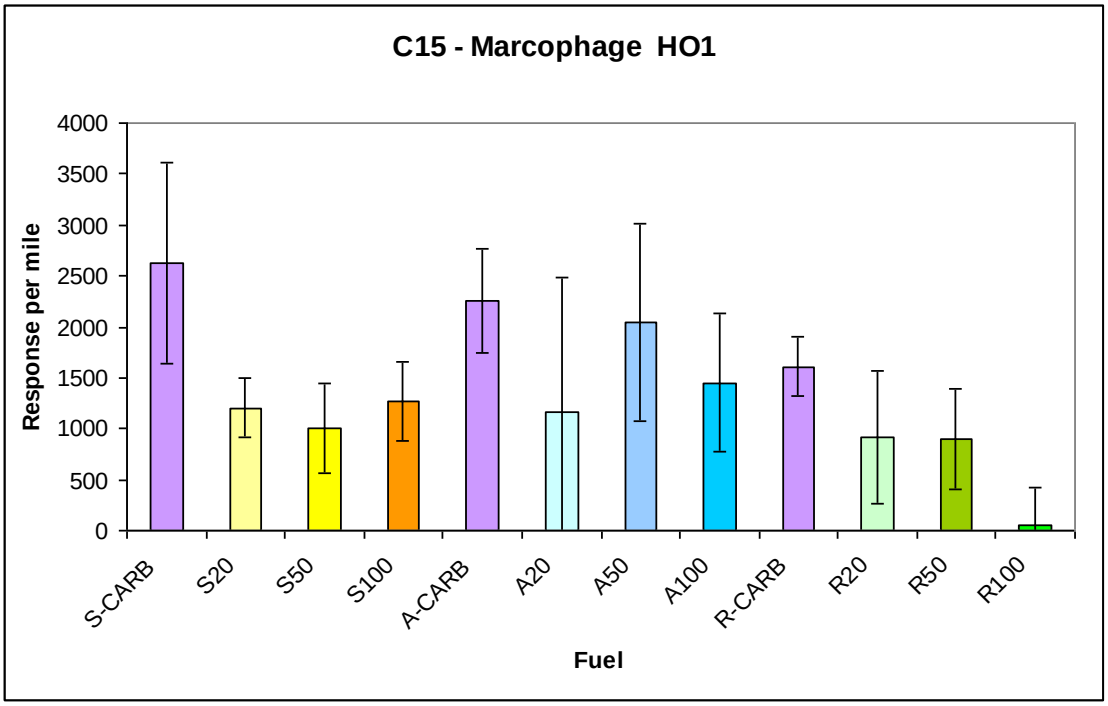


Figure 11-15. Oxidative Response for HO-1 in the macrophages on a per mile basis for the 2000 Caterpillar C-15 on the UDDS cycle

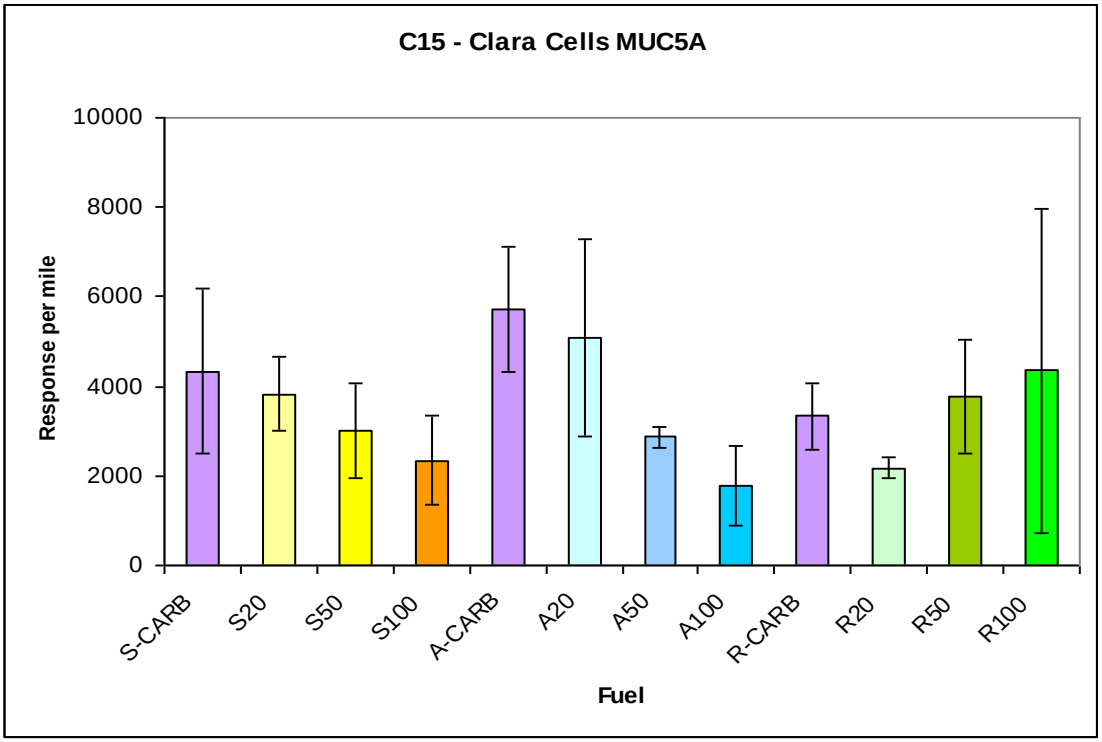


Figure 11-16. Expression of MUC5AC in the lung Clara cells on a per mile basis for the 2000 Caterpillar C-15 on the UDDS cycle

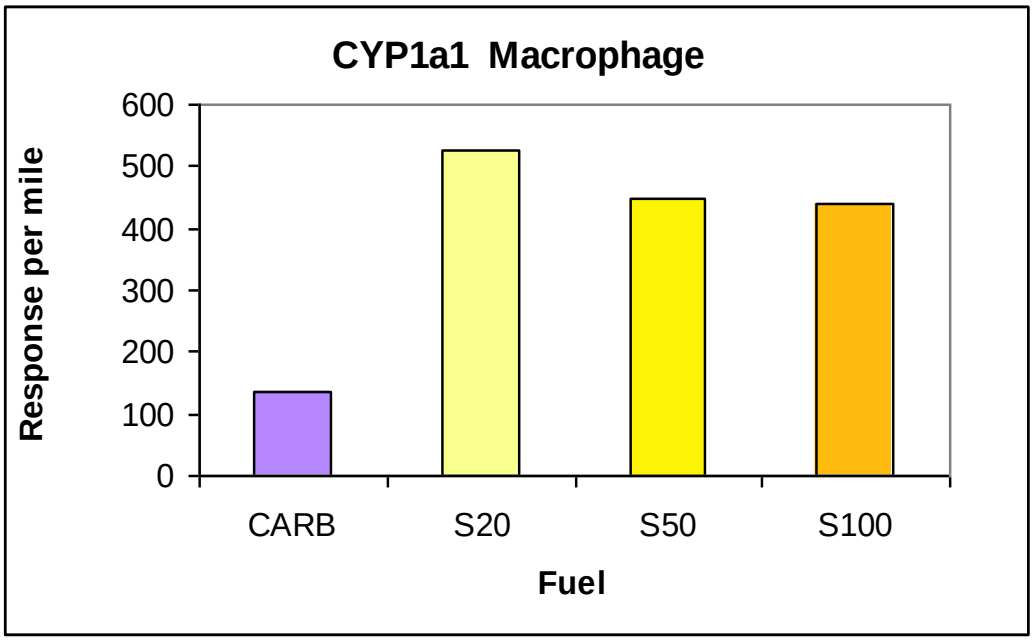


Figure 11-17. Effect of diesel and biodiesel fuels on CYP1a1 expression in the macrophages on a per mile basis for the 2007 MBE4000 over the UDDS cycle

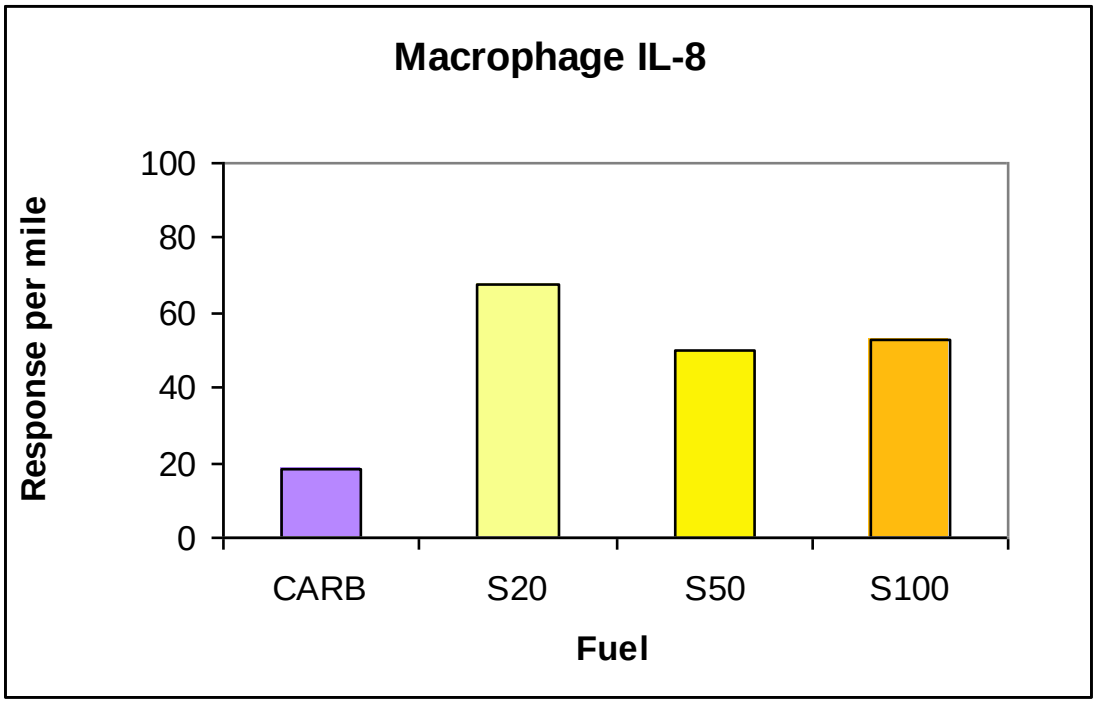


Figure 11-18. Inflammatory Response of IL-8 in the macrophages on a per mile basis for the 2007 MBE4000 over the UDDS cycle

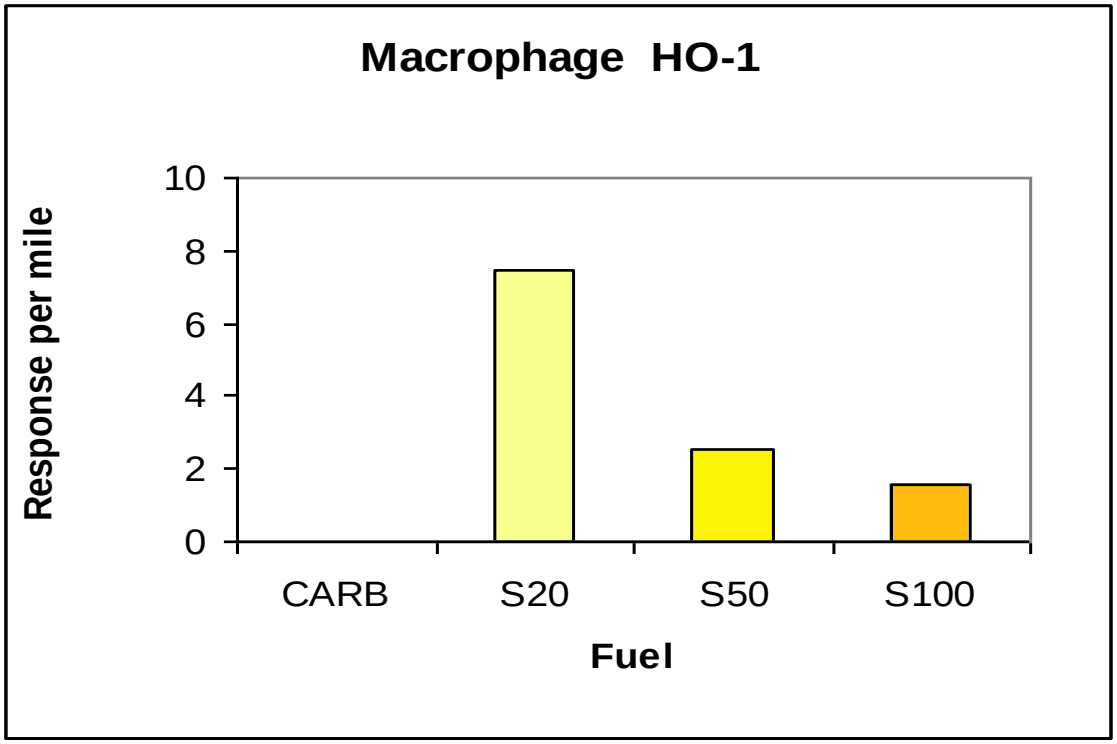


Figure 11-19. Oxidative Response for HO-1 in the macrophages on a per mile basis for the 2007 MBE4000 over the UDDS cycle. CARB fuel responses were below control in these samples.

The results show that the CARB diesel and the biodiesel blends induce CYP1A1 production through compounds that bind to and activate the Ah-Receptor. The CARB diesel and biodiesel blends also induce inflammatory markers like COX-2 and IL-8 in macrophages, and MUC5AC in lung Clara cells. The effects of the biodiesel blends on inflammatory markers like COX-2 and IL-8 tend to be lower than for the CARB diesel for the 2000 Caterpillar C-15 vehicle. However, IL-8 was higher in soy biodiesel and the blends than in the CARB diesel for the 2007 MBE4000 engine

11.3 Comet Assay Results

The Comet Assay DNA damage results for the 2000 Caterpillar C-15 vehicle are presented in Figure 11-20. The results for each test cycle represent the average of all test runs done on that particular combination. Standard Reference Material from Diesel engines (SRM 1650) was obtained from the National Institute of Standards and Technology (NIST; Gaithersburg, Md) and served as the positive control. The error bars represent one standard deviation on the average determination of pooled samples from each fuel type. Photographs of the DNA damage for different test configurations are provided in Figure 11-21.

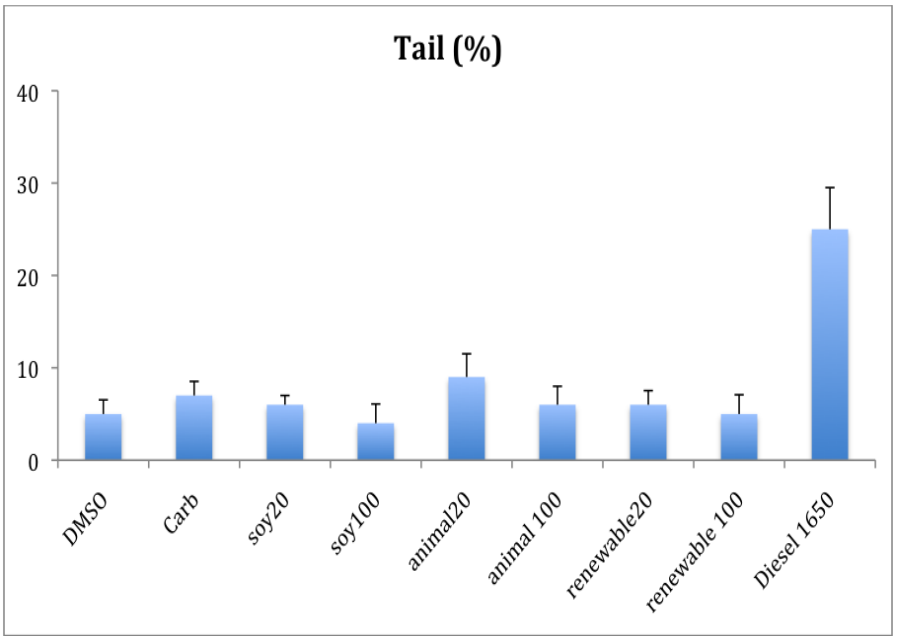
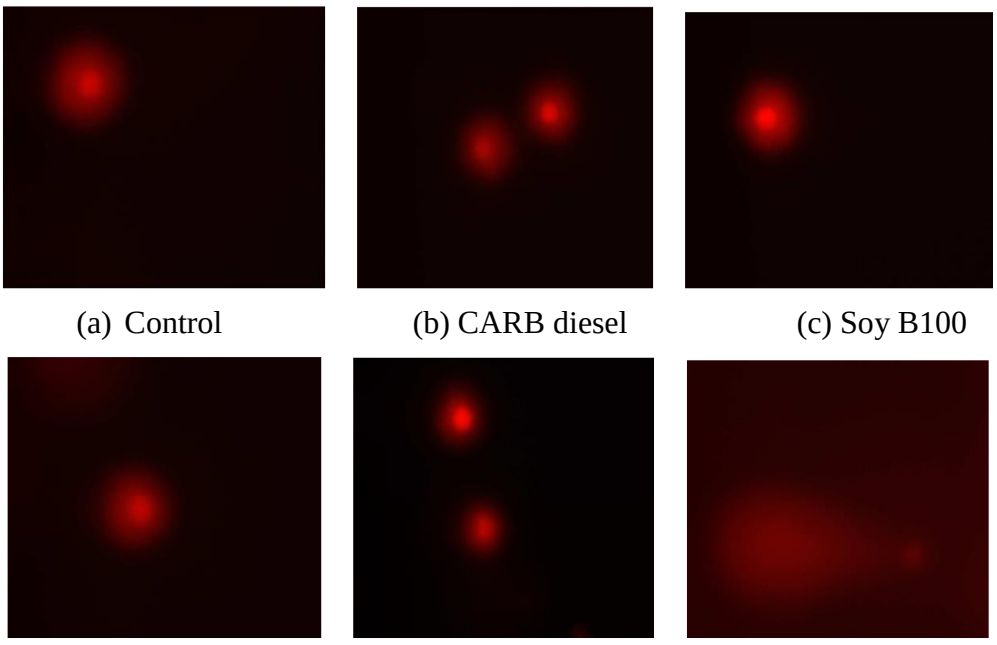


Figure 11-20 DNA Damage Measured by the Comet Assay for the 2000 Caterpillar C-15. Amount of PM extract added was equivalent to 100 ug PM /ml final concentration.



(a) Control (b) CARB diesel (c) Soy B100

(d) Animal B100 (e) R100 (f) NIST SRM1650

Figure 11-21. Comet Assay Photographs for Various Fuels for the 2000 Caterpillar C-15.

12.0 Summary

The California Air Resources Board is conducting a comprehensive study to better characterize the emissions impacts of renewable fuels under a variety of conditions in support of government initiates to increase the use of alternative fuels. The goal of this study is to understand and, to the extent possible, mitigate any impact that biodiesel has on NO_x emissions from diesel engines, and to evaluate the potential impact of biodiesel on toxic emissions.

The testing for this program included engine dynamometer testing of heavy-duty, on-highway engines and off-road engines and chassis dynamometer testing of heavy-duty, on-highway vehicles. The full test matrix of this includes testing on 2 heavy-duty engines (2006 Cummins ISM & 2007 MBE4000), 4 heavy-duty vehicles (equipped with 2000 Caterpillar C-15, 2006 Cummins ISM, 2007 MBE4000, and 2010 Cummins ISX engines), and 2 off-road engines (a John Deere and a transportation refrigerated unit (TRU)). The testing included a baseline CARB ULSD fuel, two biodiesel feedstocks (one soy-based and one animal-based) tested on blend levels of B5, B20, B50, and B100, and a renewable and a GTL diesel fuel tested at 20%, 50%, and 100% blend levels. For the on-highway engine and chassis dynamometer testing, several test cycles were also utilized to evaluate the impact of biodiesel on emissions under different operating conditions and loads. For the heavy-duty, on-highway engine testing a light loaded UDDS cycle, the FTP, and 40 mph and 50 mph CARB cruise cycles were used. For the heavy-duty chassis dynamometer testing, a medium load UDDS and a heavily loaded 50 mph CARB cruise cycle were used. The off-road engines were tested on the ISO 8178, 8-mode steady state cycle. This report summarized the results and conclusions for all elements of this study.

A summary of the results is as follows:

Biodiesel Characterization – Engine Testing Results:

- For both the 2006 Cummins and 2007 MBE4000 engines, the average NO_x emissions show trends of increasing NO_x emissions with increasing biodiesel blend level, but the magnitude of the effects differ between the different feedstocks. The soy-based biodiesel blends showed a higher increase in NO_x emissions for essentially all blend levels and test cycles in comparison with the animal-based biodiesel blends. .
- For the 2006 Cummins engine, for the soy-based biodiesel over the FTP, the NO_x impact ranged from an increase of 2.2% at the B5 level, to 6.6% at the B20 level, to 27% at the B100 level. The biodiesel emissions impacts for the other cycles were comparable to but less than those found for the FTP for the different blend levels. These increases were higher than the EPA base case estimates for all of the test cycles. The NO_x impacts found for the soy-based biodiesel were consistent, however, with the EPA estimates for the "clean base fuel" case, which would be more representative of a CARB diesel fuel.
- For the 2006 Cummins engine, for the animal-based biodiesel feedstock, the NO_x emission increases with biodiesel for the FTP cycle were consistent with the EPA base case estimates. The NO_x impact for the animal-based biodiesel over the FTP ranged from an increase of 1.5% at the B20 level to 14% at the B100 level. For the lower load UDDS cycle for the animal-based biodiesel feedstock, the emissions differences were not statistically significant for any of the blend levels. For the 50 mph cruise cycle, a

statistically significant increase in NO_x emissions was only found for the B100 animal-based biodiesel. The 50 mph cruise results were obscured, however, by changes in the engine operation and control strategy that occurred over a segment of this cycle.

- For the 2007 MBE4000 engine, the magnitude of the NO_x emissions increases, on a percentage basis, were greater than those for the 2006 Cummins engine for nearly all biodiesel blends and test cycles. The absolute differences in the emission levels for the CARB and biodiesel fuels, however, were less for the 2007 MBE4000, due to its lower overall NO_x emission levels. The emissions increases for the both the soy-based and the animal-based biodiesel were higher than those for the EPA base case estimates. The NO_x increases for the soy-based biodiesel were also higher than those for the EPA estimates for a clean base fuel for most test combinations. The animal-based biodiesel showed estimates comparable to the EPA clean base fuel estimates for the FTP, but showed a lower NO_x impact for the lighter load UDDS cycle and a higher NO_x impact for the 50 mph cruise cycle.
- NO_x emissions were found to increase as a function of engine load for both engines, as expected.
- Comparing different cycles for 2006 Cummins engine, the FTP showed the strongest NO_x increases for biodiesel for both soy-based and animal-based blends. The impact of biodiesel on NO_x emissions was not found to be a strong function of engine load, as was observed in previous studies by EPA (Sze et al., 2007). This could be related to differences in engine operation that were observed for the 50 mph cruise cycle and may have obscured the trends.
- For the 2007 MBE4000 engine, only the animal-based biodiesel testing showed increases in the NO_x differential with increasing cycle power. There were also some trends of a higher NO_x differential for the B50 and B100 soy-based biodiesels on the highest load 50 mph cruise cycle, as well as a slight trend with these fuels for the other cycles.
- PM emissions, for 2006 Cummins engine, showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. This is consistent with a majority of the previous studies of emissions from biodiesel blends. The PM reductions for both the soy-based and animal-based biodiesel blends were generally larger than those found in the EPA study, and are closer to the estimates for an base case fuel than a clean base fuel. Over the FTP, the PM reductions for the soy-based biodiesel ranged from 6% for a B5 blend, to 25% for a B20 blend, to 58% for B100. For the animal-based biodiesel over the FTP, the PM reductions ranged from 19% for the B20 blend to 64% for B100. The smallest reductions were seen for the UDDS, or the lightest loaded cycle. The PM reductions for biodiesel for the FTP and the cruise cycles were comparable for both fuels. Although there were some differences in the percent reductions seen for the soy-based and animal-based biodiesel fuels, there were no consistent differences in the PM reductions for these two feedstocks over the range of blend levels and cycles tested here.
- THC emissions for the 2006 Cummins engine, showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. The THC reductions over the FTP for the soy-based biodiesel ranged from 6% for a B10 blend, to 11% for a B20 blend, to 63% for B100. For the animal-based biodiesel over the FTP, the THC reductions ranged from 13% for the B20 blend to 71% for B100.

- Overall, the THC reductions for the 2006 Cummins engine seen in this study are consistent with and similar to those found by EPA. The THC reductions for both the soy-based and animal-based biodiesel blends for B100 were closer to those found in the EPA study for the B100 level for the base case fuels, while the lower blend levels (i.e., B20 and B50), were in between those estimated by EPA for the clean and base case fuels. For the soy-based biodiesel, the reductions are slightly less for the lower load UDDS, but for the animal-based biodiesel the THC reductions for all the test cycles were similar. There was not a strong trend in the THC reductions with biodiesel as a function of either power or fuel consumption.
- CO emissions, for 2006 Cummins Engine, showed consistent and significant reductions for the animal-based biodiesel blends, consistent with previous studies. Over the FTP, the CO reductions for the animal-based biodiesel ranged from 7% for a B5 blend, to 14% for a B20 blend, to 27% for B100. The CO reductions seen for the animal-based biodiesel are comparable to those seen for the EPA clean base fuel estimates, but are lower than those for the EPA base case. The CO trends for the soy-based biodiesel were less consistent. The CO emissions for the soy-based biodiesel did show consistent reductions with increasing biodiesel blend levels for the highest load, the 50 mph cruise cycle. For the FTP and 40 mph cruise cycles, the soy-based biodiesel blends did not show any strong trends relative to the CARB ULSD and a number of differences were not statistically significant. Interestingly, the CO emissions for the lowest load UDDS cycle showed higher emissions for the biodiesel blends, with the largest increase (62%) seen for the highest blend level. Additional testing would likely be needed to better understand the nature of these results, which are opposite the trends seen in most previous studies.
- For the 2007 MBE4000 engine, the PM, THC, and CO emissions were all well below certification limits and the emission levels for the 2006 Cummins due to the DPF. For the most part, PM, THC, and CO differences between fuels were not statistically significant. For THC, one exception to this was for the soy-based biodiesel, which actually showed statistically significant increases ranging from 20 to 33% compared to the CARB diesel over the FTP. CO emissions did show lower emissions for the B50 and B100 fuels over the FTP as well. It should be noted that in the cases where statistically significant differences were found, the differences were small on an absolute basis and additional tests would be needed to verify these trends on a larger set of fuels/engines.
- Throughout the course of testing on the 2006 Cummins engine some outliers were observed in the testing that appeared to be related to conditions set within the engine control module (ECM). Changes in engine operation were observed within the 50 mph CARB HHDDT cycle. For this test cycle, for a period of the test cycle from approximately 300 to 400 seconds, two distinct modes of operation were observed. These tests were not removed from the analysis, as it was surmised that these conditions could potentially occur in real-world operation. During initial testing, significant changes were also found when the temperature of the coolant water to the charge air cooler dropped below 68°F. This situation was remedied and these tests were removed from the subsequent analyses.
- CO_2 emissions showed a slight increase for the higher biodiesel blends. For the 2006 Cummins engine, this increase ranged from about 1-4%, with the increases being statistically significant for the B100 fuels for all of the tests, for the B50 fuel for the cruise cycles, and for some other testing combinations. For the 2007 MBE4000 engine,

only the B100 blends showed consistent, statistically significant increases in CO_2 emissions for the different cycles, with the increases ranging from 1-5%.

- The biodiesel blends showed an increase in fuel consumption with increasing levels of biodiesel. This is consistent with expectations based on the lower energy density of the biodiesel. The fuel consumption differences were generally greater for the soy-based biodiesel in comparison with the animal-based biodiesel for the 2006 Cummins engine, but not for the 2007 MBE4000 engine. The changes in fuel consumption for the soy-based biodiesel blends for the 2006 Cummins engine range from 1.4 to 1.8% for B20 to 6.8 to 9.8% for B100. The changes in fuel consumption for the animal-based biodiesel blends for the 2006 Cummins engine range from no statistical difference to 2.6% for B20 to 4.4 to 6.7% for B100. For the 2007 MBE4000 engine, the differences in fuel consumption ranged from no change to 2.5% for B50 and lower blends, while the increases for the B100 blends ranged from 5.6 to 8.3%.

Renewable and GTL Diesel Fuels – Engine Testing Results:

- For the renewable and GTL diesel fuels, the results show a steady decrease in NO_x emissions with increasingly higher levels of renewable/GTL diesel fuel. Over the FTP cycle, the NO_x reductions for the renewable and GTL diesel were comparable for each of the blend levels. For the FTP, the NO_x reductions for the renewable diesel ranged from 2.9% for the 20% blend to 9.9% for the 100% blend, while the NO_x reductions for the GTL ranged from ~1% for the 20% blend to 8.7% for the 100% blend. Larger emissions reductions were found over the UDDS and Cruise cycles, where only the renewable diesel fuel was tested. The reductions in NO_x for the renewable diesel fuel are comparable to those found in previous studies of heavy-duty engines.
- In comparison with the biodiesel feedstocks, the levels of NO_x reduction for the renewable and GTL fuels are less than the corresponding increases in NO_x seen for the soy-based biodiesel, but are more comparable to the increases seen for the animal-based biodiesel blends. With respect to NO_x mitigation, this suggests that the renewable and GTL diesel fuel levels need to be blended at slightly higher levels than the corresponding biodiesel in order to mitigate the associated NO_x increase. This is especially true for the soy-based biodiesel blends.
- PM emissions showed consistent and significant reductions for the renewable and GTL blends, with the magnitude of the reductions increasing with blend level. The reductions for the renewable diesel were statistically significant for the higher blends and ranged from 12-15% for the R50 and from 24-34% for the R100. A statistically significant 4% reduction was also found for the R20 over the FTP. The GTL fuel showed a statistically significant reduction over the FTP, with reductions ranging from 8% for the 20% blend to 29% for the 100% blend. Similar reductions are found for the UDDS, FTP, and Cruise cycles indicating that cycle load does not have a significant impact on the PM reductions.
- For the THC emissions, the GTL fuel showed statistically significant reductions over the FTP that increased with increasing blend level. These reductions ranged from 5% for the 20% blend to 28% for the 100% blend. The renewable diesel did not show consistent trends for THC emissions over the different test cycles. This finding was consistent with predictions based on the EPA's Unified Model and the associated distillation temperatures and other parameters of the fuels that showed there should not be any

significant differences between the THC emissions for the CARB fuel in comparison with the renewable winter blend used in the study (Hodge, 2009). Statistically significant THC reductions were found for the renewable diesel fuel for the lowest load UDDS cycle, with the THC reductions increasing with increasing levels of the renewable diesel fuel.

- Reductions in CO emissions with the renewable diesel fuel were found for the UDDS and FTP cycles, but not for the cruise cycle. Over these cycles, the percentage reductions increased with increasing renewable diesel fuel blend. Over the FTP, these reductions ranged from 4% for the R20 to 12% for the R100. The comparisons of CO emissions over the 50 mph cruise may have been complicated by the changes in engine operation that were seen for that cycle. The GTL fuel also showed similar reductions over the FTP, with reductions ranging from 6% for the GTL20 blend to 14% for the GTL100 blend.
- The CO_2 emissions for the neat or 100% blend renewable and GTL fuels were lower than those for the CARB ULSD for each of the test cycles. The reduction was on the order of 2-4% for the 100% blends. This slight reduction in CO_2 emissions is consistent and comparable to previous studies of the renewable diesel fuel.
- The brake specific fuel consumption increased with increasing levels of renewable and GTL fuels. The increases in fuel consumption range from 1.0-1.4% for the R20 and 5.1 to 6.6% for the R100. The increases in fuel consumption with blend level are slightly higher for the cruise cycle compared to the lower load UDDS and FTP. The fuel consumption increases for the GTL ranged from 1.3% for the 20% blend to 3.3% for the 100% blend. The fuel consumption differences are consistent with the results from previous studies, and can be attributed to the lower density or energy density of the renewable and GTL fuels compared to the CARB baseline fuel.

Off-Road Engine Testing Results

- The NO_x emissions show general increases with increasing biodiesel blend level for both off-road engines. The NO_x increases were statistically significant for the B100 blends and the soy-based B50 blends for both engines. The soy-based B20 blends also showed increases that were statistically significant for the John Deere engine and statistically significant at the less than 90% confidence level for the TRU engine. The NO_x increases for the TRU engine were comparable with the ones obtained for the 2006 Cummins engine (9.8-13.2% for B50 & 17.4-26.6% for B100), but were lower than the ones obtained for the 2007 MBE4000 (15.3-18.2% for B50 & 36.6-47.1% for B100). The magnitude of the increases in NO_x emissions for the John Deere engine were less than those for either the TRU or the on-road heavy-duty engines. The animal-based biodiesel also did not show as great a tendency to increase NO_x emissions compared to the soy-based biodiesel for the John Deere engine, with only the B100 animal-based biodiesel showing statistically significant increases in NO_x emissions of 7.6%.
- PM emissions showed consistent reductions with increasing biodiesel blend level for both the John Deere and the TRU engines. The magnitude of the reductions in the PM emissions for the John Deere engine were comparable to those of the 2006 Cummins ISM engine dynamometer tests, while the reduction seen for the TRU engine were less than those seen for the 2006 Cummins.

- THC emissions showed consistent reductions with increasing biodiesel blend level for both the John Deere and the TRU engines. The magnitude of the reductions in the PM emissions depended on the specific engine/fuel/blend level combination. The THC reductions for the off-road engines were either comparable to slightly less than those seen for the 2006 Cummins ISM engine dynamometer testing.
- CO emissions showed consistent reductions with increasing biodiesel blend level for both the John Deere and TRU engines. The CO reductions for the John Deere engine were comparable to those seen for the 2006 Cummins ISM engine for the engine dynamometer testing, while the CO reductions for the TRU engine were generally greater than those found for the 2006 Cummins.
- CO_2 emissions showed some slight increases (i.e., 1-3%) for the biodiesel blends for both the John Deere and TRU engines. These increases were statistically significant for the TRU engine for both the B50 and B100 blends on the first series of tests and for the B100 blend on the second series of tests. Increases of 1-5% in CO_2 emissions were also seen for the 2006 Cummins and 2007 MBE4000 in the on-road engine dynamometer testing. For the TRU engine, N_2O and CH_4 emissions were characterized along with CO_2 to provide total tailpipe greenhouse gases. These results showed that the B50 and B100 blends produced some increases in tailpipe greenhouse gas equivalent emissions relative to the CARB diesel. It must be emphasized that these increases represent only the tailpipe contribution to the greenhouse gas emissions. The actual contribution of each fuel towards total greenhouse gas emissions would need to be assessed through a full lifecycle analysis, which would account for the emissions attributed to harvesting, extracting, and producing the various fuels.

Heavy-Duty Chassis Dynamometer Testing – Regulated and Unregulated Emissions Results:

- For the heavy-duty chassis results, the NO_x emissions showed a consistent trend of increasing emissions with increasing biodiesel blend level. These differences were statistically significant or marginally statistically significant (i.e., a p-value between 0.05 and 0.1) for nearly all of the test sequences for the B50 and B100 fuels, and for some B20 blends, but not others. The percentage increases for the NO_x emissions with biodiesel were generally greater for soy-based biodiesel compared with the animal-based biodiesel. The magnitude of the increases in NO_x emissions for the biodiesel blends for the 2006 Cummins ISM engine were either greater than or comparable to those found for the engine testing on this engine. For the 2007 MBE4000, the overall NO_x increases are in the same range for the chassis and engine dynamometer testing, with some differences seen for cycle/fuel/blend level combinations. The results for the renewable diesel fuel showed NO_x reductions for the UDDS cycle, but not statistically significant reductions over the 50-mph cruise cycle. The magnitude of the reductions found for the renewable diesel was similar to those found in the engine testing.
- PM emissions showed consistent reductions for the all biodiesel blends and both cycles, with the magnitude of the reductions increasing with blend level for the 2000 Caterpillar C-15 and the 2006 Cummins ISM. These reductions were statistically significant for nearly all of the B50 and B100 cases, but for only a subset of the B20 results. The PM emissions reductions for the chassis dynamometer testing are comparable to the reductions seen in the engine testing for the 2006 Cummins ISM engine for most testing

combinations. The renewable blend also showed some statistically significant PM reductions for the R100 on the 2000 Caterpillar C-15, but no consistent trends for the other blend levels. PM emissions did not show any consistent trends for the DPF equipped 2007 MBE4000, since most of the combustion-related PM is eliminated by the DPF.

- THC emissions showed reductions for the B100 for nearly all cycles for the non-DPF equipped engines and for the B50 for the 2006 Cummins ISM and the B50 animal-based biodiesel for the 2000 Caterpillar C-15. The reductions for the highest blend levels are less than those seen in the corresponding engine tests for the Cummins ISM and for the EPA estimates. The renewable diesel also showed lower THC emissions, but these were only statistically significant or marginally statistically significant for the R100 for the 2000 Caterpillar C-15 over the UDDS cycle.
- CO emission results showed consistent and generally significant reductions for all biodiesel blends for the non-DPF-equipped engines, with higher reductions with increasing blend levels. The CO reductions were statistically significant for most of the B50 and B100 blends, and some of the B20 blends. For the renewable diesel, both the R50 and R100 showed reductions in CO that were either statistically significant or marginally statistically significant. CO emissions did not show consistent trends for the DPF equipped 2007 MBE4000, although statistically significant CO reductions were found for the B100 soy-based and animal-based blends for the UDDS cycle.
- CO_2 emissions showed some reductions for the R100 and R50 fuels for the 2000 Caterpillar C-15 and some increases for the animal-based and soy-based biodiesel blends for the 2007 MBE4000, although these trends are not consistent across the range of vehicles/engines testing on the chassis dynamometer. The CO_2 increases fall within the 1-5% range that was seen in the heavy-duty engine dynamometer testing for the various biodiesel blends.
- The VOC emissions measured for the chassis testing included benzene, toluene, ethylebenzene, 1,3-butadiene, *m-/p*-xylene and *o*-xylene. The VOC emissions typically only showed trends for the higher biodiesel blend levels, with the emissions for biodiesel being lower than those for CARB. Generally, the reductions in aromatic VOCs were consistent with the reduction in aromatics in the fuel. For the lower biodiesel blend levels, the differences with the CARB diesel were typically not significant. VOC emissions were typically higher on a g/mi basis for the UDDS cycle compared with the 50 mph Cruise cycle. Benzene emissions were the highest of the VOCs for both test cycles and each of the fuels for the Caterpillar C-15, while benzene and 1,3-butadiene were the highest VOCs for the Cummins ISM.
- The PM mass was composed predominantly of carbonaceous material for all fuel combinations. The total carbon and the elemental carbon components of the PM both showed reductions increasing in magnitude at progressively higher biodiesel blends. Both of these trends are consistent with the overall reduction in PM mass with higher biodiesel levels. The organic carbon levels did not show significant differences between the different fuel blends, and in fact were relatively flat as a function of blend level. The renewable diesel blends showed trends of decreasing elemental and total carbon emissions as a function of blend level, but this was only statistically significant for the R100 fuel.

- The ion and trace element emissions were generally very low, comprising less than 1% and 2%, respectively, of the total PM mass and did not show any consistent trends between the different fuels. Overall, it does not appear that biodiesel or renewable blends will have a significant impact on ion or trace element emissions, based on the results of this study.
- Particle number (PN) showed some differences between fuels, but in general, the differences in PN were not as consistent as those found for PM mass, and they did not follow the same trends that were observed for the PM mass. Particle size distributions showed an increase in nucleation and a decrease in accumulation mode particles for the biodiesels for the non-DPF equipped vehicles, and an opposite increase in accumulation modes particles and a decrease in nucleation for the biodiesel for the DPF-equipped vehicle. Particle length measurements were relatively similar over the whole spectrum of fuel types and driving conditions for the 2006 Cummins vehicle, and for the 2007 MBE4000 vehicle showed some increase for the B100 blends for the UDDS and some decreases for the intermediate blends for the 2006 Cummins vehicle. Particle-bound PAHs showed a consistent trend of decreasing pPAHs with increasing biodiesel level for the 2006 Cummins ISM vehicle, but showed some increases in pPAHs for the 2007 MBE4000, corresponding to an increase in accumulation mode particles.

NO_x Mitigation – Engine Testing Results:

- The impact of biodiesel on NO_x emissions depends on the feedstock or fundamental properties of the biodiesel being blended. Blends of two biodiesels with different emissions impacts for NO_x provides a blend that shows a NO_x impact that is intermediate between the two primary biodiesel feedstocks. This can be seen for the results of the CARB80/B10-S/B10-A, which showed a NO_x increase intermediate to that of the B20-S and the B20-A. This indicates that the NO_x impact for a particular biodiesel feedstock can be mitigated in part by blending with another biodiesel feedstock with a lower tendency for increasing NO_x.
- Two additives were tested for NO_x mitigation for 2006 Cummins engine, 2-EHN and DTBP. Of these two additives, the DTBP was effective in this testing configuration. A 1% DTBP additive blend was found to fully mitigate the NO_x impacts for a B20 and B10 soy biodiesel. The 2-EHN was tested at 1% level in both a B20-soy and B5-soy blend and did not show any significant NO_x reductions from the pure blends.
- The testing showed that renewable diesel fuels can be blended with biodiesel to mitigate the NO_x impact. This included higher levels of renewable diesel (R80 or R55) with a B20-soy biodiesel. Several lower level blends, designed to be more comparable to those that could potentially be used to meet the low carbon fuel standard, also showed NO_x neutrality, including a CARB75/R20/B5-soy blend, a CARB80/R13/B3-soy/B4-animal blend, a CARB80/R15/B5-soy blend, and a CARB80/GTL15/B5-soy blend. Overall, the renewable and GTL diesels provide comparable levels of reductions for NO_x neutrality at the 15% blend level with a B5-soy.

- The level of renewable or GTL diesel fuels can be reduced if a biodiesel fuel with more favorable NO_x characteristics is used. This is demonstrated by the success of the

CARB80/R13/B3-S/B4-A blend that combined both the soy and animal-based biodiesel. The use of an additive in conjunction with lower levels of renewable diesel and GTL can also be used to provide NO_x neutrality, as shown by the success of the CARB80/R10/B10-S 0.25% DTBP blend.

- For the 2007 MBE4000 engine only two blends were tested. The blends included a CARB80/R15/B5-soy and, a B-5 soy with a 0.25% DTBP additive. Of these two blends, only the CARB95/B5-S 0.25% DTBP blend was found to provide NO_x neutrality. Overall, it appears that different strategies will provide mitigation for different engines, but that the specific response will vary somewhat from engine to engine.
- The NO_x mitigation formulations for the 2006 Cummins showed reductions in PM, THC, and CO that were consistent with those for the biodiesel and renewable diesel fuels by themselves, with some slightly larger reductions seen when higher levels of biodiesel and renewable diesel were combined or when additives were used.
- For the 2007 MBE4000, the differences in PM, THC, and CO were generally not statistically significant due to the low emissions levels from the DPF. For CO_2, between the two engines, about half of the formulations showed statistically significant differences. This included reductions for some of the higher blends that were on the order of 2% or less, consistent with the main test results, as well as some mixed results of increases in CO_2 emissions that would need to be verified with further testing. Fuel consumption was also higher for all the NO_x formulations, consistent with expectations, with increases ranging up to ~6% for the higher blend levels.

Toxicological Characterization – Chassis Testing Results:

The toxicity characterization phase of the study was conducted on the CARB MTA Heavy Duty Chassis Dynamometer testing facility. The vehicles tested were equipped with a 2000 Caterpillar C-15 engine and a 2007 MBE4000 engine. The testing included the baseline CARB diesel, two biodiesel feedstocks (one soy-based and one animal-based) tested on blend levels of B20, B50, and B100% and the renewable diesel fuel at a R20, R50 and R100 blend levels. The data were mostly collected for a UDDS test cycle, with carbonyls also being collected for the 50 mph Cruise test cycle. For the carbonyls, the 2006 ISM Cummins equipped was also tested.

- The results show that formaldehyde and acetaldehyde were the most prominent carbonyls consistent with previous studies. Acetone emissions were also prominent for the 2000 Caterpillar C-15. The carbonyl emissions for the 2000 Caterpillar C-15 and the Cummins ISM were considerably higher than those for the DPF-equipped 2007 MBE4000. There was also a trend of higher emissions for the UDDS than the 50-mph cruise for the 2000 Caterpillar C-15 and for formaldehyde and acetaldehyde for the 2007 MBE4000. This trend was not seen for the 2006 Cummins ISM. Overall, carbonyl emissions did not show any consistent trends between different fuels.
- Reactive carbonyl emissions - The results showed that certain reactive carbonyls were higher for the 2000 Caterpillar C-15 for the soy-based B50 and B100 and the animal-based B50 and B100 fuels, including acrolein. There were also trends of lower aromatic aldehyde emissions for the pure biodiesel fuels compared to CARB diesel. The reactive carbonyls did not show any differences for the renewable diesel relative to the CARB

diesel for the 2000 Caterpillar C-15. Overall, the reactive carbonyl emissions were much lower for the 2007 MBE4000 in comparison with the 2000 Caterpillar C-15.

- PAH emissions for the 2000 Caterpillar C-15 vehicle were investigated in the CARB diesel, the soy- and animal- based biodiesel, renewable diesel, and their respective blends with the CARB diesel (20% and 50%) over the UDDS cycle both in the particle and vapor-phases. They also were investigated for the 2007 MBE4000 vehicle for the CARB, soy biodiesel and their blends (20% and 50%). PAH emissions in both particle and in the vapor-phase decreased significantly for the 2007 MBE4000 compared to the 2000 Caterpillar C-15 vehicle. The reduction was close to two orders of magnitude. The result shows that the DPF for the 2007 MBE4000 was effective in reducing PAH emissions both in the particle and in the vapor-phase. PAH emissions for the 2000 Caterpillar C-15 vehicle decreased as a function of increasing blend level of soy biodiesel, animal-based biodiesel and renewable diesel. Emission reductions for different feedstocks were generally similar, except that the reduction in renewable diesel for particle associated PAHs was slightly lower than the reduction observed for the soy-and animal-based biodiesels. This may be explained by relatively higher PM emissions from renewable diesel compared to the soy or animal biodiesel. For the 2007 MBE4000 vehicle, the concentrations were orders of magnitude lower than for the 2000 Caterpillar C-15 vehicle, essentially masking any significant differences between CARB diesel, soy biodiesel, and the blends.
- Nitro-PAH emissions were measured in the same particle and vapor phase samples as for PAHs for the 2000 Caterpillar C-15 and 2007 MBE4000 vehicles. Nitro-PAH emissions in both the particle and vapor-phases also decreased significantly for the 2007 MBE4000 compared to the 2000 Caterpillar C-15 vehicle. They were detected in only very low concentrations for the 2007 MBE4000. Also, some artifact contribution can not be ruled out in the measurements obtained for the 2007 MBE4000, due to the NO_x present. The DPF for the 2007 MBE4000 was effective in reducing nitro-PAH emissions. Nitro-PAH emissions for the 2000 Caterpillar C-15 vehicle decreased as a function of increasing blend levels of soy biodiesel, animal-based biodiesel, and renewable diesel. Emission reductions for different feedstocks were similar. However, for semivolatile nitro-PAHs, the renewable diesel may be slightly more effective in emission reductions than soy- or animal-based biodiesels. For the 2007 MBE4000 vehicle, the low concentrations that were orders of magnitude lower than for the 2000 Caterpillar C-15 vehicle, essentially masked any significant differences between CARB diesel, soy biodiesel, and the blends.
- Oxy-PAH emissions over the UDDS cycle were investigated in the particle samples for the 2000 Caterpillar C-15 vehicle only. The results were obtained for the CARB diesel, the soy and animal- based biodiesel, renewable diesel, and their respective blends with the CARB diesel (20% and 50%), except the soy 100% biodiesel was not analyzed due to the sample availability. Emissions of some oxy-PAHs were as high as the volatile PAHs, and much higher than nitro-PAHs. The emission trends observed for biodiesel and renewable diesel were different for different compounds. For example, the results for 1,2-naphthoquinone (2-ring oxy-PAH) showed generally higher emissions in soy and animal-based biodiesels compared to CARB diesel, whereas perinaphthenone, 9-fluorenone, and 1,8-naphthalic anhydride (3-ring oxy-PAHs) emissions decreased in animal biodiesel and renewable diesel.

- Genotoxicity - Mutagen emissions – Mutagen emissions generally decreased as a function of increasing biodiesel blend level for the 2000 CaterpillarC-15 vehicle. For the 2000 Caterpillar C-15 PM samples, the TA98 strains (+ or – S9) were more sensitive than the TA100 strains for all fuels. The vapor phase samples showed lower mutagen emissions than the PM samples, and the TA100 strain measurements were slightly more sensitive. For the 2007 MBE4000 vehicle, the mutagen emissions, in general, were considerably lower for both particle and vapor-phase than emissions from the 2000 Caterpillar C-15 vehicle. The levels were orders of magnitude lower for the PM and many fold lower for the vapor-phase than the emissions from the 2000 Caterpillar C-15 vehicle.
- Inflammatory and oxidative response – CARB diesel, biodiesel, and renewable diesel all induced inflammatory markers, such as COX-2 and IL-8 in human macrophages and the mucin related MUC5AC markers in Clara type cells. In general, the emissions of the inflammatory markers were higher in the 2000 Caterpillar C-15 engine vehicle than the 2007 MBE4000 engine vehicle.
- Comet assay – At the limited dose levels tested, there was little increase of chromosomal damage (gross DNA damage) from the various fuels tested, including the CARB diesel.

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Appendix A – Full Fuel Properties

Table A-1 CARB ULSD and Renewable Diesel D975 Specifications

	Units	Test Method	CARB ULSD	NExBTL	GTL
Sulfur Content	Mass ppm	D5453-93	4.7	0.3	0.9
Total Aromatic Content	mass%	D5186-96	18.7	0.4	0.5
PAH	mass%	D5186-96	1.5	0.1	<0.27
Nitrogen Content	Mass ppm	D4629-96	0.8	1.3	<1
Natural Cetane #	Rating	D613-94	55.8	72.3	>74.8
Derived Cetane #	Index	IQT*		74.7	
Cetane Index	Index	D976	56.8	76.9	76.3
Gravity, API	API @ 60°F	D287-82	39.3	51.3	48.4
Viscosity	Mm2/sec @ 40°C	D445-83	2.7	2.5	3.6
Flash Point	°F	D93-80	148	146	98.5
Distillation		D86-96			
ibp			337	326	419
10%	°F		408	426	482
50%	°F		519	521	568
90%	°F		612	547	648
ep	°F		659	568	673
Cloud point	°C	D2500	-6.6	-27.1	-1
Pour Point	°C	D-97	-12	-47	-6
Ash	Mass %	D-482	<0.001%	<0.001	<0.001
Ramsbottom Residue		D524	0.03	0.02	0.023
Water and Sediment	mL	D1796	< 0.02	< 0.02	< 0.02
Conductivity	pS/m	D2624	55	135	10
Corrosion	3 hr @ 50°C	D130	1b	1a	1a

Table A-2 Neat Biodiesel ASTM 6751 Specifications

		Test Method	Soy-based	Animal based
Calcium & Magnesium	5 max ppm (ug/g)	EN 14538	<2	<2
Flash Point	93 oC min	D93	169.3	164.3
Kin. Viscosity, 40 oC	1.9-6.0 mm2/sec	D445	4.2	4.41
Sulfate Ash	0.02 max % mass	D874	0.0	0.000%
Sulfur S15	0.0015 max % mass ppm	D5453	0.7	2
Copper Corrosion	No. 3 max	D130	1a	1a
Cetane number	47 min	D613	47.7	57.9
Cloud Point	Report oC	D2500	0	12.5
Carbon Residue	0.05 max % mass	D4530	0.033%	0.015%
Acid Number	0.50 max mg KOH/g	D664	0.20	0.26
Free Glycerin	.020 % mass	D6854	0.001%	0.008%
Total glycerin	.240 % mass	D6874	0.080%	0.069%
Phosphorous	0.001 max % mass	D4951	<0.001%	<0.001%
Distillation, T90 AET	360 oC max	D1160	350	347.5
Na/K, combined	5 max ppm (ug/g)	EN 14538	<2	<2
water and sediment		D2709	<0.01	<0.01
API Gravity		D1298/D287	29	28.5
Oxidation Stability	3 hour min (6 hr min)	EN 14112	6.7	3.9
Visual Appearance**		D4176	1, 72F	1, 72F

*Ignition Quality Test **Free of un-dissolved water, sediment and suspended matter

Table A-3 Characteristics of Biodiesel Blends

		B5 - soy	B20 - soy	B50 - soy	B5 - animal	B20 - animal	B50 - animal
Flash Point, °C, min	ASTM D93	67.2	67.2	78.9	66.1	67.2	89.4
Water and sediment, vol%, max.	ASTM D2709 or D1796	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Physical Distillation, T90, °C, max	ASTM D86	624.1	635.1	641.1	627.5	633.6	637.4
Kinematic Viscosity, cST@40 °C	ASTM D445	2.828	2.969	3.384	2.855	3.038	3.508
Ash, mass%, max	ASTM D482	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Sulfur, ppm, max	ASTM D5453	3.2	2.5	2.2	3.8	3.7	3.8
Copper strip corrosion	ASTM D130	1B	1A	1B	1A	1A	1B
Cetane Number, min.	ASTM D613	56	55.4	56	58.4	59.8	59.7
Cloud point[2]	ASTM D2500	-16	-15	-1	-15	-14	2
Ramsbottom carbon residue 10% distill. residue, wt%, ma	STM D524	0.05	0.07	0.07	0.06	0.06	0.05
Acid number, mg KOH/g, max.	ASTM D664	<0.05	<0.05	0.07	<0.05	<0.05	0.11
Phosphorus, wt%, max.	ASTM D4951	<5	<5	<5	<5	<5	<5
FAME Content (IR)	EN 14078	5.3	20.8	52.5	5.4	21.2	52.8
Oxidation Stability, Induction time, hours min	EN14112 (Rancimat)	12	12	12	12	12	12

Table A-4 Characteristics of Renewable Diesel Blends

	TEST		R-20 Bio-Diesel	R-50 Bio-Diesel	GTL50
Sulfur	D5453	ppm	3.1	2.1	
Cetane Number	D613		59.3	65.0	61.5*
Total Aromatics	D5186	Mass%	15.2	10.2	
PolyArom		Mass%	1.2	0.9	
API_60F	D287	degAPI	41.7	45.1	
SPGr@60F	D4052s		0.82	0.80	
Copper	D130		1a	1a	
Wat_Sed1	D1796	ml	< 0.02	< 0.02	
Cloud Pt	D2500	Deg C	-15.0	-18.0	
EConduct	D2624	pS/m	23.3	38.3	
Temperat		deg C	21.1	21.1	
Viscosty	D445 40c	cSt	2.7	2.8	
Nitrogen	D4629	ppm	<1.0	<1.0	
Ash	D482	mass %	0.0	0.0	
RamsBottom	D524_10%	wt%	0.0	0.0	
IBP	D86	degF	345.0	337.2	
FBP		degF	656.5	637.7	
D10		degF	419.4	425.0	
D50		degF	521.7	523.3	
D90		degF	605.2	583.4	
Flash Point	D93	degF	153.3	145.7	
Pour Point	D97	Deg C	-18.0	-24.0	
Cetane Index	D976		60.0	66.3	

* 50% GTL blend with a CARB basefuel with a 46.7 cetane number

Appendix B – Development of the Light Load UDDS and CARB Heavy Heavy-Duty Diesel Truck Engine Dynamometer Test Cycles

Collection of Data on Engine Operating Parameters

The light load UDDS and the heavily loaded 40 mph CARB heavy heavy-duty diesel truck (HHDDT) cruise cycles for the 2006 Cummins ISM and the light load UDDS and the heavily loaded 50 mph CARB heavy heavy-duty diesel truck (HHDDT) cruise cycles for the 2007 MBE4000 were both developed from engine operating parameters. The engine operating parameters were obtained by operating the test vehicle with the specific engine installed on a chassis dynamometer while recording the J1939 signal from the engine ECM. This allowed the development on an engine dynamometer test cycle that had a direct correspondence to the loads the engine would experience when operated on a chassis dynamometer.

The 2006, 11 liter Cummins ISM was equipped in an International truck chassis. This truck had an empty weight of 13,200 lbs. and a fully loaded capacity of 66,000 lbs. The 2007, 12.8 liter MBE4000 was equipped in an Freightliner truck chassis. This truck had an empty weight of 16,270 lbs. and a fully loaded capacity of 57,490 lbs.

The chassis dynamometer test cycles were run at CARB's Heavy-Duty Vehicle Emissions Testing Laboratory in Los Angeles, CA. The vehicles were operated over the appropriate chassis cycles while the J1939 signal was collected to obtain the engine parameters. The "light" UDDS was run with the truck loaded to its empty weight, without a trailer. For the 40 and 50 mph CARB cruise cycle, the truck was loaded on the dynamometer to its fully loaded capacity.

A total of at least 7 iterations were performed for each test cycle to obtain a sufficiently robust data set for the development of the engine dynamometer test cycles. During each test run, regulated and standard gas phase data were collected including NMHC, CO, NO_x, and CO_2.

Description of the test cycles

The speed/time traces for the UDDS, the 40 mph CARB cruise cycle, and the 50 mph CARB cruise cycle are provided below in Figures B-1, B-2, and B-3, respectively. Federal heavy-duty vehicle Urban Dynamometer Driving Schedule (UDDS) is a cycle commonly used to collect emissions data on engines already in heavy, heavy-duty diesel (HHD) trucks. This cycle covers a distance of 5.55 miles with an average speed of 18.8 mph and maximum speed of 58 mph.

The CARB Heavy Heavy-Duty Diesel Truck (HHDDT) 40 mph Cruise schedule is part of a four mode test cycle developed for chassis dynamometer testing by the California Air Resources Board with the cooperation of West Virginia University. This cycle covers a distance of 23.1 miles with an average speed of 39.9 mph and maximum speed of 59.3 mph.

The CARB Heavy Heavy-Duty Diesel Truck (HHDDT) 50 mph Cruise schedule was developed for chassis dynamometer testing by the California Air Resources Board with the cooperation of West Virginia University. This cycle covers a distance of 10.5 miles with an average speed of 48.9 mph and maximum speed of 66.9 mph.

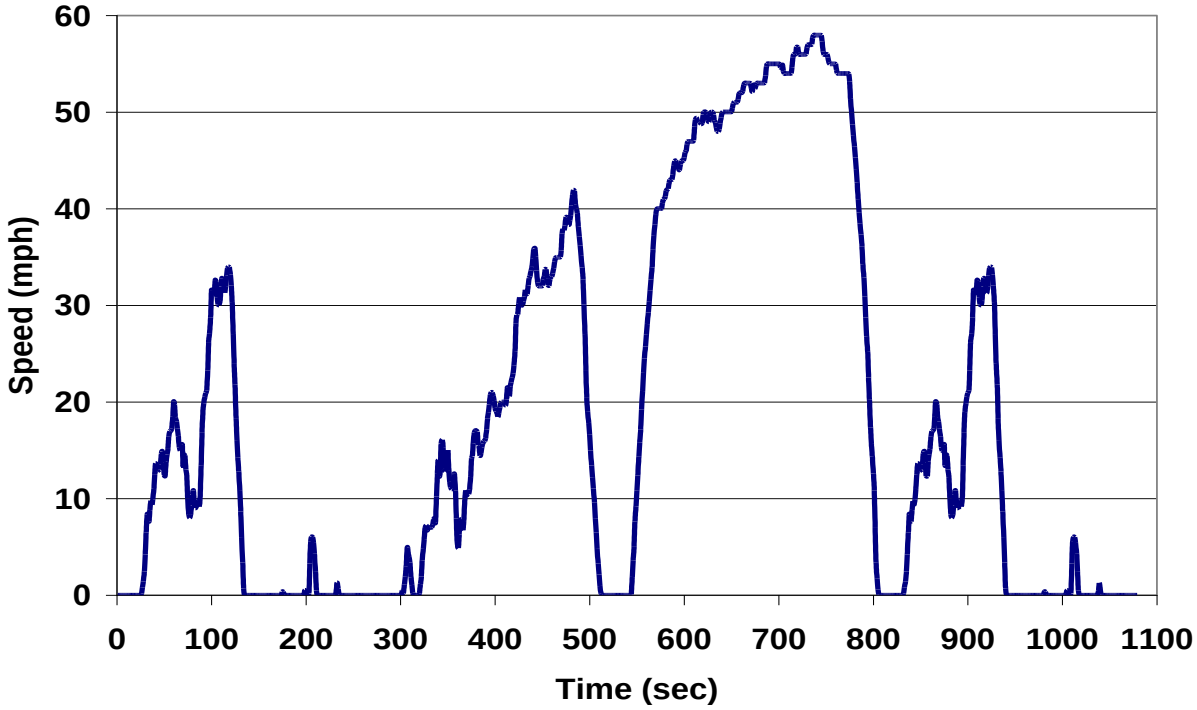


Figure B-1. Speed/Time Trace for UDDS cycle for the chassis dynamometer.

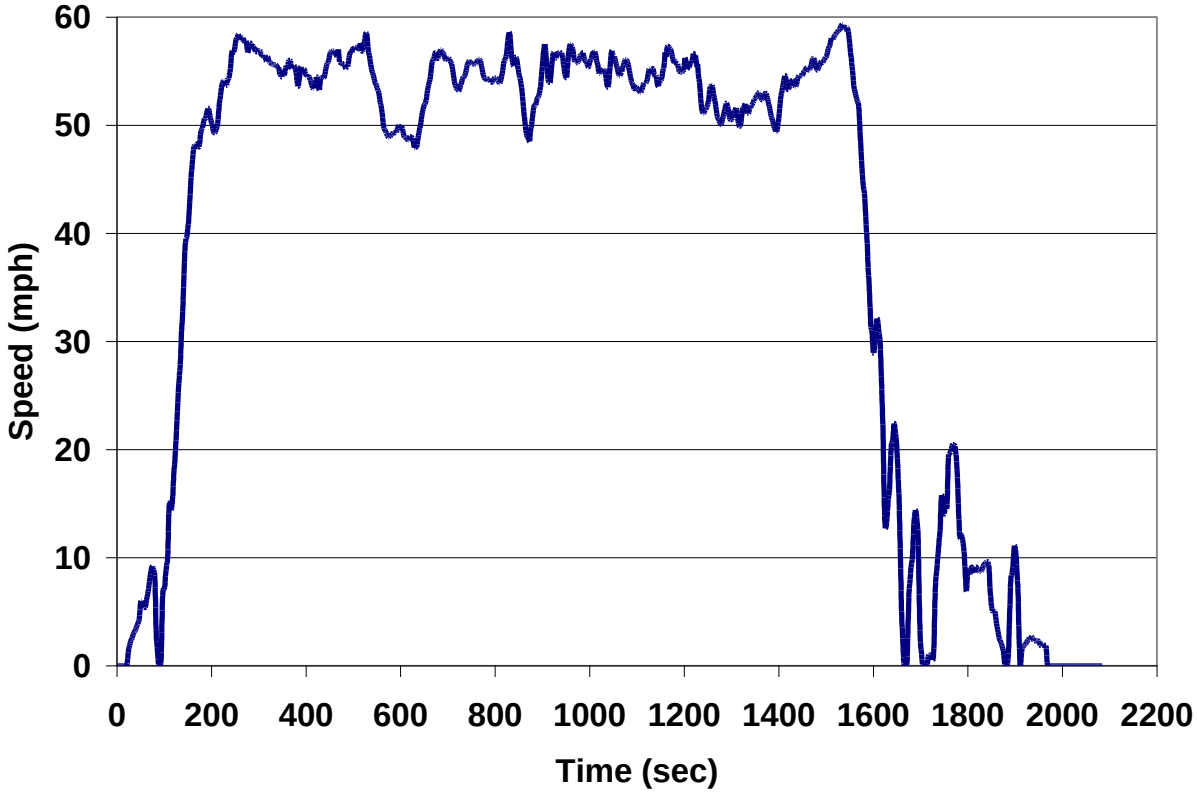


Figure B-2. Speed/Time Trace for the 40 mph CARB Cruise cycle for the chassis dynamometer.

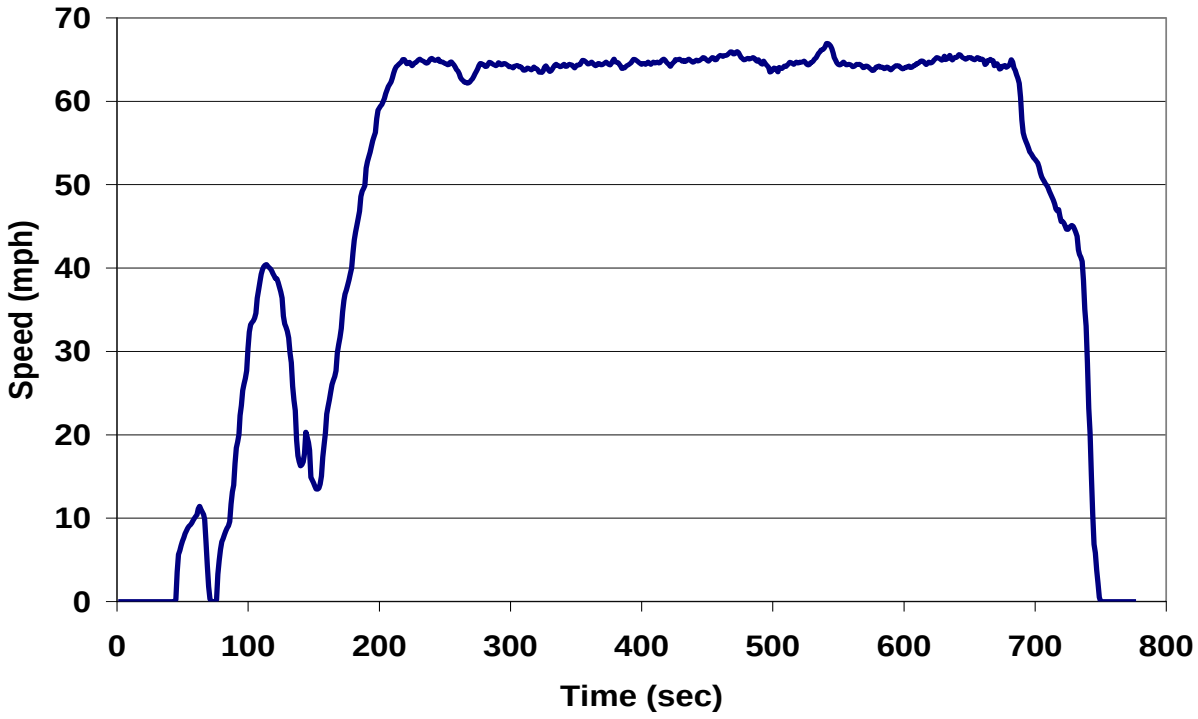


Figure B-3. Speed/Time Trace for the 50 mph CARB Cruise chassis dynamometer cycle.

Initial Development of the Engine Dynamometer Test Cycles

The engine dynamometer cycles were developed from the engine speed and torque values from the J1939 data stream. Initially, the engine speed and torque were averaged over all of the test iterations. It was found that slight differences in time alignment between different test iterations resulted in differences in the exact location of the peaks in torque and engine speed. Specifically, the engine parameters would be near a peak in load for one cycle, while the loads for other test cycles would be lower at the same point. As such, the peaks in engine speed and torque could not be adequately represented with a cycle based solely on averaging.

It was decided instead to utilize a single test iteration that was determined to be most representative of the test run series on each cycle. Two main criteria were used in selecting the most representative set of engine parameters for the cycle development.

--- NO_x emissions for the corresponding chassis test set compared with the average value.
--- CO_2 emissions for the corresponding chassis test set compared with the average value.

Since NO_x is the most important parameter of interest for the engine dynamometer testing, engine parameter data sets where the NO_x emissions differed by more than one standard deviation from the mean value were excluded from consideration. From the remaining cycles, the cycle that was most representative of the average NO_x and CO_2 values was selected, with an emphasis on NO_x emissions that were comparable to the average value.

Once the most representative engine parameter data set was selected, the engine RPM and torque

values were normalized to develop the engine cycle. The torque values were normalized from 0 to 100% for the maximum torque value based on the reference torque, the actual torque from the J1939 signal, and the frictional torque from the J1939 signal. Engine RPM was normalized from 0 to 100%, where 0 represents idle and 100% represents the maximum engine speed.

Testing and Final Development of Engine Dynamometer Test Cycles

The engine dynamometer test cycles were initially run on the dynamometer without any modification to evaluate how well the cycles could be followed on the engine dynamometer and to provide a comparison with the regression parameters currently used for the FTP. With these initial tests, the cruise cycle showed reasonable agreement between the torque and rpm set points, but the light-duty UDDS showed a greater deviation from the set points than is typically seen for the FTP. The cycle did not meet the regression criteria used for the standard FTP and visual comparisons showed that the measured torque did not follow the setpoint torque during segment of the cycle associated with gearshifts. In an effort to improve the performance of the cycle on the engine dynamometer, additional tests were conducted with varying settings of the dynamometer controls, such as throttle response.

These issues are similar to those identified in the development work for the cycles for the ACES program, and can be attributed to the use of a clutch in the actual vehicle that removes the inertia load from the engine during gearshifting. Since the engine driveshaft is directly coupled to the dynamometer, this decoupling of the engine driveline can not be simulated on the engine dynamometer. As such, these events were considered to be representative of the behavior that can be expected when translating engine parameters between a vehicle chassis and an engine dynamometer.

To improve the operation of the cycles on the engine dynamometer, the cycles were modified slightly after the initial runs. Specifically, the rpm and torque values were set to zero for period of the cycle where the engine was in an idling segment. This eliminated small variations in rpm that occur near the idle point in real operation and small torque values that would likely be associated with auxiliary equipment when the engine was operating in the chassis.

For the 2006 Cummins ISM, the normalized cycles in their final form are presented in Figures B-4 and B-5, respectively, for the light UDDS and 40 mph cruise cycles. The normalized cycles in their final form for the 2007 MBE4000 are presented in Figures B-6 and B-7, respectively, for the light UDDS and 50 mph cruise cycles.

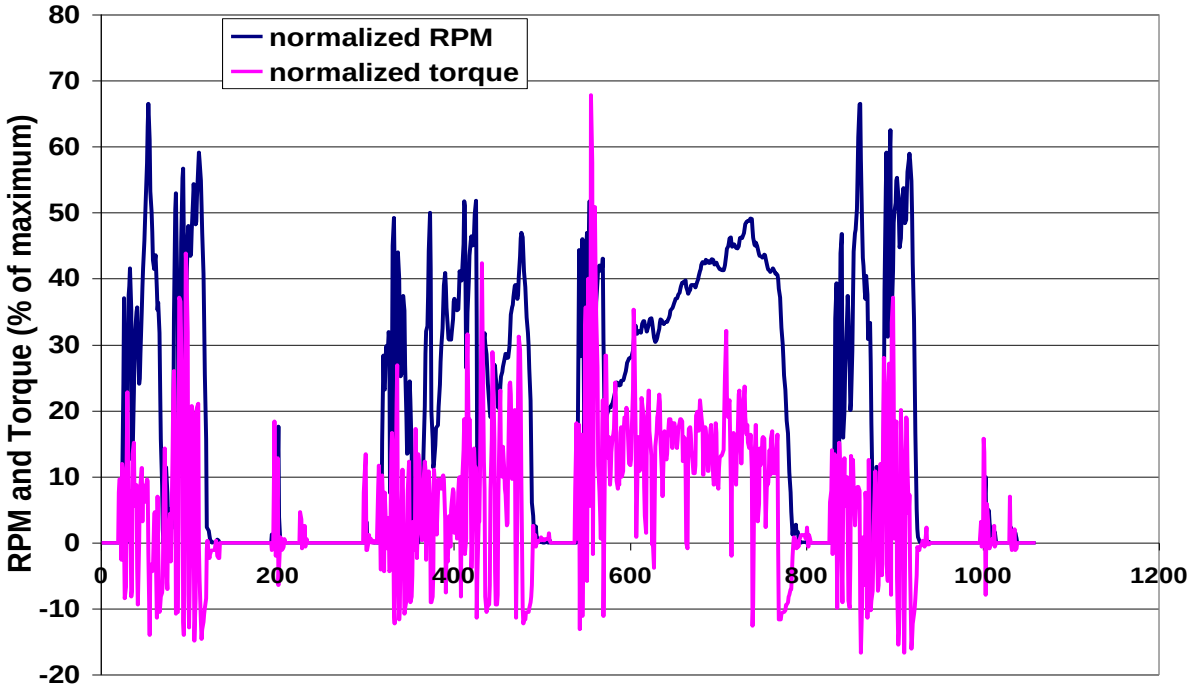


Figure B-4. "Light-Duty" UDDS Engine Dynamometer Test Cycle for the 2006 Cummins ISM

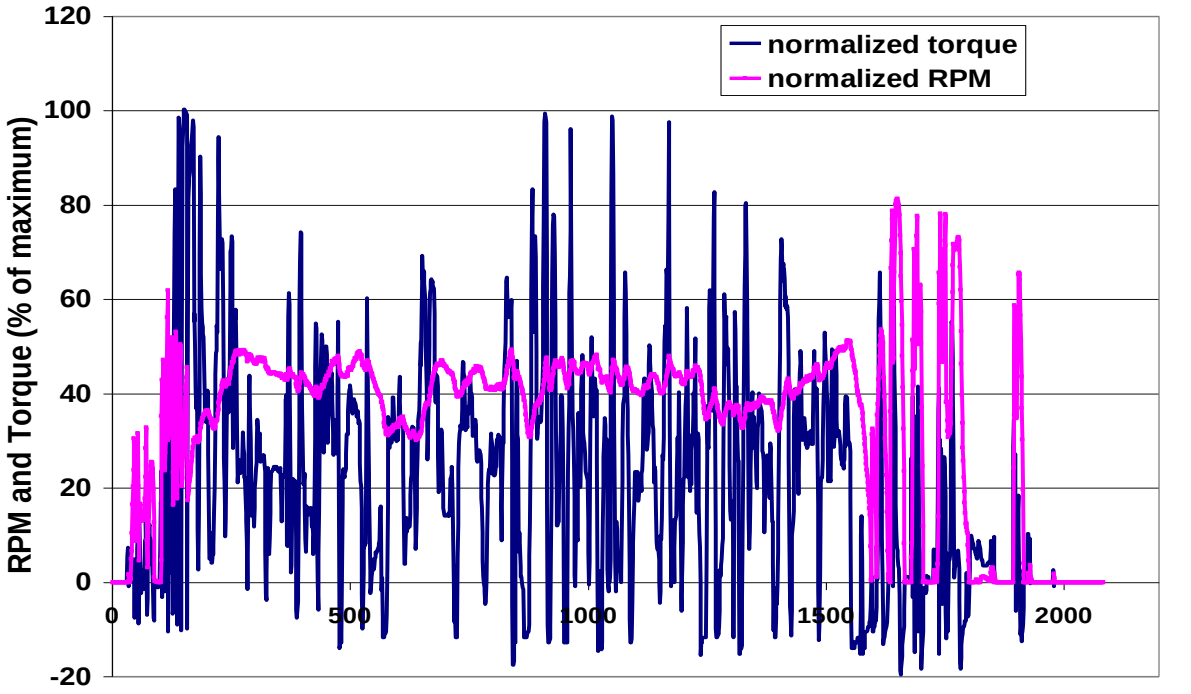


Figure B-5. 40 mph CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Cruise for the 2006 Cummins ISM

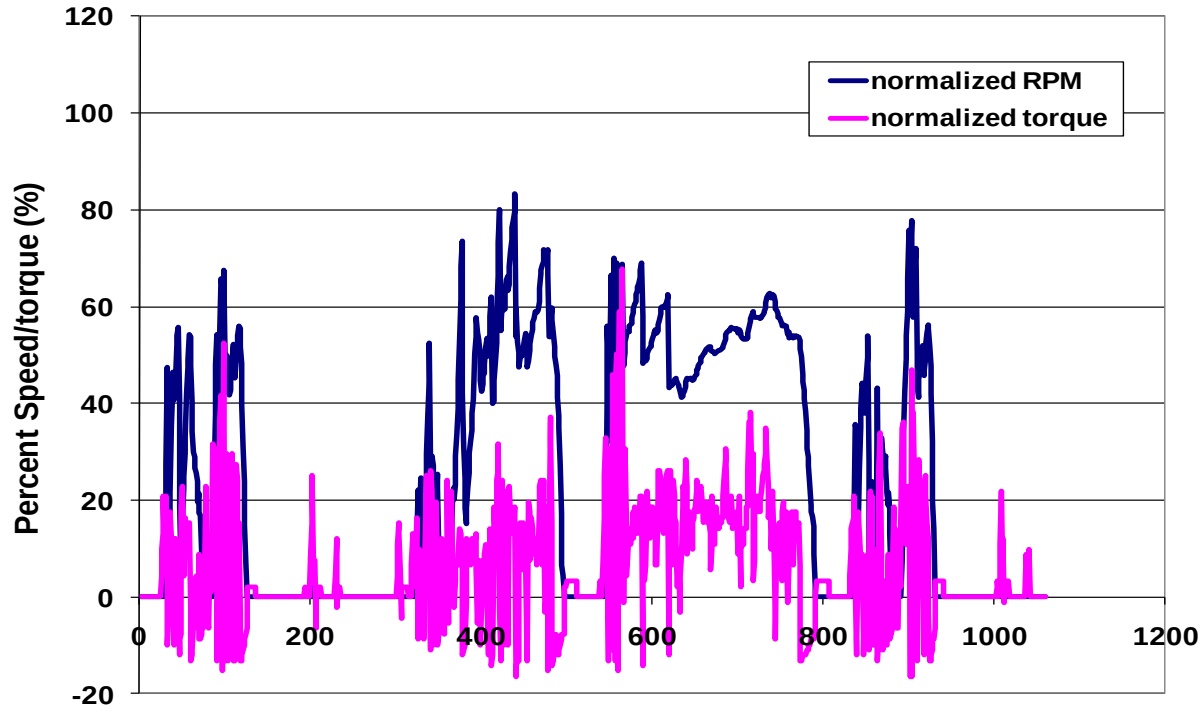


Figure B-6. "Light-Duty" UDDS Engine Dynamometer Test Cycle for the 2007 MBE4000

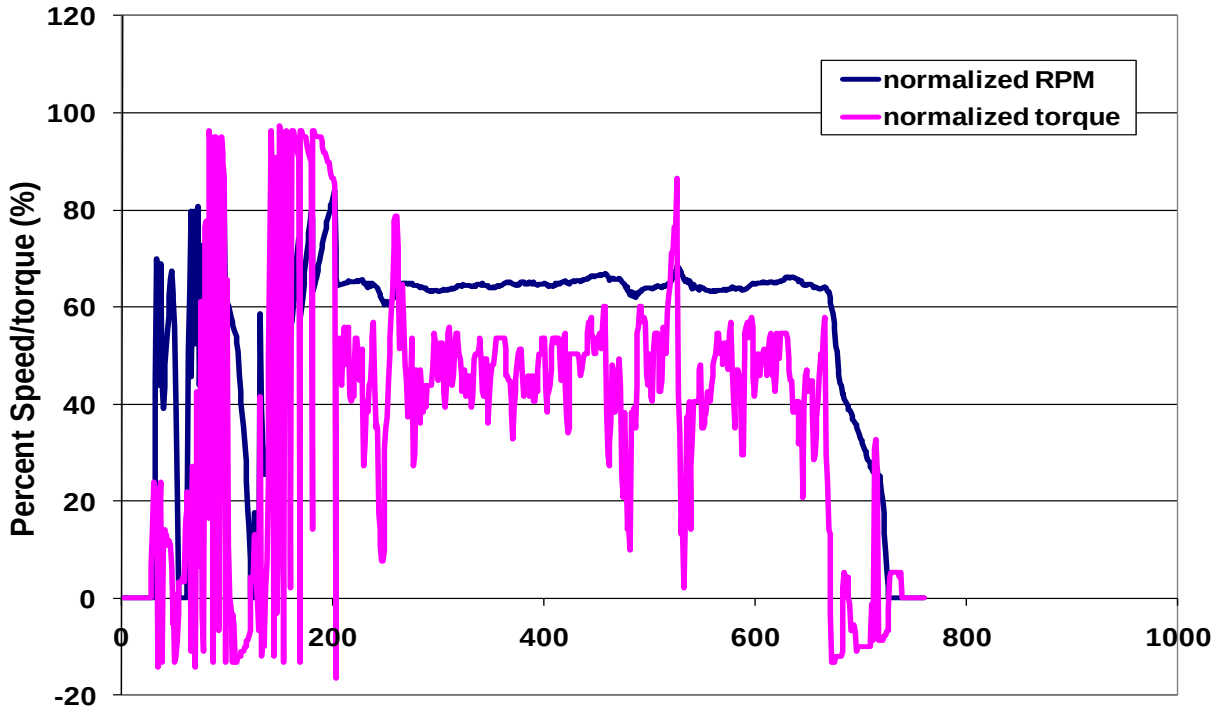


Figure B-7. 50 mph CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Cruise for the 2007 MBE4000

For the 2006 Cummins ISM, the 50 mph cruise cycle was initially not incorporated into the test program, so chassis dynamometer data for this specific vehicle were not available. Since logistics of replacing the engine back into the vehicle to generate the J1939 data for this specific engine were too impractical, an engine dynamometer test cycle version of this cycle that was developed for the ACES program was utilized (Clark et al., 2007). This cycle was developed from data collected through the E55/59 chassis dynamometer study of heavy-duty trucks. The engine rpm/torque profile for the 50 cruise engine dynamometer test cycle that was used is provided in Figure B-8.

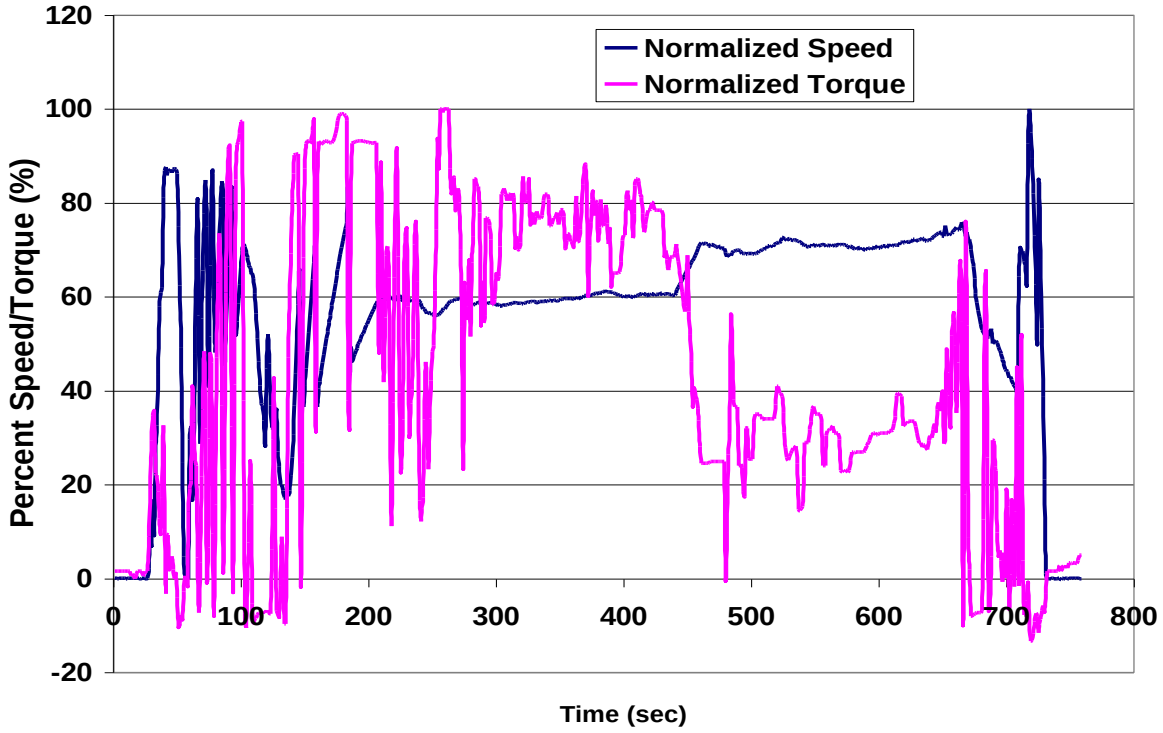


Figure B-8. 50 mph CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Cruise for the 2006 Cummins ISM

Regression Statistics

Since the two developed cycles were inherently different from the FTP, new regression statistics were developed for each cycle. The new regression statistics were developed based on replicate runs of the cycles and comparisons between the regression runs for these cycles and those used for the FTP.

The techniques used for the development of the new regression statistics were similar to those used in the ACES program cycle development. The new regression statistics were scaled to comparable values for the FTP based on the tolerance, or how closely the parameter was met for the standard FTP. The equations utilized for these comparisons were the same as those utilized in the ACES programs, as provided below. In essence, these equations provide the same margin of error on a percentage basis for the new cycles, as is typically utilized in the FTP. These were utilized in cases where greater tolerance was needed for the statistics than is typically given in

the FTP. In cases where the FTP regression statistics could be readily met without modification, the standard FTP criteria were maintained.

$$X_{upper} = \left(\frac{EPA_{upper} - FTP_{actual}}{FTP_{actual}} \right) \cdot actual + actual$$

$$X_{lower} = -\left(\frac{FTP_{actual} - EPA_{lower}}{FTP_{actual}} \right) \cdot actual + actual$$

In the case of the intercept for the power, examination of the data indicated that the power intercept was slightly greater than that for the FTP for the UDDS and cruise, but that the tolerance in this statistic could still be readily met by simply doubling the value of the intercept used in the FTP. A comparison of the FTP regression statistic criteria with the values obtained for the developed cycles is provided in Table B-1 for the 2006 Cummins ISM and in Table B-2 for the 2007 MBE4000.

Table B-1. Comparison of regression statistics criteria for the FTP with values obtained for the UDDS and Cruise. Shaded areas indicate criteria where the values were greater than those for the FTP and were modified for the regression criteria.

		Speed				Torque				Power			
		Slope	Intercept	SteYX	Rsq	Slope	Intercept	SteYX	Rsq	Slope	Intercept	SteYX	Rsq
FTP	upper	1.03	50	100	1	1.03	15	188.5	1	1.03	5	30.95	1
	lower	0.97	-50	0	0.97	0.83	-15	0	0.88	0.89	-5	0	0.91
UDDS	upper	1.03	41.8	44.1	1.00	0.91	28.9	108.1	0.880	0.92	30.4	13.9	0.89
	lower	0.97	-41.8	0	0.97	0.74	-28.9	0	0.775	0.79	-30.4	0	0.81
Cruise	upper	1.03	-7.9	44.1	1.00	1.05	22.2	153.8	1.01	1.02	26.6	21.7	0.99
	lower	0.97	7.9	0.0	0.97	0.84	-22.2	0.0	0.89	0.88	-26.6	0.0	0.90

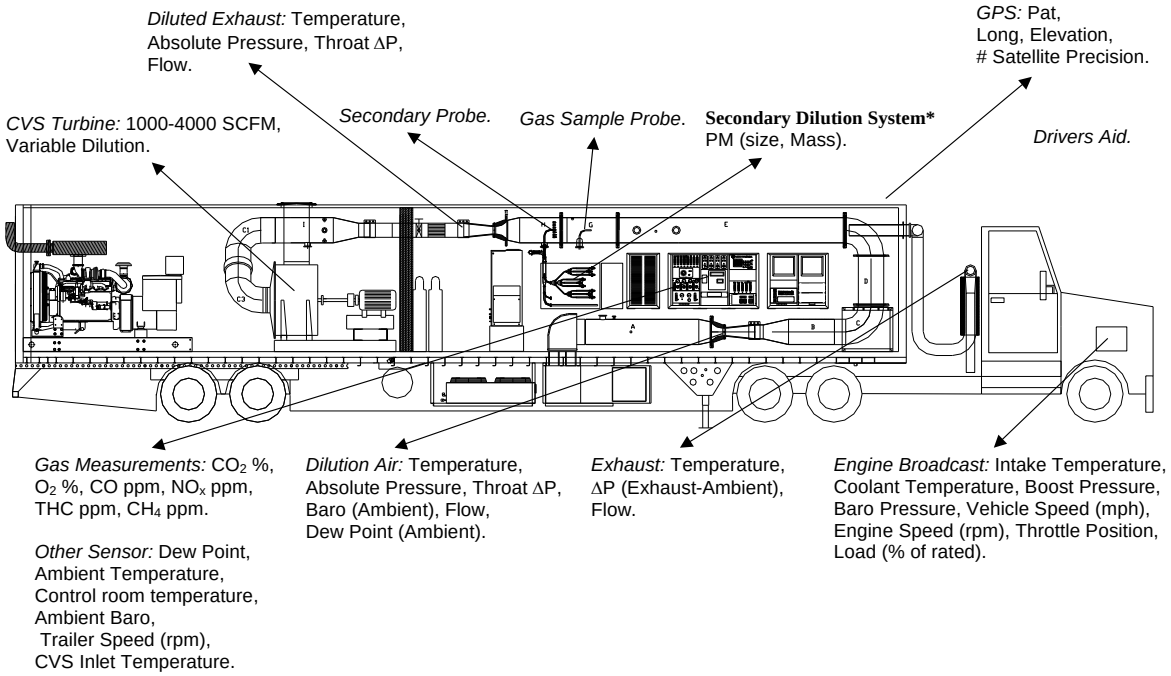
value doubled

Table B-2. Comparison of regression statistics criteria for the FTP with values obtained for the UDDS and Cruise. Shaded areas indicate criteria where the values were greater than those for the FTP and were modified for the regression criteria.

		Speed				Torque				Power			
		Slope:	Intercept:	SteYX:	Rsq:	Slope:	Intercept:	SteYX:	Rsq:	Slope:	Intercept:	SteYX:	Rsq:
FTP	upper	1.03	50	100	1	1.03	15	188.5	1	1.03	5	30.95	1
	lower	0.97	-50	0	0.97	0.83	-15	0	0.88	0.89	-5	0	0.91
UDDS	upper	1.04	64.7	136.3	1.00	0.92	21.9	157.0	0.768	0.96	8.8	16.3	0.93
	lower	0.98	-64.7	0	0.97	0.74	-21.9	0	0.676	0.83	-8.8	0	0.84
Cruise2	upper	1.03	38.2	75.3	1.00	1.00	62.3	165.9	0.99	1.02	35.5	26.8	0.99
	lower	0.97	-38.2	0.0	0.97	0.81	-62.3	0.0	0.87	0.88	-35.5	0.0	0.90
										valued doubled to 10			

Appendix C – Background Information on UCR's Mobile Emission Lab

Extensive detail is provided in (Cocker, et al., 2004a,b) so this section is provided for those that may not have access to that reference. Basically the mobile emissions lab (MEL) consists of a number of operating systems that are typically found in a stationary lab. However the MEL lab is on wheels instead of concrete. A schematic of MEL and its major subsystems is shown in the figure below. Some description follows.



Major Systems within the Mobile Emission Lab

The primary dilution system is configured as a full-flow constant volume sampling (CVS) system with a smooth approach orifice (SAO) venturi and dynamic flow controller. The SAO venturi has the advantage of no moving parts and repeatable accuracy at high throughput with low-pressure drop. As opposed to traditional dilution tunnels with a positive displacement pump or a critical flow orifice, the SAO system with dynamic flow control eliminates the need for a heat exchanger. Tunnel flow rate is adjustable from1000 to 4000 scfm with accuracy of 0.5% of full scale. It is capable of total exhaust capture for engines up to 600 hp. Colorado Engineering Experiment Station Inc. initially calibrated the flow rate through both SAOs for the primary tunnel.

The mobile laboratory contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical instruments measure NO_x, methane (CH_4), total hydrocarbons (THC), CO, and CO_2 at a frequency of 10 Hz and were selected based on optimum response time and on road stability. The 200-L Tedlar bags are used to collect tunnel and dilution air samples over a

complete test cycle. A total of eight bags are suspended in the MEL allowing four test cycles to be performed between analyses. Filling of the bags is automated with Lab View 7.0 software (National Instruments, Austin, TX). A summary of the analytical instrumentation used, their ranges, and principles of operation is provided in the table below. Each modal analyzer is time-corrected for tunnel, sample line, and analyzer delay time.

Summary of gas-phase instrumentation in MEL

Gas Component	Range	Monitoring Method
NO_x	10/30/100/300/1000 (ppm)	Chemiluminescence
CO	50/200/1000/3000 (ppm)	NDIR
CO_2	0.5/2/8/16 (%)	NDIR
THC	10/30/100/300/1000 & 5000 (ppmC)	Heated FID
CH_4	10/30/100/300/1000 & 5000 (ppmC)	Heated FID

.

Appendix D – Quality Assurance/Quality Control

Internal calibration and verification procedures are performed regularly in accordance with the CFR. A partial summary of routine calibrations performed by the MEL as part of the data quality assurance/quality control program is listed in Table D-1. The MEL uses precision gas blending to obtain required calibration gas concentrations. Calibration gas cylinders, certified to 1 %, are obtained from Scott-Marrin Inc. (Riverside, CA). By using precision blending, the number of calibration gas cylinders in the lab was reduced to 5 and cylinders need to be replaced less frequently. The gas divider contains a series of mass flow controllers that are calibrated regularly with a Bios Flow Calibrator (Butler, New Jersey) and produces the required calibration gas concentrations within the required $\pm$1.5 percent accuracy.

In addition to weekly propane recovery checks which yield >98% recovery, CO_2 recovery checks are also performed. A calibrated mass of CO_2 is injected into the primary dilution tunnel and is measured downstream by the CO_2 analyzer. These tests also yield >98% recovery. The results of each recovery check are all stored in an internal QA/QC graph that allows for the immediate identification of problems and/or sampling bias.

Table D-1. Summary of Routine Calibrations

EQUIPMENT	FREQUENCY	VERIFICATION PERFORMED	CALIBRATION PERFORMED
CVS	Daily	Differential Pressure	Electronic Cal
	Daily	Absolute Pressure	Electronic Cal
	Weekly	Propane Injection	
	Monthly	CO_2 Injection	
	Per Set-up	CVS Leak Check	
	Second by second	Back pressure tolerance ±5 inH_20	
Cal system MFCs	Annual	Primary Standard	MFCs: Drycal Bios Meter
	Monthly	Audit bottle check	
Analyzers	Pre/Post Test Daily Monthly	 Zero span drifts Linearity Check	Zero Span
Secondary System Integrity and MFCs	Semi-Annual	Propane Injection: 6 point primary vs. secondary check	
	Semi-Annual		MFCs: Drycal Bios Meter & TSI Mass Meter
Data Validation	Variable	Integrated Modal Mass vs. Bag Mass	
	Per test	Visual review	
PM Sample Media	Weekly	Trip Tunnel Banks	
	Monthly	Static and Dynamic Blanks	
Temperature	Daily	Psychrometer	Performed if verification fails
Barometric Pressure	Daily	Aneroid barometer ATIS	Performed if verification fails
Dewpoint Sensors	Daily	Psychrometer Chilled mirror	Performed if verification fails

Appendix E – Additional Information on the Outliers

For the 2006 Cummins ISM, the 50 mph CARB HHDDT cycles showed emissions at two distinct levels during the 300-400 second period of the cycle, as discussed in section 2.7. A summary table showing the number of tests exhibiting the low vs. the high level are shown in Table E-1.

Table E-1. Breakdown of 50 mph Cruise Cycle Tests for "High" vs. "Low" Tests.

	Low-level Tests	High-level Tests	Total Tests
CARB	10	22	32
B5-soy	3	3	6
B20-soy	5	1	6
B20-animal	6	0	6
R20-renewable	6	0	6
B50-soy	4	2	6
B50-animal	5	1	6
R50-renewable	6	0	6
B100-soy	2	4	6
B100-animal	5	1	6
R100-renewable	6	0	6
Totals	58	34	92

The impact of this event on emissions over the full cycle was characterized for each of the primary testing segments of the testing. The differences in the high/low emissions are summarized in Table E-2 for the CARB base fuel for the different testing segments. The primary impact in the regulated emissions was an increase in NO_x emissions, which ranged from 4.0 to 7.4% over the different test periods. The results also show that the fuel consumption and other regulated emissions such as THC, CO, and PM tend to be reduced for the tests with the corresponding higher NO_x emissions.

Table E-2. Impact of Outlier Events on Total Cruise Cycle Emissions for Each Test Period

Testing Segment	THC	CO	NO_x	PM	CO_2	BSFC
Soy-based	-1.4%	-6.8%	7.4%	-6.2%	-1.5%	-1.5%
Animal-based	-4.2%	-4.6%	5.4%	-4.3%	-2.4%	-1.9%
Renewable-based	-1.0%	-2.4%	4.0%	-1.5%	-0.7%	-0.7%

The percentages are the difference between all CARB tests with the high NO_x emissions and those with the low NO_x emissions

The changes in engine operation can be seen directly in the various engine parameters. The fuel consumption measurements show a reduction in fuel use over the 300-400 seconds segment for the tests showing NO_x at the high level. Figure E-1 shows various independent measures of the fuel used, including the fuel rate from the dynamometer, the ECM and the CO_2 emissions, all showing the differences in fuel use over the relevant period.

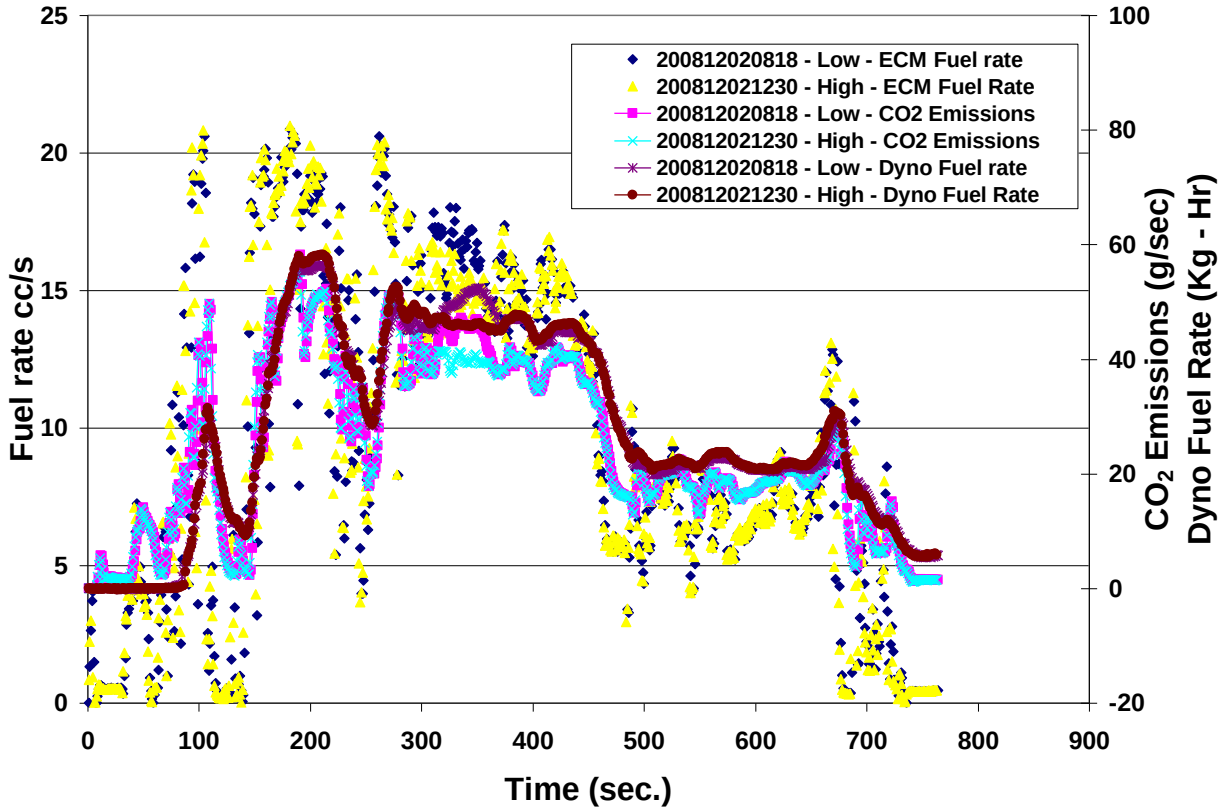


Figure E-1. Real-time Measurements of Fuel Use from the Engine ECM the Dynamometer Measurements and the CO_2 Emissions.

The engine load, as measured by the ECM, also shows a distinct difference during the 300-400 second period. This is shown in Figure E-2, which shows the ECM "seeing" the engine load at two different points during this period. It should be noted that the actual load, as measured off the engine dynamometer does not vary over this same period, indicating that the ECM is inferring a different load based on a full range of engine parameters.

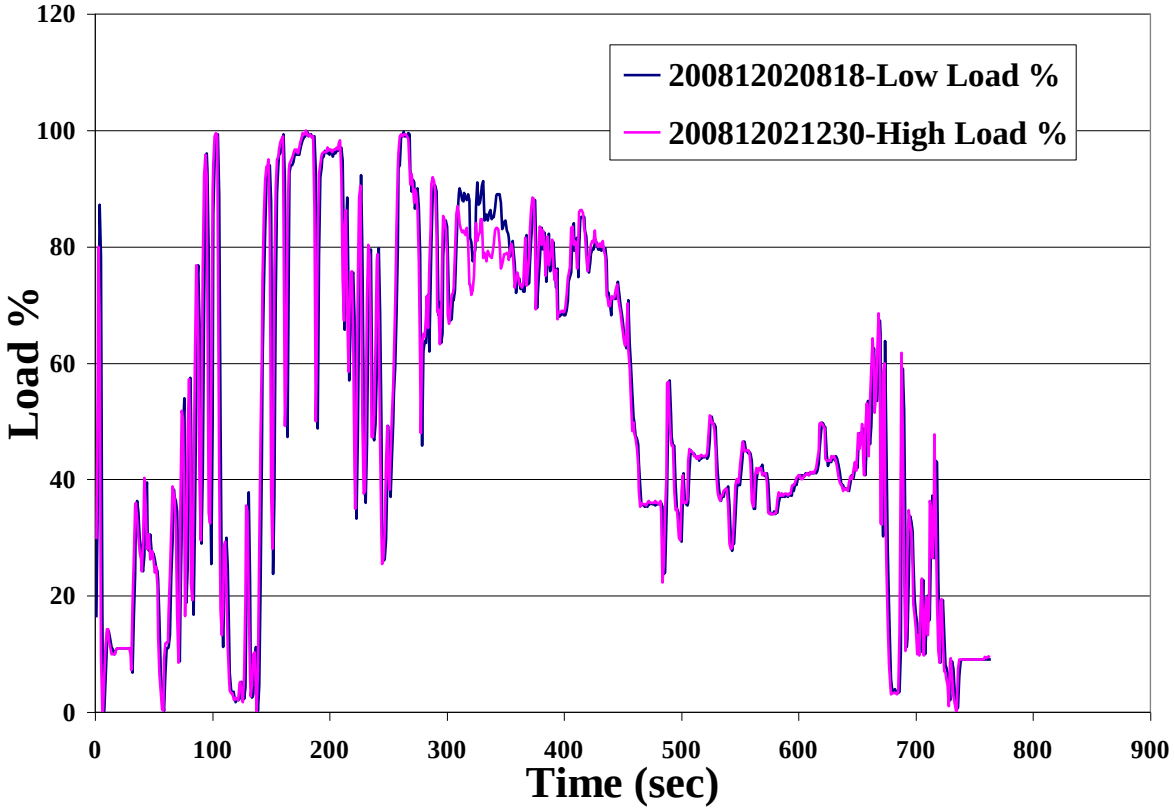


Figure E-2. Percentage Load from the ECM during a High and Low Cruise-2 Test.

Finally, the boost pressure shows differences during this same period, with the boost pressure higher for the test showing low NO_x emissions, and correspondingly lower for the tests showing higher NO_x emissions. This is shown for both the ECM and the dynamometer measurements in Figure E-3.

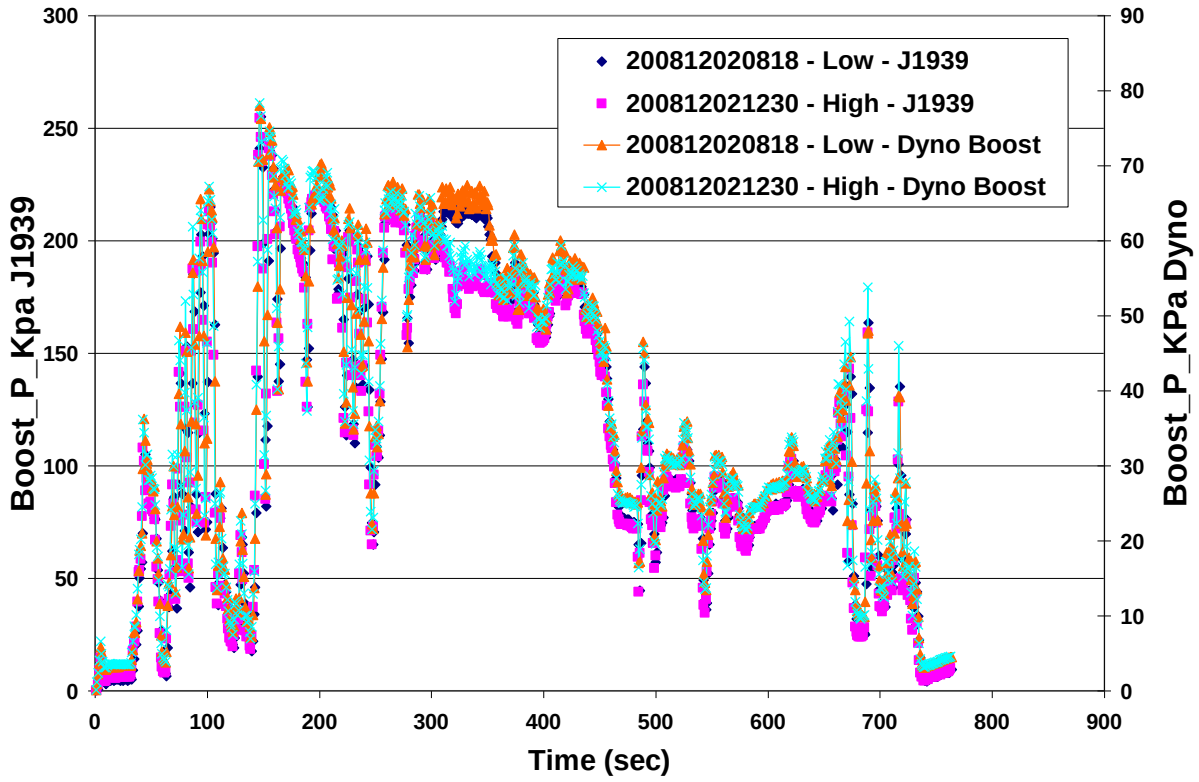


Figure E-3. Real-time Boost Pressure Readings from the ECM and the Dynamometer Measurements.

Appendix F-Quality Insurance/ Quality Control of Reactive Carbonyls

Quality Control Program for Reactive Carbonyls-Mist Chamber:
Acrolein is a notoriously difficult chemical to quantify due to its high reactivity. Therefore, this project had several quality control mechanisms to ensure the accuracy of the results.

Enrichment of all samples with deuterated acrolein, acetalydehyde, benzaldehyde and glyoxal:
All sample solutions were enriched with isotopically labeled acrolein-d_4, acetaldehyde-d_4, benzaldehyde-d_6 and glyoxal-d_2 prior to sample collection. These deuterated compounds were designed to account for chemical loss due to volatilization, degradation or incomplete derivatization. These internal standards were also added to all blanks and calibration standards at the same concentrations as the samples.

Calibration Curves Prepared in the Field:
Calibration curves were prepared from stock solutions in the field for each field sampling episode. The derivatization procedure is sensitive to the duration of the derivatization, thus it was decided that is would be the most accurate to prepare the calibration curve in the field and store it with the samples. The calibration curve was prepared by adding a small amount of the standard mix (0, 1, 3, 10, 30 and 100μL) to a randomly-selected set of bisulfite solutions. One of the "standards" had no chemicals added, other than the internal standard mixture, and thus it provided a reagent blank.

Replication of Standard Analysis during Instrumental Analysis:
Mass spectrometers are sensitive instruments that are subject to drift from sample contamination. To identify possible instrumental drift, all sample analyses were bracketed by a calibration curve at the beginning of the sample run and at the end of the sample run. Consistency between these two calibration curves proves the lack of instrumental drift during the sample analysis run. Furthermore, calibration standards were analyzed every 6 to 8 field samples to monitor for drift. The results showed that no significant instrument drift occurred during the sample analyses in this study.

Dual Quantification of Acrolein:
The derivatization agent, namely pentafluorohydroxylamine (PFBHA), contains a double bond at the site of attachment. Therefore, most of the carbonyls give two peaks in the chromatogram corresponding to the *cis*- and *trans*- isomers. For most of the carbonyls, the base ion in the larger of the two peaks was used for quantification.

The quantification of acrolein was conducted slightly differently. The main quantification was conducted using the base ion (*m*/*z* 231) in the larger of the two isomer peaks as with the other carbonyls, but this quantification was "double-checked" by quantifying a different ion (*m*/*z* 251) in the smaller isomer peak. If the two quantification measures provided similar results, then we had a great deal of confidence that peaks observed were due to acrolein and not an interfering compound. Therefore, acrolein was quantified using the larger peak and confirmed using a

different quantification ion in the smaller peak. Qualifying ions were also used in both peaks to ensure the identity of the peaks.

Consistency of Acrolein Standards:

Acrolein is notoriously unstable and the standards might degrade during a long project such as this one even when stored under ideal conditions (diluted in acetonitrile, sealed in amplules and frozen at -20 °C). Therefore, a brand new standard was purchased at the end of the study and compared to the standards used during the study. The results (n=3 for each standard) showed that the two standards gave results that were only 15% different. Therefore, it appears that the original standards had degraded by about 15% over the 4-year long project. This is a relatively minor bias would not significantly affect the results since most of the C-15 experiments were conducted in a relatively short period of time.

Field Blanks:

Two field blanks were prepared during each sampling episode. The field blanks were prepared and handled in the exact same fashion as the samples except that the vacuum pumps were not turned on. Therefore, the field blanks were spiked with the internal standard mix, allowed to react for 10 minutes, then poured into the mist chambers, sat in the mist chambers for 10 minutes with the vacuum pumps off, and then poured into the reaction tubes along with two rinses of the mist chambers. These field blanks are the best representation of the contamination resulting from both the reagents themselves and sampling handling/storage in the field.

The minimum detectable limit (MDL) was calculated using the field blanks rather than the reagent blanks or instrument signal-to-noise ratios. The limit of detection was the mean field blank from the sampling episode plus three standard deviations of the blank. Values below the MDL are reported as "Not detected". The minimum quantification limit (MQL) was defined as the mean field blank plus six standard deviations of the blank. Values below the MQL but above the MDL were positively detected, but the absolute quantification of the analytes in rather uncertain. Numerical values are reported, but they are flagged to indicate that they represent the "best estimate" of the value but they are not as reliable as values above the MQL.

Retention of Internal Standards:

The addition of internal standards was designed for the isotope-dilution method of quantification where the analyte is quantified against the internal standard so that any chemical losses, such as spillage, incomplete derivatization, etc, can be accounted for during quantification. The second use of the internal standards is to determine the amount of internal standard lost during the sample collection, derivatization and extraction process. In this case, the instrument response for the internal standards is divided by the instrument response for the injection standard, which normalizes instrument response and sample volume between analyses. The degree of internal standard loss is then calculated as the average internal standard relative response factors for the samples divided by the average internal standard relative response factor for the standards. This gives the result as a ratio, so it is typically multiplied by 100 to turn the value into a percent. While the internal standard would account for this loss during the quantification processes, a low recovery of an internal standard results in poorer quantification since the uncertainty about the internal standard concentration becomes larger.

The quality control program using the labeled carbonyls showed that the analytical method was generally effective for most of the carbonyls except for acetaldehyde (Table F-1). Acetaldehyde is effectively derivatized, extracted and quantified in blanks, the calibration curves and spiked filter samples, so the low recovery of acetaldehyde from the gas-phase samples is most likely due to blow-off during sample collection. Therefore, acetaldehyde is not reported for this study.

The peculiar and interesting result was the enhanced response of acrolein-d_4 and glyoxal-d_2 in the gas-phase MB4000 tests, and the renewable biodiesel tests to a lesser extent. This enrichment was not observed in the filter samples processed at the same time with the same standards and reagents. The main difference between the filter samples and the gas samples was that the gas samples were spiked with the labeled standards prior to sample collection while the filter samples were spiked after sample collection to prevent blow-off and mixing with the gas-phase standards. Therefore, the labeled standards in the gas-phase samples encountered the sample air while the labeled standards in the filter did not. The enrichment in the recovery of these two compounds was observed in both the dilution air and the exhaust air samples, but not the field blanks (which were treated exactly the same as samples except no air is pulled through the sample). Therefore, it would appear that a component of the dilution air or sampling configuration caused an increase in the derivatization and/or partitioning equilibrium in these samples. It is worth noting that benzaldehyde-d_6 was not affected, but it is the least sensitive chemical to changing derivatization conditions as was shown during the method development study (Seaman et al. 2006). One last difference that occurred in the last sampling round was that a DNPH cartridge was connected to the mist chamber sampling line with a "T" fitting, so it is possible that some of the DNPH reagents back-flushed into the mist chambers if the vacuum pump driving the mist chambers was a stronger pump that the DNPH vacuum pump. If any DNPH reagents were pulled backwards into the mist chambers, then the derivatization equilibrium could be disrupted.

Subsequent tests were run with newly purchased standards and reagents to confirm that the batch of standards and reagents used in the MBE4000 series of tests were good. The results of these QAQC tests showed that the reagents performed very well and standards were still good with the acrolein standard having only degraded by about 15% during the 4+ year project. Ultimately, the whole idea behind using an isotopic standard for quantification of analytes (isotope dilution method) is that process that affects the labeled standard should affect the unlabeled analyte at the same rate, thus the calculation of the relative response factor causes these systematic biases to cancel out and thus the results should still be valid. Therefore the results from the MBE4000 tests should still be valid, but the excessive recovery of acrolein-d_4 and glyoxal-d_2 indicated the some aspect of the sampling system was behaving in an unexpected fashion.

Table F-1 - Recovery (%) of labeled standards added to sample collection matrix for the different sampling episodes. The gas-phase samples were spiked with the labeled standards prior to sample collection while the filter samples were spiked after sample collection. All samples, blanks and field prepared standards were spiked with the same amount of the labeled standard.

labeled standard	Soy (C-15) (*n*=16)	Animal (C-15) (*n*=20)	Renewable (C-15) (*n*=22)	Soy (MBE4000) (*n*=26)
Gas-phase samples				
Acetaldehyde-d_4	4.8	5.1	10.4	20.3
Acrolein-d_4	96.3	91.2	138	416
Glyoxal-d_2	93.4	103	208	899
Benzaldehyde-d_6	96.0	97.2	86.4	82.3
Filter samples				
Acetaldehyde-d_4	102	100	84.1	121
Acrolein-d_4	106	89.7	95.6	124
Glyoxal-d_2	128	103	60.1	94.7
Benzaldehyde-d_6	105	97.2	88.4	90.0

Appendix G – Average Emissions Results for Each Fuel/Cycle Combination (2006 Cummins ISM)

Soy-Based Biodiesel Testing

Fuel	Cycle		THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2 g/bhp-hr	BSFC gals/bhp-hr
CARB ULSD	UDDS	Ave.	0.830	2.116	5.868	0.065	828.4	0.085
		St. Dev.	0.032	0.124	0.103	0.007	18.6	0.002
		COV	3.9%	5.9%	1.8%	11.4%	2.2%	2.2%
		Replicates	9	9	9	9	9	9
CARB ULSD	FTP	Ave.	0.309	0.747	2.012	0.081	624.9	0.064
		St. Dev.	0.008	0.023	0.038	0.008	5.0	0.001
		COV	2.7%	3.0%	1.9%	10.3%	0.8%	0.8%
		Replicates	10	10	10	10	10	10
CARB ULSD	40 mph Cruise	Ave.	0.247	0.599	2.030	0.049	572.6	0.058
		St. Dev.	0.009	0.021	0.017	0.004	3.0	0.000
		COV	3.8%	3.5%	0.8%	7.5%	0.5%	0.5%
		Replicates	6	6	6	6	6	6
CARB ULSD	50 mph Cruise	Ave.	0.185	0.471	1.733	0.054	544.8	0.055
		St. Dev.	0.005	0.020	0.067	0.002	5.3	0.001
		COV	2.6%	4.2%	3.9%	4.4%	1.0%	1.0%
		Replicates	18	18	18	18	18	18
B20 - S	UDDS	Ave.	0.727	2.215	6.107	0.050	834.7	0.086
		St. Dev.	0.012	0.088	0.142	0.008	7.9	0.001
		COV	1.6%	4.0%	2.3%	15.6%	0.9%	0.9%
		Replicates	6	6	6	6	6	6
B20 - S	FTP	Ave.	0.275	0.724	2.145	0.061	627.2	0.064
		St. Dev.	0.010	0.028	0.033	0.003	3.5	0.000
		COV	3.6%	3.9%	1.5%	5.5%	0.6%	0.6%
		Replicates	7	7	7	7	7	7
B20 - S	40 mph Cruise	Ave.	0.207	0.582	2.109	0.036	577.4	0.059
		St. Dev.	0.005	0.017	0.025	0.002	4.2	0.000
		COV	2.4%	2.9%	1.2%	4.2%	0.7%	0.7%
		Replicates	5	5	5	5	5	5
B20 - S	50 mph Cruise	Ave.	0.164	0.462	1.741	0.044	547.9	0.056
		St. Dev.	0.002	0.015	0.063	0.004	5.2	0.001
		COV	1.4%	3.3%	3.6%	8.9%	0.9%	0.9%
		Replicates	6	6	6	6	6	6
B50 - S	UDDS	Ave.	0.601	2.662	6.444	0.046	848.9	0.089
		St. Dev.	0.017	0.135	0.106	0.005	18.4	0.002
		COV	2.8%	5.1%	1.6%	11.7%	2.2%	2.2%
		Replicates	6	6	6	6	6	6
B50 - S	FTP	Ave.	0.219	0.720	2.278	0.044	628.2	0.066
		St. Dev.	0.003	0.023	0.033	0.004	3.0	0.000
		COV	1.4%	3.2%	1.4%	9.1%	0.5%	0.5%
		Replicates	6	6	6	6	6	6

Fuel	Cycle		THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2 g/bhp-hr	BSFC gals/bhp-hr
B50 - S	40 mph Cruise	Ave.	0.158	0.599	2.214	0.026	580.0	0.060
		St. Dev.	0.004	0.025	0.000	0.001	6.3	0.001
		COV	2.7%	4.2%	0.0%	2.8%	1.1%	1.1%
		Replicates	2	2	2	2	2	2
B50 - S	50 mph Cruise	Ave.	0.128	0.442	1.842	0.031	551.4	0.057
		St. Dev.	0.003	0.005	0.023	0.001	3.2	0.000
		COV	2.5%	1.0%	1.3%	1.7%	0.6%	0.6%
		Replicates	6	6	6	6	6	6
B100 - S	UDDS	Ave.	0.376	3.419	6.890	0.044	863.1	0.093
		St. Dev.	0.015	0.158	0.039	0.007	13.9	0.001
		COV	4.1%	4.6%	0.6%	16.2%	1.6%	1.6%
		Replicates	5	5	5	5	5	5
B100 - S	FTP	Ave.	0.115	0.770	2.547	0.034	634.0	0.068
		St. Dev.	0.008	0.038	0.050	0.008	5.6	0.001
		COV	7.4%	5.0%	2.0%	22.7%	0.9%	0.9%
		Replicates	5	5	5	5	5	5
B100 - S	40 mph Cruise	Ave.	0.075	0.602	2.454	0.015	589.9	0.063
		St. Dev.	0.007	0.015	0.026	0.001	3.0	0.000
		COV	8.8%	2.4%	1.1%	3.8%	0.5%	0.5%
		Replicates	3	3	3	3	3	3
B100 - S	50 mph Cruise	Ave.	0.059	0.404	2.050	0.027	558.9	0.060
		St. Dev.	0.003	0.017	0.032	0.004	3.2	0.000
		COV	4.8%	4.2%	1.6%	13.5%	0.6%	0.6%
		Replicates	6	6	6	6	6	6
B5 - S	40 mph Cruise		0.249	0.615	2.062	0.045	582.8	0.059
B5 - S	50 mph Cruise		0.183	0.478	1.727	0.051	544.9	0.056
CARB B5	40 mph Cruise		0.251	0.602	2.028	0.048	573.3	0.058
CARB B5	50 mph Cruise		0.186	0.473	1.747	0.054	544.8	0.055

Animal-Based Biodiesel Testing

Fuel	Cycle		THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2 g/bhp-hr	BSFC gals/bhp-hr
CARB ULSD	UDDS	Ave.	0.799	2.052	6.010	0.065	841.3	0.086
		St. Dev.	0.013	0.061	0.211	0.003	15.9	0.001
		COV	1.6%	3.0%	3.5%	3.9%	1.9%	1.3%
		Replicates	7	7	7	6	7	7
CARB ULSD	FTP	Ave.	0.303	0.712	2.075	0.076	627.5	0.064
		St. Dev.	0.004	0.013	0.013	0.002	3.2	0.001
		COV	1.5%	1.9%	0.6%	3.0%	0.5%	1.7%
		Replicates	12	12	12	12	12	12
CARB ULSD	50 mph Cruise	Ave.	0.180	0.469	1.788	0.056	544.7	0.056
		St. Dev.	0.006	0.019	0.037	0.004	5.8	0.001
		COV	3.3%	4.1%	2.1%	6.3%	1.1%	1.2%
		Replicates	7	7	7	7	7	7
B20 - A	UDDS	Ave.	0.670	1.842	5.923	0.058	836.3	0.087
		St. Dev.	0.011	0.034	0.102	0.004	21.5	0.003
		COV	1.6%	1.9%	1.7%	6.9%	2.6%	3.5%
		Replicates	6	6	6	6	6	6
B20 - A	FTP	Ave.	0.263	0.665	2.106	0.062	628.2	0.065
		St. Dev.	0.003	0.020	0.009	0.004	4.2	0.001
		COV	1.1%	3.0%	0.4%	5.7%	0.7%	2.1%
		Replicates	6	6	6	6	6	6
B20 - A	50 mph Cruise	Ave.	0.155	0.437	1.748	0.047	548.7	0.057
		St. Dev.	0.003	0.008	0.057	0.001	3.7	0.001
		COV	1.8%	1.9%	3.3%	2.9%	0.7%	1.8%
		Replicates	6	6	6	6	6	6
B50 - A	UDDS	Ave.	0.495	1.800	6.018	0.049	851.1	0.089
		St. Dev.	0.006	0.037	0.066	0.007	8.5	0.002
		COV	1.3%	2.1%	1.1%	13.8%	1.0%	1.9%
		Replicates	6	6	6	6	6	6
B50 - A	FTP	Ave.	0.194	0.609	2.208	0.044	630.4	0.066
		St. Dev.	0.004	0.010	0.012	0.003	3.8	0.001
		COV	1.9%	1.6%	0.5%	6.9%	0.6%	1.4%
		Replicates	6	6	6	6	6	6
B50 - A	50 mph Cruise	Ave.	0.114	0.426	1.802	0.036	552.8	0.058
		St. Dev.	0.002	0.052	0.052	0.005	3.7	0.001
		COV	2.1%	12.1%	2.9%	15.1%	0.7%	1.2%
		Replicates	6	6	6	6	6	6
B100 - A	UDDS	Ave.	0.214	1.634	6.127	0.045	862.4	0.092
		St. Dev.	0.011	0.035	0.101	0.007	9.8	0.003
		COV	5.0%	2.1%	1.6%	15.2%	1.1%	3.1%
		Replicates	6	6	6	6	6	6
B100 - A	FTP	Ave.	0.087	0.522	2.368	0.027	632.1	0.067
		St. Dev.	0.004	0.012	0.015	0.003	4.0	0.002
		COV	4.7%	2.4%	0.6%	11.7%	0.6%	2.8%
		Replicates	6	6	6	6	6	6

Fuel	Cycle		THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2 g/bhp-hr	BSFC gals/bhp-hr
B100 - A	50 mph Cruise	Ave.	0.049	0.354	1.883	0.023	553.1	0.059
		St. Dev.	0.003	0.007	0.021	0.003	3.0	0.001
		COV	5.5%	2.1%	1.1%	12.8%	0.5%	2.4%
		Replicates	6	6	6	6	6	6
B5 - A	FTP	Ave.	0.295	0.686	2.089	0.070	624.7	0.067
		St. Dev.	0.005	0.015	0.007	0.001	2.0	0.001
		COV	1.8%	2.2%	0.3%	1.5%	0.3%	1.9%
		Replicates	6	6	6	6	6	6
CARB B5	FTP		0.303	0.715	2.083	0.076	626.5	0.065

Renewable Diesel Testing

Fuel	Cycle		THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2 g/bhp-hr	BSFC gals/bhp-hr
CARB ULSD	UDDS	Ave.	0.769	2.091	5.891	0.063	838.540	0.086
		St. Dev.	0.020	0.136	0.071	0.007	13.868	0.001
		COV	2.6%	6.5%	1.2%	11.9%	1.7%	1.7%
		Replicates	7	7	7	7	7	7
CARB ULSD	FTP	Ave.	0.294	0.701	2.088	0.073	630.719	0.064
		St. Dev.	0.008	0.021	0.010	0.002	9.125	0.001
		COV	2.6%	2.9%	0.5%	3.1%	1.4%	1.4%
		Replicates	8	8	8	8	8	8
CARB ULSD	50 mph Cruise	Ave.	0.176	0.452	1.809	0.053	548.879	0.056
		St. Dev.	0.006	0.009	0.028	0.002	8.525	0.001
		COV	3.2%	2.0%	1.5%	4.4%	1.6%	1.6%
		Replicates	7	7	7	7	7	7
R20	UDDS	Ave.	0.744	1.753	5.603	0.060	834.940	0.086
		St. Dev.	0.010	0.089	0.067	0.005	8.782	0.001
		COV	1.3%	5.1%	1.2%	7.7%	1.1%	1.1%
		Replicates	6	6	6	6	6	6
R20	FTP	Ave.	0.296	0.675	2.027	0.070	628.759	0.065
		St. Dev.	0.007	0.014	0.015	0.002	5.575	0.001
		COV	2.2%	2.1%	0.7%	3.0%	0.9%	0.9%
		Replicates	6	6	6	6	6	6
R20	50 mph Cruise	Ave.	0.180	0.454	1.740	0.052	548.719	0.057
		St. Dev.	0.004	0.019	0.047	0.001	7.333	0.001
		COV	2.4%	4.1%	2.7%	2.8%	1.3%	1.3%
		Replicates	6	6	6	6	6	6
R50	UDDS	Ave.	0.726	1.612	5.289	0.055	832.459	0.088
		St. Dev.	0.019	0.050	0.087	0.004	13.922	0.001
		COV	2.6%	3.1%	1.7%	7.1%	1.7%	1.7%
		Replicates	6	6	6	6	6	6
R50	FTP	Ave.	0.293	0.643	1.975	0.062	624.157	0.066
		St. Dev.	0.008	0.012	0.016	0.002	3.588	0.000
		COV	2.6%	1.9%	0.8%	3.9%	0.6%	0.6%
		Replicates	6	6	6	6	6	6
R50	50 mph Cruise	Ave.	0.180	0.459	1.667	0.046	548.859	0.058
		St. Dev.	0.005	0.008	0.069	0.002	3.304	0.000
		COV	3.0%	1.8%	4.1%	3.6%	0.6%	0.6%
		Replicates	6	6	6	6	6	6
R100	UDDS	Ave.	0.677	1.392	4.825	0.045	810.709	0.090
		St. Dev.	0.026	0.043	0.094	0.002	10.626	0.001
		COV	3.9%	3.1%	1.9%	4.7%	1.3%	1.3%
		Replicates	6	6	6	6	6	6
R100	FTP	Ave.	0.284	0.614	1.882	0.048	609.513	0.068
		St. Dev.	0.011	0.012	0.008	0.002	3.774	0.000
		COV	3.9%	2.0%	0.4%	5.2%	0.6%	0.6%
		Replicates	6	6	6	5	6	6
R100	50 mph Cruise	Ave.	0.174	0.467	1.553	0.040	537.082	0.059
		St. Dev.	0.006	0.010	0.017	0.001	4.395	0.000

	COV	3.2%	2.2%	1.1%	2.6%	0.8%	0.8%
	Replicates	6	6	6	6	6	6

GTL Diesel Testing

Fuel		THC g/bhp-hr	CO g/bhp-hr	NOx g/bhp-hr	PM g/bhp-hr	CO2 g/bhp-hr	BSFC gals/bhp-hr
CARB ULSD	Ave.	0.303	0.740	2.099	0.071	636.672	0.065
	St. Dev.	0.008	0.015	0.021	0.002	5.680	0.001
	COV	2.5%	2.0%	1.0%	2.7%	0.9%	0.9%
	Replicates	21	21	21	21	21	21
GTL20	Ave.	0.288	0.693	2.079	0.065	636.873	0.066
	St. Dev.	0.004	0.010	0.021	0.001	1.327	0.000
	COV	1.4%	1.5%	1.0%	1.9%	0.2%	0.2%
	Replicates	6	6	6	6	6	6
GTL50	Ave.	0.255	0.664	1.989	0.062	624.369	0.066
	St. Dev.	0.004	0.010	0.035	0.002	9.635	0.001
	COV	1.7%	1.5%	1.8%	3.7%	1.5%	1.5%
	Replicates	6	6	6	6	6	6
GTL100	Ave.	0.219	0.633	1.917	0.050	614.614	0.067
	St. Dev.	0.002	0.010	0.017	0.000	1.773	0.000
	COV	1.0%	1.6%	0.9%	0.9%	0.3%	0.3%
	Replicates	6	6	6	6	6	6

NO_x Mitigation Testing Round #1

Fuel		THC g/bhp-hr	CO g/bhp-hr	NOx g/bhp-hr	PM g/bhp-hr	CO2 g/bhp-hr	BSFC gals/bhp-hr
CARB ULSD	Ave.	0.295	0.701	2.100	0.072	631.690	0.064
	St. Dev.	0.005	0.018	0.017	0.002	3.239	0.000
	COV	1.8%	2.6%	0.8%	2.9%	0.5%	0.5%
	Replicates	33	33	33	33	33	33
B5 - S	Ave.	0.291	0.695	2.147	0.068	632.013	0.064
	St. Dev.	0.007	0.024	0.008	0.003	2.177	0.000
	COV	2.5%	3.4%	0.4%	4.8%	0.3%	0.3%
	Replicates	6	6	6	6	6	6
B10 - S	Ave.	0.277	0.690	2.155	0.060	630.894	0.064
	St. Dev.	0.003	0.016	0.007	0.003	2.191	0.000
	COV	1.0%	2.3%	0.3%	5.2%	0.3%	0.3%
	Replicates	6	6	6	6	6	6
B20-S 1% DTBP	Ave.	0.247	0.567	2.100	0.060	626.016	0.064
	St. Dev.	0.002	0.009	0.006	0.001	2.487	0.000
	COV	0.9%	1.6%	0.3%	1.4%	0.4%	0.4%
	Replicates	6	6	6	6	6	6
B10-S 1% DTBP	Ave.	0.268	0.602	2.076	0.068	630.144	0.064
	St. Dev.	0.002	0.009	0.013	0.002	0.891	0.000
	COV	0.7%	1.4%	0.6%	2.8%	0.1%	0.1%
	Replicates	6	6	6	6	6	6
B20-S 1% 2-EHN	Ave.	0.247	0.596	2.231	0.060	632.941	0.065
	St. Dev.	0.002	0.022	0.011	0.003	1.338	0.000
	COV	0.9%	3.7%	0.5%	4.5%	0.2%	0.2%
	Replicates	6	6	6	6	6	6
B5-S 1% 2-EHN	Ave.	0.277	0.617	2.165	0.069	631.298	0.064
	St. Dev.	0.005	0.020	0.009	0.002	2.648	0.000
	COV	1.9%	3.2%	0.4%	3.1%	0.4%	0.4%
	Replicates	6	6	6	6	6	6
R80/B20-soy	Ave.	0.256	0.593	2.037	0.038	618.768	0.068
	St. Dev.	0.001	0.003	0.006	0.001	1.343	0.000
	COV	0.6%	0.6%	0.3%	2.0%	0.2%	0.2%
	Replicates	6	6	6	6	6	6
CARB25/R55/B20-S	Ave.	0.260	0.613	2.084	0.043	622.311	0.067
	St. Dev.	0.003	0.018	0.011	0.001	2.632	0.000
	COV	1.3%	2.9%	0.5%	1.9%	0.4%	0.4%
	Replicates	6	6	6	6	6	6
CARB70/R20/B10-S	Ave.	0.273	0.681	2.119	0.060	628.917	0.065
	St. Dev.	0.010	0.012	0.012	0.002	3.039	0.000
	COV	3.8%	1.8%	0.6%	3.6%	0.5%	0.5%
	Replicates	6	6	6	6	6	6
CARB75/R20/B5-S	Ave.	0.287	0.680	2.104	0.064	633.646	0.066
	St. Dev.	0.004	0.006	0.009	0.001	0.462	0.000
	COV	1.2%	0.9%	0.4%	1.8%	0.1%	0.1%
	Replicates	3	3	3	3	3	3

NO_x Mitigation Testing Round #2

Fuel		THC g/bhp-hr	CO g/bhp-hr	NOx g/bhp-hr	PM g/bhp-hr	CO2 g/bhp-hr	BSFC gals/bhp-hr
CARB ULSD	Ave.	0.303	0.740	2.099	0.071	636.672	0.065
	St. Dev.	0.008	0.015	0.021	0.002	5.680	0.001
	COV	2.5%	2.0%	1.0%	2.7%	0.9%	0.9%
	Replicates	21	21	21	21	21	21
CARB80/B10-S/B10-A	Ave.	0.267	0.694	2.181	0.053	644.603	0.066
	St. Dev.	0.003	0.010	0.011	0.001	1.078	0.000
	COV	1.1%	1.5%	0.5%	2.0%	0.2%	0.2%
	Replicates	6	6	6	6	6	6
CARB80/R15/B5-S	Ave.	0.295	0.711	2.114	0.063	637.659	0.066
	St. Dev.	0.003	0.010	0.013	0.002	2.532	0.000
	COV	1.1%	1.4%	0.6%	3.1%	0.4%	0.4%
	Replicates	6	6	6	6	6	6
CARB80/R13/B3-S/B4-A	Ave.	0.296	0.713	2.093	0.064	639.504	0.066
	St. Dev.	0.004	0.033	0.008	0.003	2.596	0.000
	COV	1.3%	4.6%	0.4%	5.2%	0.4%	0.4%
	Replicates	6	6	6	6	6	6
CARB53/G27/B20-S	Ave.	0.240	0.664	2.143	0.048	628.070	0.066
	St. Dev.	0.002	0.009	0.013	0.001	2.543	0.000
	COV	0.9%	1.4%	0.6%	1.8%	0.4%	0.4%
	Replicates	6	6	6	6	6	6
CARB80/G10/B10-S	Ave.	0.282	0.700	2.149	0.058	640.199	0.066
	St. Dev.	0.004	0.019	0.017	0.001	1.633	0.000
	COV	1.3%	2.8%	0.8%	1.6%	0.3%	0.3%
	Replicates	6	6	6	6	6	6

NO_x Mitigation Testing Round #3

Fuel		THC g/bhp-hr	CO g/bhp-hr	NOx g/bhp-hr	PM g/bhp-hr	CO2 g/bhp-hr	BSFC gals/bhp-hr
CARB ULSD	Ave.	0.305	0.739	2.075	0.069	630.820	0.064
	St. Dev.	0.007	0.014	0.017	0.002	3.111	0.000
	COV	2.2%	1.9%	0.8%	3.2%	0.5%	0.5%
	Replicates	9	9	9	9	9	9
CARB80/G15/B5-S	Ave.	0.282	0.705	2.061	0.062	627.186	0.065
	St. Dev.	0.004	0.014	0.008	0.001	1.131	0.000
	COV	1.4%	1.9%	0.4%	2.4%	0.2%	0.2%
	Replicates	6	6	6	6	6	6
CARB80/R10/B10-S 0.25% DTBP	Ave.	0.277	0.658	2.047	0.061	625.883	0.064
	St. Dev.	0.003	0.020	0.009	0.002	2.505	0.000
	COV	1.1%	3.1%	0.4%	3.6%	0.4%	0.4%
	Replicates	6	6	6	6	6	6

Appendix H – Average Emissions Results for Each Fuel/Cycle Combination (2007 MBE4000)

Soy-Based Biodiesel Testing

Fuel	Cycle		THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2	BSFC
CARB ULSD	UDDS	Ave.	0.023	0.022	2.378	0.004	730.031	0.074
		St. Dev.	0.013	0.02512	0.059304	0.003078	8.793	0.001
		COV	0.565217	1.141818	0.024939	0.7695	0.012045	0.013514
		Replicates	7	7	7	7	7	7
CARB ULSD	FTP	Ave.	0.004	0.081	1.285	0.001	578.891	0.059
		St. Dev.	0.001	0.031	0.017	0.001	3.892	0
		COV	0.25	0.382716	0.01323	1	0.006723	0
		Replicates	13	13	13	13	13	13
CARB ULSD	50 mph Cruise	Ave.	0.003	0.015	1.21	0.001	505.763	0.051
		St. Dev.	0.001	0.00838	0.021648	0.000559	3.605	0
		COV	0.333333	0.558667	0.017891	0.559	0.007128	0
		Replicates	7	7	7	7	7	7
B20 - S	UDDS	Ave.	0.021	0.008	2.482	0	730.195	0.075
		St. Dev.	0.018	0.03852	0.045296	0.005292	6.857	0.001
		COV	0.857143	4.815	0.01825	#DIV/0!	0.009391	0.013333
		Replicates	6	6	6	6	6	6
B20 - S	FTP	Ave.	0.006	0.091	1.361	0.001	578.65	0.059
		St. Dev.	0.001	0.04	0.021	0.001	4.822	0
		COV	0.166667	0.439560	0.015431	1	0.008333	0
		Replicates	6	6	6	6	6	6
B20 - S	50 mph Cruise	Ave.	31.151	0.003	0.014	1.293	508.0043	0.052
		St. Dev.	0	0.00327	0.019977	0.000589	2.926	0
		COV	0	1.09	1.426904	0.000456	0.00576	0
		Replicates	6	6	6	6	6	6

B50 - S	UDDS	Ave.	0.03	-0.003	2.743	0.004	736.776	0.076
		St. Dev.	0.004	0.02554	0.036945	0.0028	13.366	0.002
		COV	0.133333	-8.51333	0.013469	0.7	0.018141	0.026316
		Replicates	4	4	4	4	4	4
B50 - S	FTP	Ave.	0.006	0.04	1.481	0.001	579.867	0.06
		St. Dev.	0.001	0.02589	0.018118	0.000293	7.103	0.001
		COV	0.166667	0.64725	0.012233	0.293	0.012249	0.016667
		Replicates	4	4	4	4	4	4
B50-S	50 mph Cruise	Ave.	0.003	0.01	1.43	0.001	507.535	0.052
		St. Dev.	0.001	0.00275	0.027964	9.27E-05	5.955	0.001
		COV	0.333333	0.275	0.019555	0.0927	0.011733	0.019231
		Replicates	4	4	4	4	4	4
B100-S	UDDS	Ave.	0.019	0.007	3.249	0.002	766.186	0.08
		St. Dev.	0.021	0.04502	0.046921	0.002	9.303	0.002
		COV	1.105263	6.431429	0.014442	1	0.012142	0.025
		Replicates	4	4	4	4	4	4
B100-S	FTP	Ave.	0.005	0.021	1.774	0.001	592.639	0.062
		St. Dev.	0.001	0.01389	0.017671	0	2.588	0.002
		COV	0.2	0.661429	0.009961	0	0.004367	0.032258
		Replicates	4	4	4	4	4	4
B100-S	50 mph Cruise	Ave.	0.003	0.012	1.78	0	518.93	0.054
		St. Dev.	0.001	0.00332	0.043007	0	1.304	0.001
		COV	0.333333	0.276667	0.024161		0.002513	0.018519
		Replicates	4	4	4	4	4	4
B5 - S	FTP		0.006	0.061	1.307	0	580.317	0.059
CARB B5	FTP		0.004	0.076	1.296	0.001	580.043	0.059

Animal-Based Biodiesel Testing

Fuel	Cycle		THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2	BSFC
CARB ULSI	UDDS	Ave.	0.026	0.013	2.414	0	733.64	0.074
		St. Dev.	0.008	0.01922	0.046	0.001	3.016	0
		COV	0.307692	1.478462	0.019056		0.004111	0
		Replicates	7	7	7	7	7	7
CARB ULSI	FTP	Ave.	0.005	0.084	1.29	0	581.328	0.059
		St. Dev.	0.002	0.022	0.013	0	2.299	0
		COV	0.4	0.261905	0.010078		0.003955	0
		Replicates	13	13	13	13	13	13
CARB ULSI	50 mph Cruise	Ave.	0.003	0.018	1.224	0.001	508.127	0.052
		St. Dev.	0.001	0.00708	0.016	0	2.247	0
		COV	0.333333	0.393333	0.013072	0	0.004422	0
		Replicates	7	7	7	7	7	7
B20 - A	UDDS	Ave.	0.034	0.016	2.454	0.001	733.891	0.075
		St. Dev.	0.007	0.02551	0.053	0.003	9.784	0.001
		COV	0.205882	1.594375	0.021597	3	0.013332	0.013333
		Replicates	6	6	6	6	6	6
B20 - A	FTP	Ave.	0.006	0.082	1.354	0	581.701	0.059
		St. Dev.	0.002	0.03155	0.026	0	2.181	0
		COV	0.333333	0.384756	0.019202		0.003749	0
		Replicates	6	6	6	6	6	6
B20 - A	50 mph Cruise	Ave.	0.004	0.017	1.297	0	508.356	0.052
		St. Dev.	0.001	0.005	0.02	0	1.541	0
		COV	0.25	0.294118	0.01542		0.003031	0
		Replicates	6	6	6	6	6	6
B50 - A	UDDS	Ave.	0.03	-0.003	2.743	0.004	736.776	0.076
		St. Dev.	0.008	0.02454	0.045	0.002	5.799	0.001
		COV	0.266667	-8.18	0.016405	0.5	0.007871	0.013158
		Replicates	4	4	4	4	4	4
B50 - A	FTP	Ave.	0.028	0.011	2.592	0.001	740.725	0.075
		St. Dev.	0.004	0.03576	0.028	0.000577	1.468	0
		COV	0.142857	3.250909	0.010802	0.57735	0.001982	0
		Replicates	4	4	4	4	4	4
B50-A	50 mph Cruise	Ave.	0.003	0.012	1.424	0	510.231	0.052
		St. Dev.	0.001	0.005	0.015	0	1.873	0

		COV	0.333333	0.416667	0.010534		0.003671	0
		Replicates	4	4	4	4	4	4
B100-A	UDDS	Ave.	0.027	0.028	2.801	0.004	745.008	0.08
		St. Dev.	0.006	0.01572	0.012	0.002062	8.44	0.001
		COV	0.222222	0.561429	0.004284	0.515388	0.011329	0.0125
		Replicates	4	4	4	4	4	4
B100-A	FTP	Ave.	0.006	0.023	1.669	0	590.872	0.064
		St. Dev.	0.002	0.014	0.026	0	3.669	0
		COV	0.333333	0.608696	0.015578		0.006209	0
		Replicates	4	4	4	4	4	4
B100-A	50 mph Cruise	Ave.	0.003	0.008	1.706	0	514.595	0.056
		St. Dev.	0.002	0.00245	0.01	0.000577	2.628	0
		COV	0.666667	0.30625	0.005862		0.005107	0
		Replicates	4	4	4	4	4	4
B5 - A	FTP		0.006	0.072	1.314	0	584.678	0.059
CARB B5	FTP		0.005	0.081	1.297	0	583.123	0.059

Appendix I – Average Emissions Results for Off-Road Engine #1 (pre-Tier 1 1998 Kubota)

Table I-1. Percentages changes for Soy-Biodiesel blends relative to CARB and associated statistical p values for Pre Tier 1-1998 Kubota off-road engine

		THC	CH_4	CO	NO_X	N_2O	PM	CO_2
ULSD	**Avg.**	1.831	0.083	7.574	12.20	0.015	1.942	821.7
B50		1.477	0.052	5.793	13.44	0.014	1.617	832.5
B100		0.801	0.026	3.819	14.77	0.013	1.219	845.0
ULSD	**Std.**	0.138	0.010	0.491	0.366	0.001	0.078	3.263
B50	**Dev.**	0.089	0.008	0.332	0.518	0.001	0.115	3.038
B100		0.178	0.004	0.264	0.609	0.001	0.157	3.538
ULSD	**COV**	0.075	0.123	0.065	0.030	0.049	0.040	0.004
B50		0.061	0.151	0.057	0.039	0.035	0.071	0.004
B100		0.222	0.156	0.069	0.041	0.039	0.129	0.004
% Diff	**B50 - ULSD**	-19.4%	-37.5%	-23.5%	10.1%	-6.23%	-16.8%	1.31%
	B100 - ULSD	-56.2%	-68.9%	-49.6%	21.1%	-12.5%	-37.2%	2.84%

Appendix J – Graphs of Carbonyl Species for the Chassis Dynamometer Testing on Various Vehicles

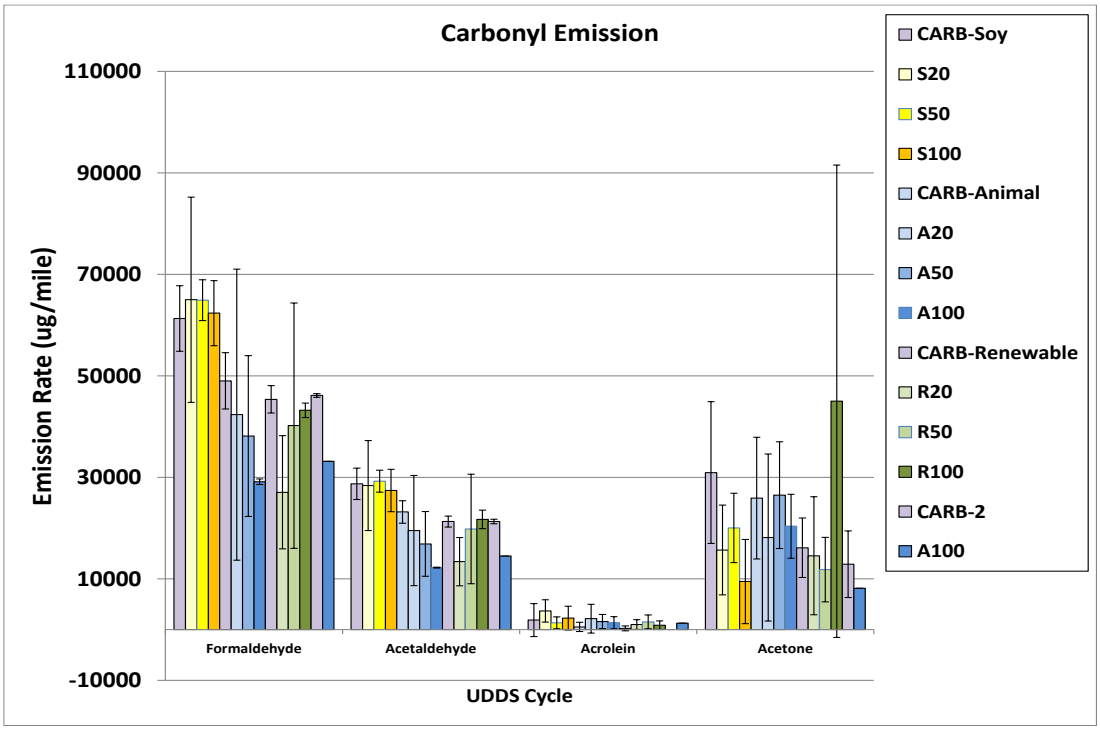


Figure J-1. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for UDDS Cycle for C-15.

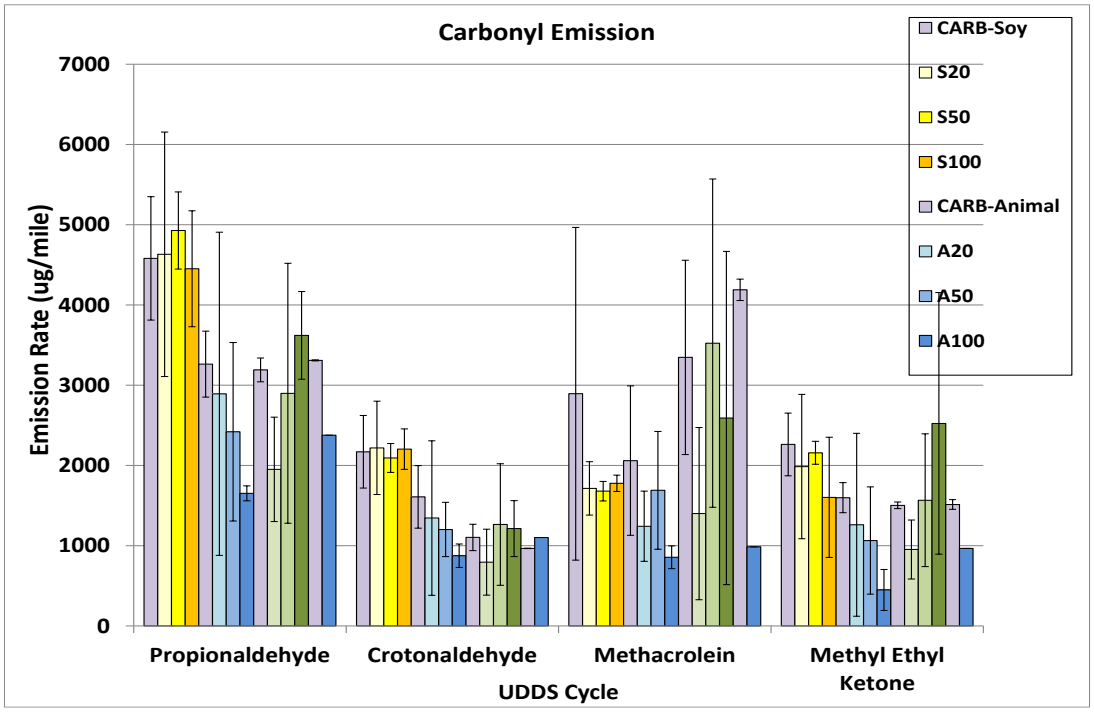


Figure J-2. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for UDDS Cycle for C-15.

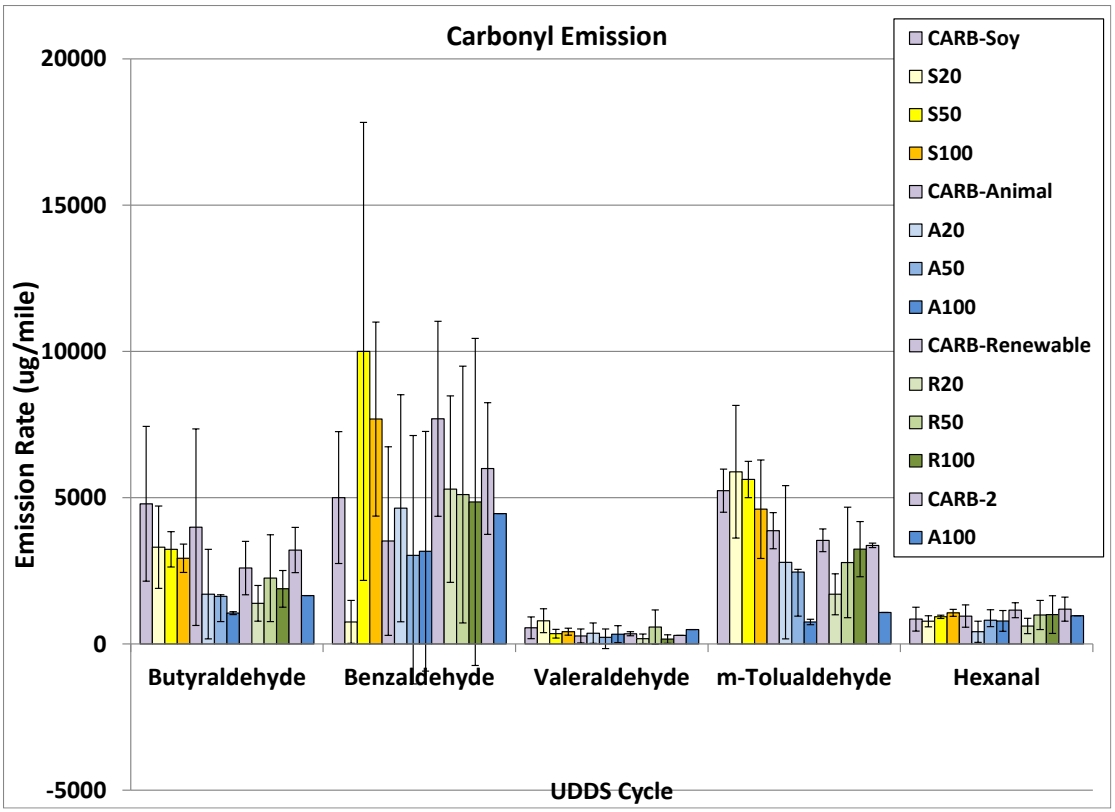


Figure J-3. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for UDDS Cycle for C-15.

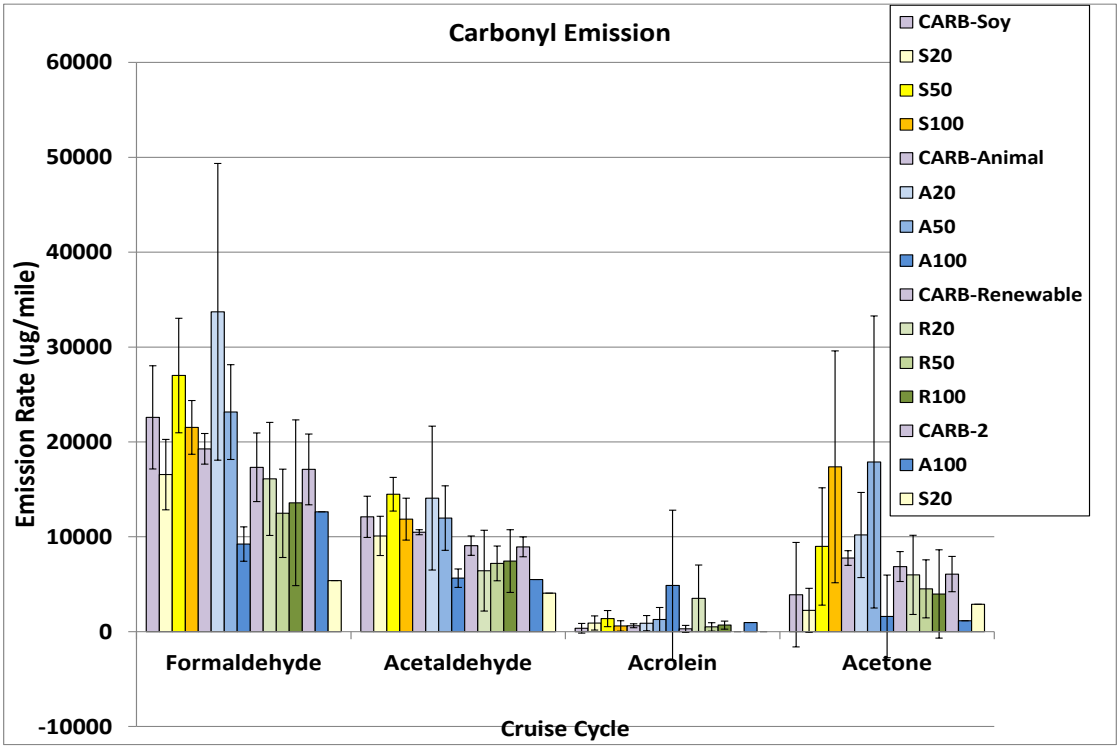


Figure J-4. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for Cruise Cycle for C-15.

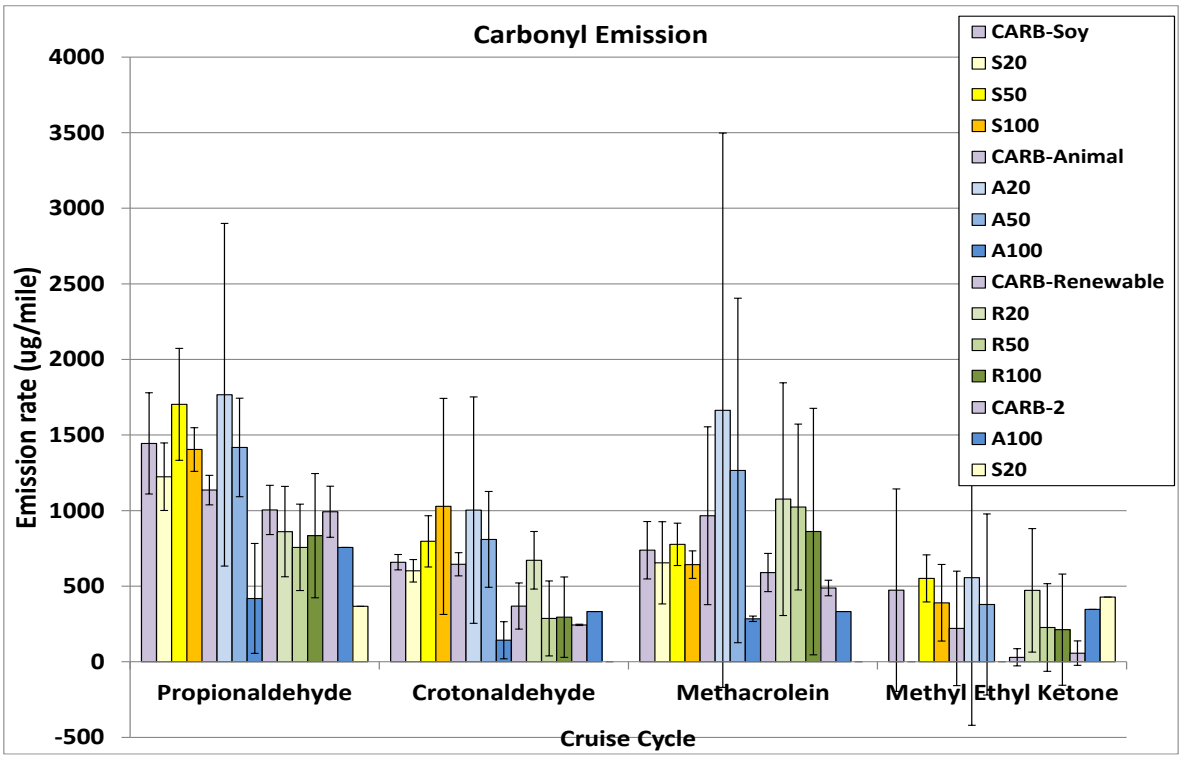


Figure J-5. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for Cruise Cycle for C-15.

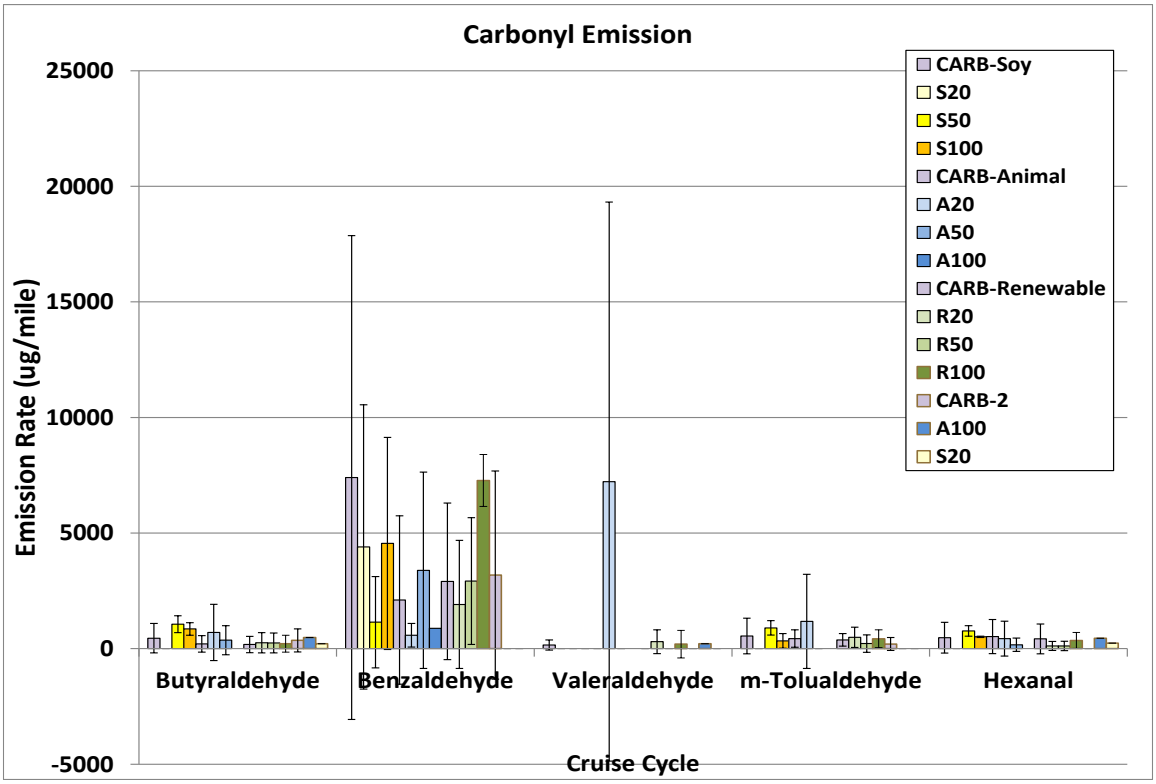


Figure J-6. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for Cruise Cycle for C-15.

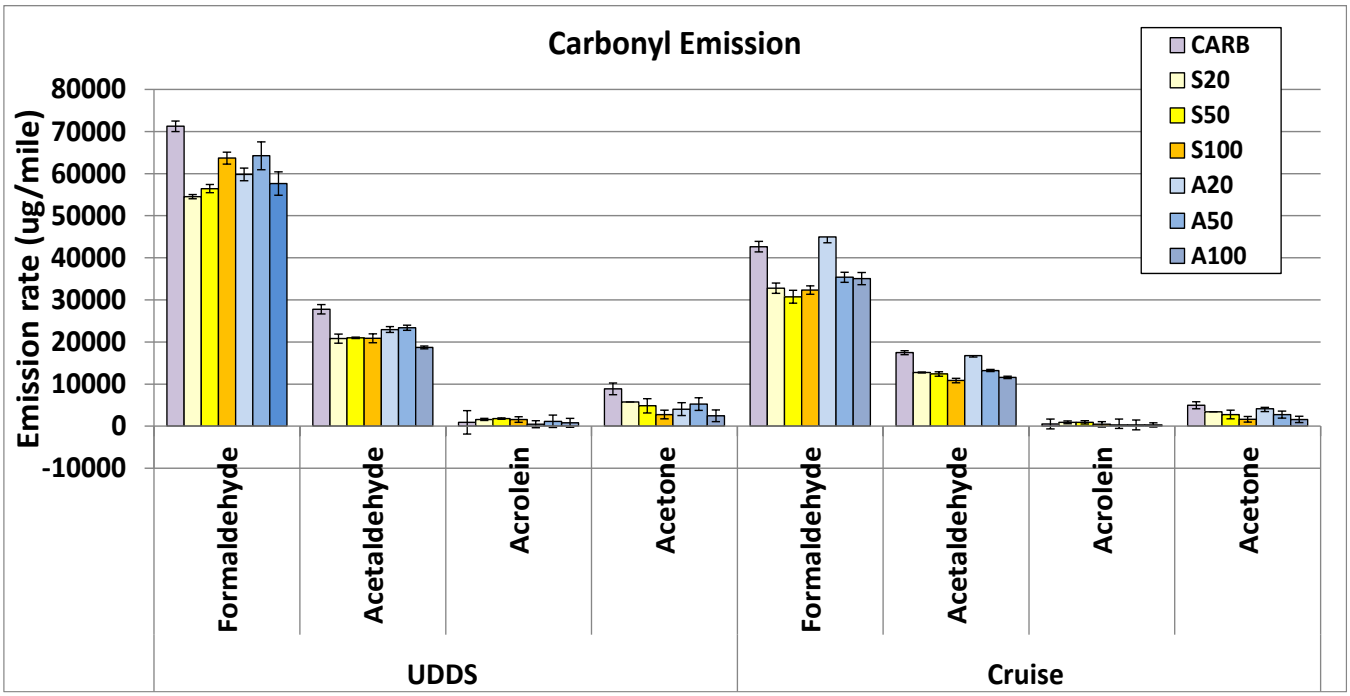


Figure J-7. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for 2006 Cummins ISM.

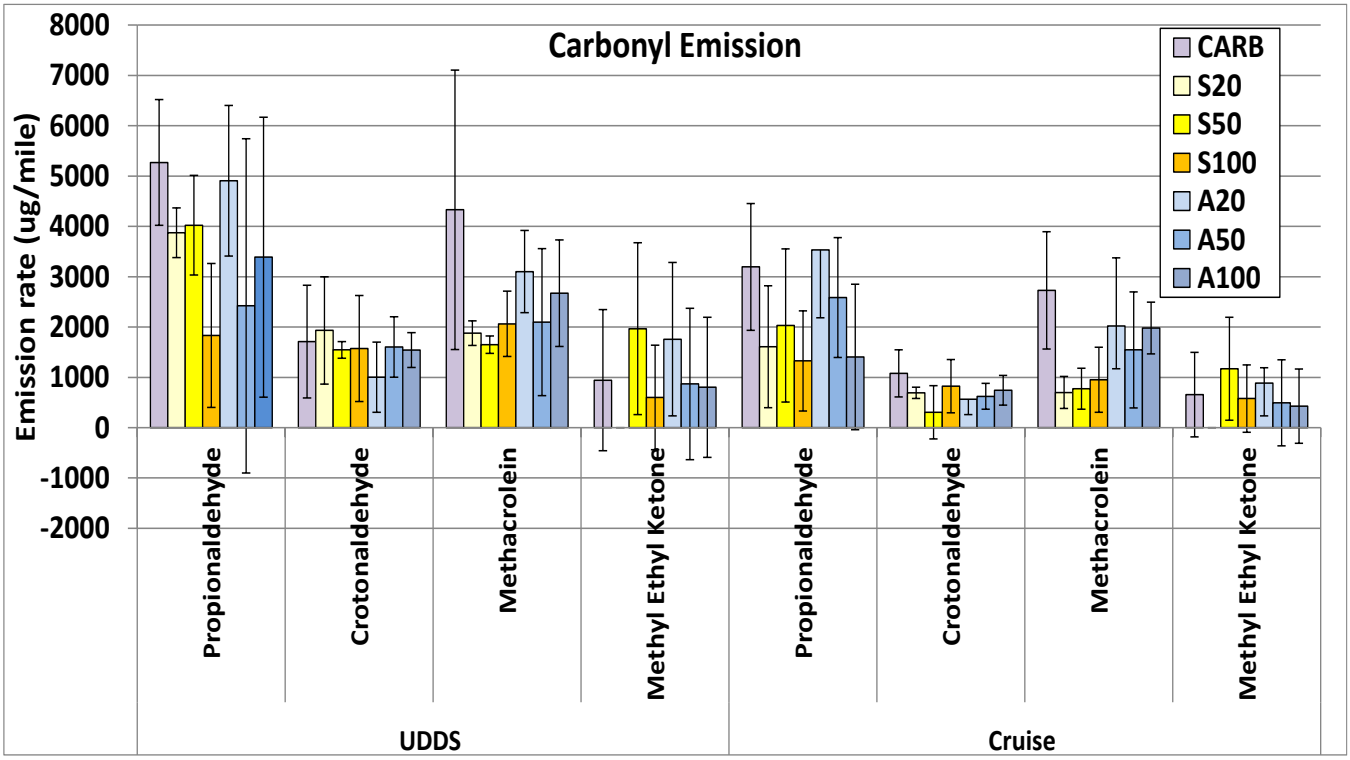


Figure J-8. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for 2006 Cummins ISM.

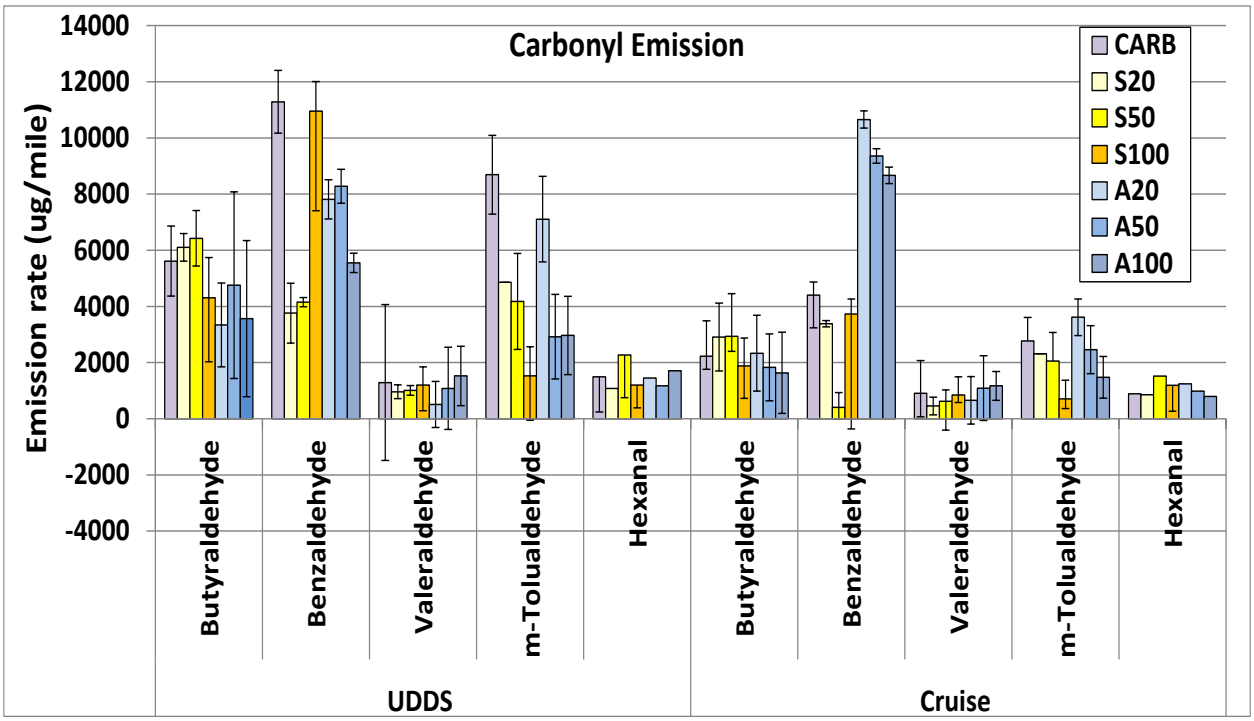


Figure J-9. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for 2006 Cummins ISM.

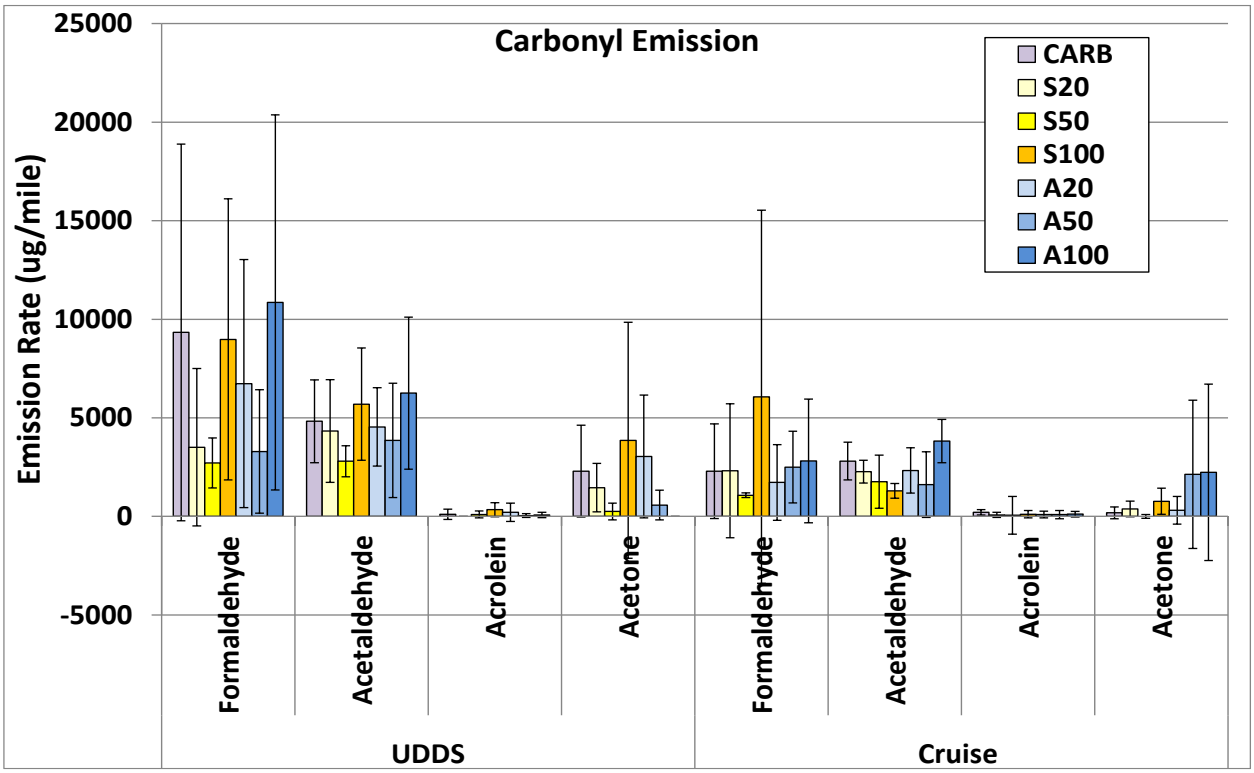


Figure J-10. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for 2007 MBE4000.

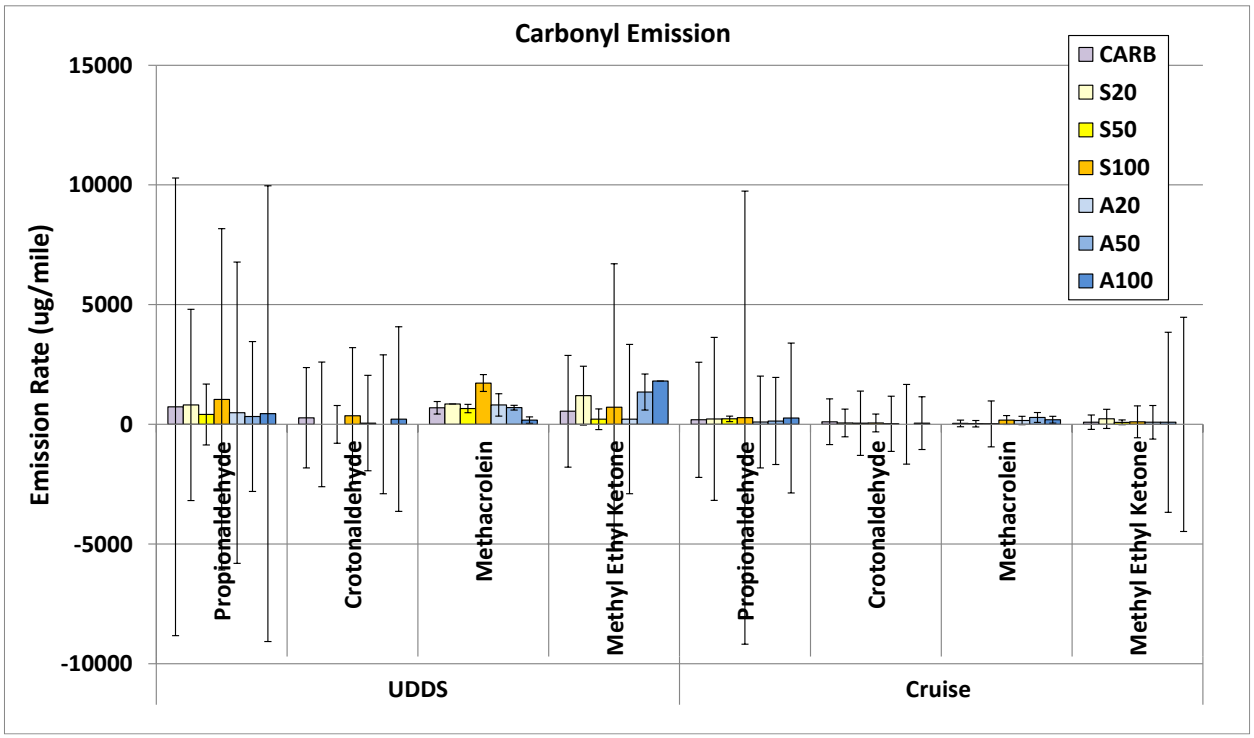


Figure J-11. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for 2007 MBE4000.

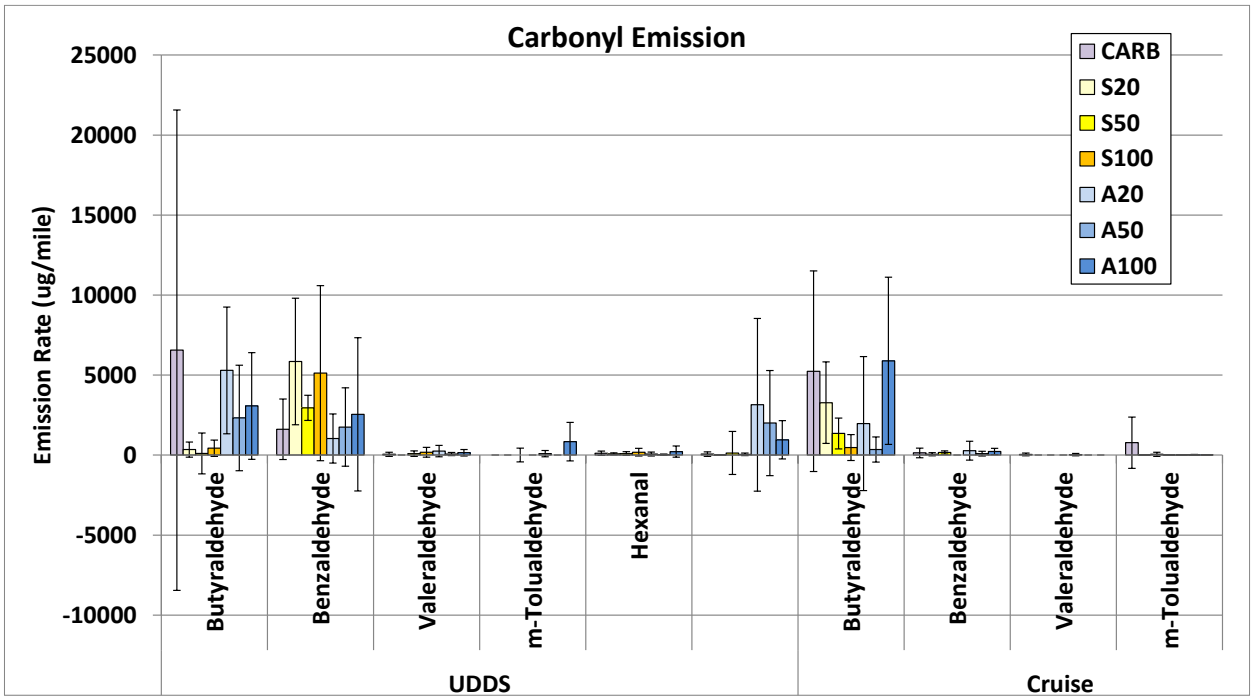


Figure J-12. Average Carbonyl Emission Results for the Biodiesel and Renewable Blends for 2007 MBE4000.

Appendix K – Results for Elements Measured During the Chassis Dynamometer Testing

Plots of Elements

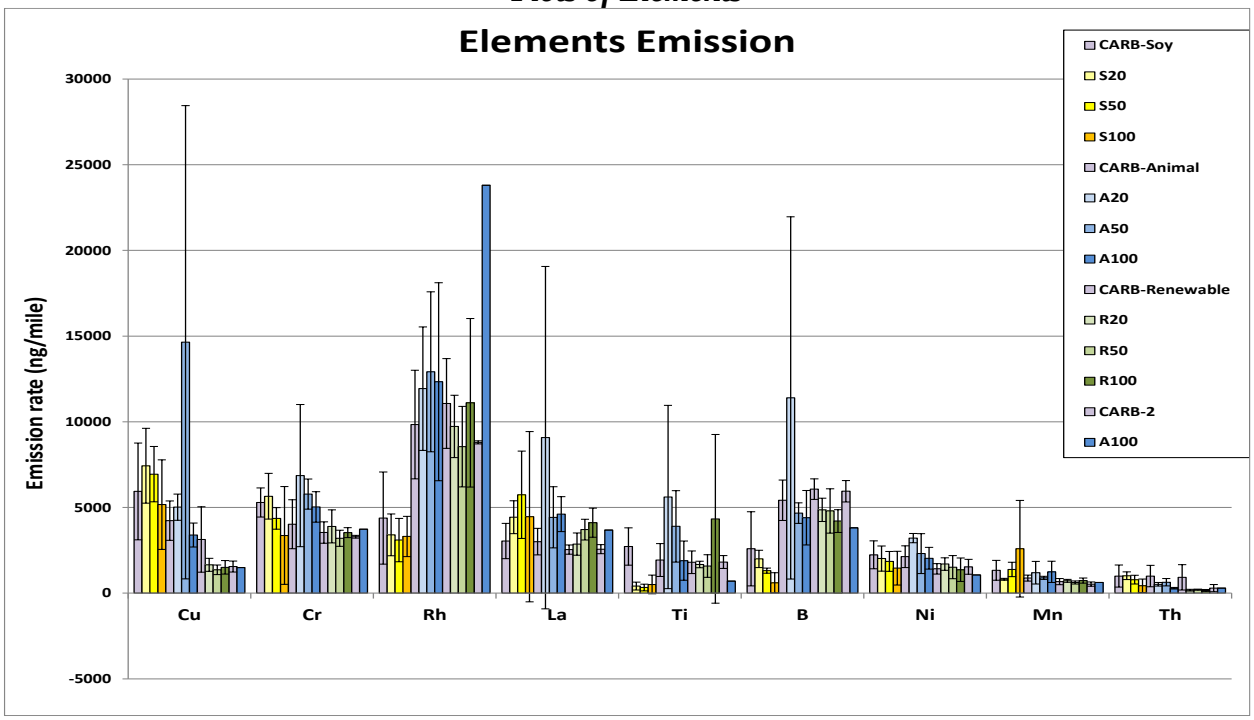


Figure K-1. Average Element Emission Results for the Biodiesel and Renewable Blends for 2000 Caterpillar C-15

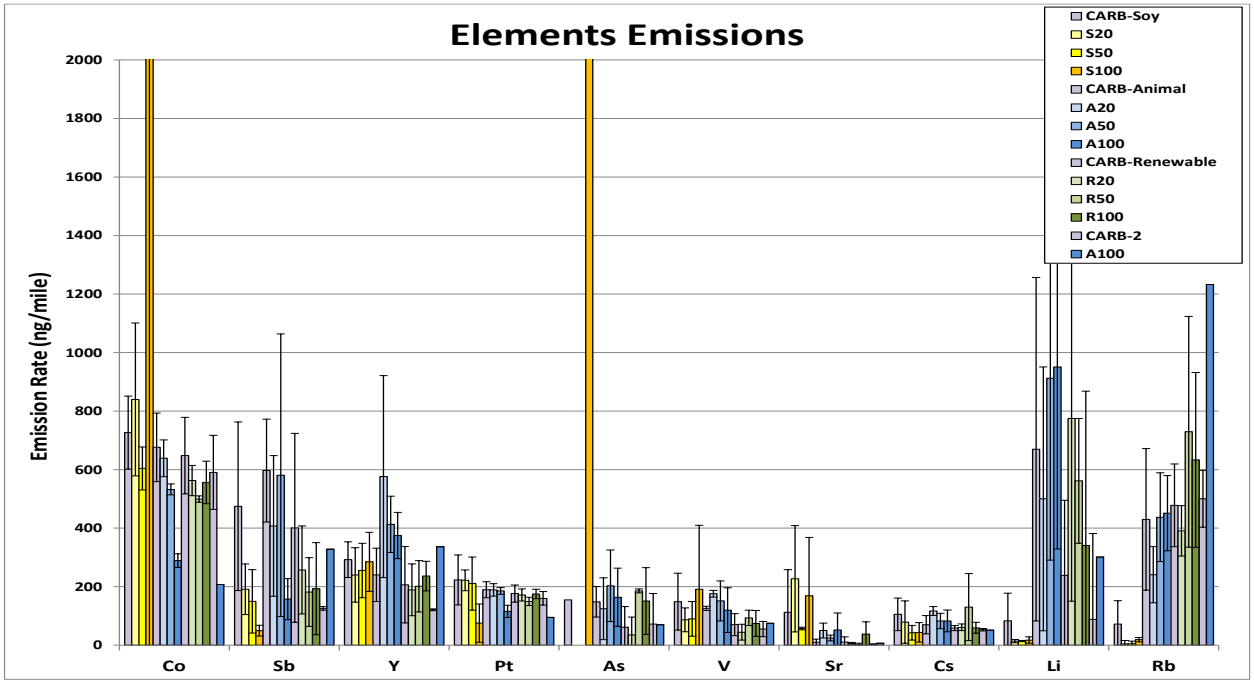


Figure K-2. Average Element Emission Results for the Biodiesel and Renewable Blends for 2000 Caterpillar C-15

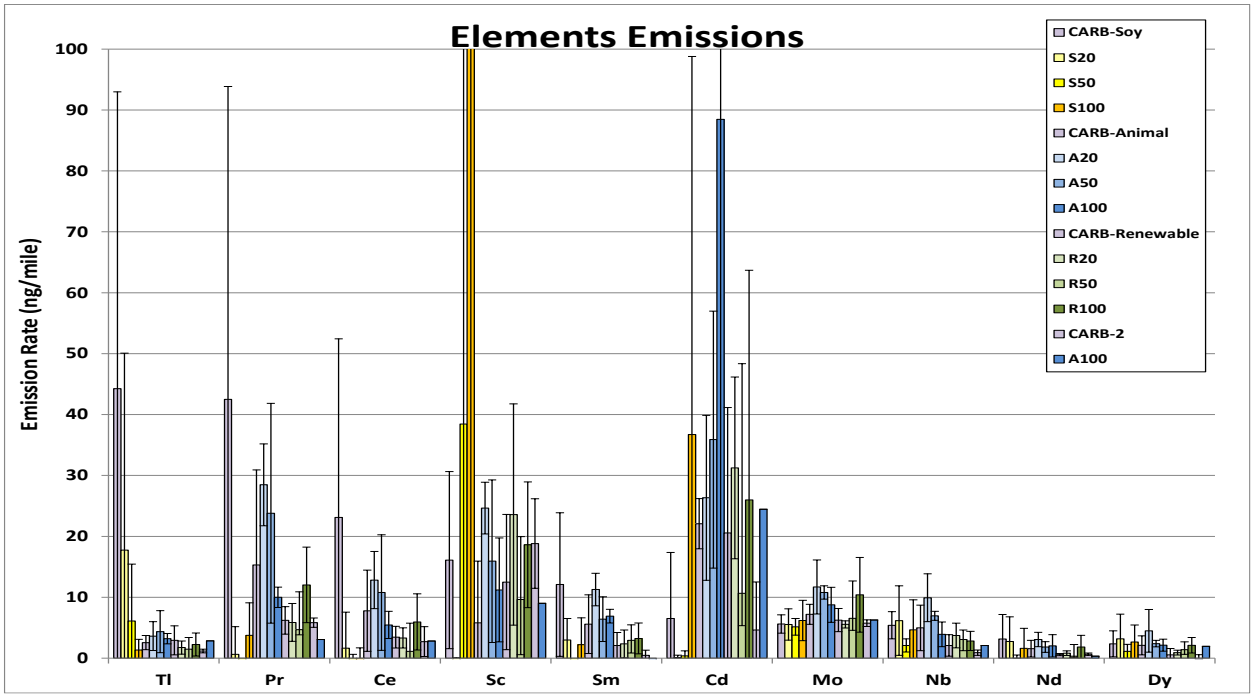


Figure K-3. Average Element Emission Results for the Biodiesel and Renewable Blends for 2000 Caterpillar C-15

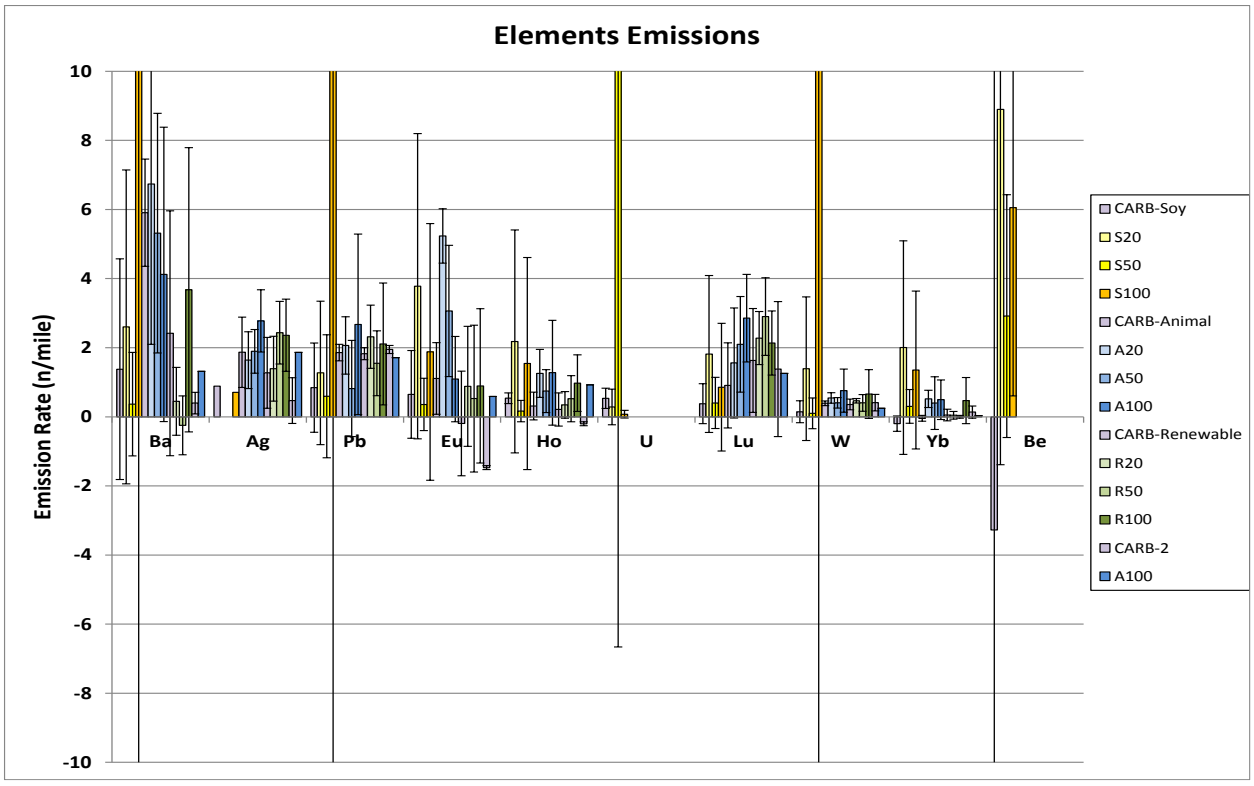


Figure K-4. Average Element Emission Results for the Biodiesel and Renewable Blends for 2000 Caterpillar C-15

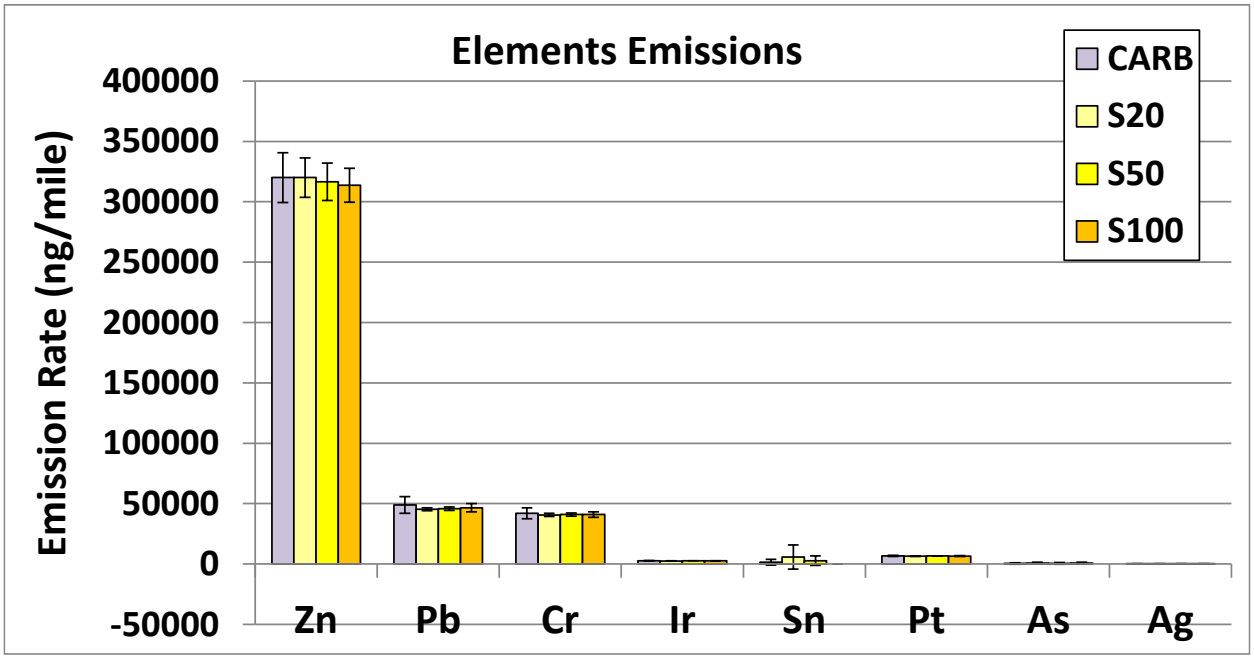


Figure K-5. Average Element Emission Results for the Soy-based Biodiesel for 2007 MBE 4000

Table K-1. Different Elements Percentage Differences Between the Biodiesel and Renewable Blends and CARB ULSD base fuel for UDDS Cycle for the MBE4000

		2000 Caterpillar C-15					
		Soy-based		Animal-based		Renewable-based	
		% Difference	P-values	% Difference	P-values	% Difference	P-values
Li7(LR)	B-20	-83%	0.274	-25%	0.712	225%	0.173
	B-50	-83%	0.276	36%	0.648	135%	0.139
	B-100	-79%	0.298	42%	0.599	43%	0.744
Be9(LR)	B-20	-372%	0.343	NA	NA	NA	NA
	B-50	-189%	0.499	NA	NA	NA	NA
	B-100	-285%	0.484	NA	NA	NA	NA
B11(LR)	B-20	-23%	0.669	110%	0.386	-20%	0.054
	B-50	-49%	0.366	-14%	0.384	-21%	0.138
	B-100	-77%	0.199	-19%	0.422	-31%	0.012
Na23(MR)	B-20	-71%	0.361	70%	0.184	2%	0.952
	B-50	-57%	0.456	1%	0.979	-6%	0.871
	B-100	-52%	0.515	36%	0.560	20%	0.655
Mg25(MR)	B-20	-39%	0.433	18%	0.541	-9%	0.689
	B-50	-64%	0.172	32%	0.356	-24%	0.324
	B-100	30%	0.758	8%	0.791	-1%	0.972
Al27(MR)	B-20	-76%	0.116	252%	0.122	-10%	0.901
	B-50	-87%	0.094	61%	0.115	-16%	0.835
	B-100	-56%	0.224	-8%	0.879	30%	0.747
P31(MR)	B-20	3%	0.910	-5%	0.834	-15%	0.530
	B-50	1%	0.979	6%	0.825	-25%	0.285
	B-100	-38%	0.320	0%	0.992	-13%	0.595
S34(MR)	B-20	NA	NA	-17%	0.310	-27%	0.135
	B-50	NA	NA	-13%	0.303	-47%	0.031
	B-100	133%	NA	-22%	0.148	-27%	0.192
Ca42(MR)	B-20	2%	0.948	NA	NA	NA	NA
	B-50	-8%	0.816	NA	NA	NA	NA
	B-100	-12%	0.733	NA	NA	NA	NA
Ca44(MR)	B-20	10%	0.758	32%	0.444	-15%	0.633
	B-50	2%	0.952	42%	0.031	-29%	0.348
	B-100	4%	0.870	17%	0.549	-10%	0.765
Sc45(MR)	B-20	-111%	0.103	324%	0.306	89%	0.358
	B-50	139%	0.597	174%	0.355	-23%	0.733
	B-100	973286%	0.374	93%	0.519	49%	0.491
Ti49(MR)	B-20	-85%	0.023	190%	0.306	-7%	0.752
	B-50	-88%	0.020	102%	0.211	-12%	0.678
	B-100	-81%	0.035	-2%	0.969	140%	0.342
V51(MR)	B-20	-42%	0.366	40%	0.003	-37%	0.366
	B-50	-39%	0.425	20%	0.557	33%	0.408
	B-100	28%	0.775	-5%	0.898	6%	0.903
Cr52(MR)	B-20	7%	0.710	71%	0.325	10%	0.579
	B-50	-17%	0.206	44%	0.142	-10%	0.470
	B-100	-36%	0.326	25%	0.355	0%	0.988
Mn55(MR)	B-20	-39%	0.194	36%	0.470	7%	0.690

		2000 Caterpillar C-15					
		Soy-based		Animal-based		Renewable-based	
	B-50	3%	0.917	1%	0.920	-7%	0.694
	B-100	94%	0.492	41%	0.388	9%	0.656
Fe56(MR)	B-20	NA	NA	48%	0.401	63%	0.151
	B-50	NA	NA	23%	0.352	28%	0.346
	B-100	-98%	NA	29%	0.451	13%	0.586
Fe57(MR)	B-20	9%	0.374	NA	NA	NA	NA
	B-50	26%	0.226	NA	NA	NA	NA
	B-100	57%	0.229	NA	NA	NA	NA
Co59(MR)	B-20	16%	0.536	-6%	0.653	-13%	0.343
	B-50	-17%	0.217	-21%	0.104	-23%	0.113
	B-100	1974%	0.384	-57%	0.005	-14%	0.329
Ni60(MR)	B-20	-10%	0.746	51%	0.053	20%	0.317
	B-50	-17%	0.543	8%	0.826	7%	0.806
	B-100	-35%	0.351	-4%	0.866	-4%	0.889
Cu63(MR)	B-20	25%	0.508	18%	0.382	-47%	0.253
	B-50	17%	0.622	246%	0.263	-56%	0.181
	B-100	-13%	0.746	-20%	0.340	-52%	0.215
Zn66(MR)	B-20	-11%	0.627	-5%	0.797	-14%	0.530
	B-50	-19%	0.385	-2%	0.913	-29%	0.214
	B-100	-49%	0.155	-20%	0.436	-22%	0.368
Ga71(LR)	B-20	105%	0.257	-16%	0.747	-42%	0.634
	B-50	21%	0.795	37%	0.516	203%	0.032
	B-100	83%	0.328	10%	0.823	146%	0.252
As75(HR)	B-20	NA	NA	-16%	0.747	-42%	0.634
	B-50	NA	NA	37%	0.516	203%	0.032
	B-100	114016%	NA	10%	0.823	146%	0.252
Rb85(MR)	B-20	-93%	0.221	-44%	0.277	-18%	0.393
	B-50	-93%	0.222	2%	0.967	53%	0.281
	B-100	-74%	0.313	5%	0.901	32%	0.395
Sr88(MR)	B-20	102%	0.442	388%	0.066	-50%	0.631
	B-50	-49%	0.547	141%	0.164	-99%	0.370
	B-100	50%	0.714	405%	0.288	253%	0.284
Y89(LR)	B-20	-18%	0.460	140%	0.179	-8%	0.853
	B-50	-13%	0.594	72%	0.087	-3%	0.955
	B-100	-3%	0.917	56%	0.126	14%	0.728
Nb93(LR)	B-20	14%	0.840	100%	0.189	78%	0.303
	B-50	-61%	0.081	40%	0.416	46%	0.509
	B-100	-14%	0.820	-21%	0.691	35%	0.591
Mo95(MR)	B-20	-2%	0.960	62%	0.175	-11%	0.577
	B-50	-8%	0.711	50%	0.034	5%	0.842
	B-100	10%	0.803	22%	0.457	66%	0.248
Rh103(LR)	B-20	-22%	0.597	21%	0.491	-12%	0.487
	B-50	-29%	0.497	31%	0.398	-23%	0.247
	B-100	-24%	0.563	25%	0.548	0%	0.990
Ag109(LR)	B-20	NA	NA	-12%	0.778	9%	0.880
	B-50	NA	NA	2%	0.968	92%	0.181
	B-100	-20%	NA	49%	0.310	86%	0.227

		2000 Caterpillar C-15					
		Soy-based		Animal-based		Renewable-based	
Cd111(LR)	B-20	-99%	0.363	19%	0.630	52%	0.484
	B-50	-94%	0.384	63%	0.328	-48%	0.462
	B-100	464%	0.453	301%	0.402	26%	0.814
Sb121(MR)	B-20	-60%	0.178	-32%	0.332	-36%	0.513
	B-50	-68%	0.141	-3%	0.959	-55%	0.321
	B-100	-90%	0.063	-74%	0.016	-52%	0.358
Cs133(LR)	B-20	-25%	0.643	67%	0.080	4%	0.745
	B-50	-60%	0.149	18%	0.621	122%	0.254
	B-100	-58%	0.176	19%	0.668	2%	0.926
Ba137(MR)	B-20	89%	0.721	14%	0.783	-81%	0.402
	B-50	-73%	0.646	-10%	0.800	-110%	0.268
	B-100	85528%	0.375	-30%	0.532	52%	0.681
La139(LR)	B-20	46%	0.161	202%	0.353	12%	0.406
	B-50	89%	0.164	47%	0.275	46%	0.017
	B-100	47%	0.653	53%	0.097	62%	0.016
Ce140(LR)	B-20	-93%	0.281	65%	0.344	-4%	0.931
	B-50	-104%	0.227	39%	0.678	-67%	0.148
	B-100	-105%	0.228	-30%	0.598	73%	0.356
Pr141(LR)	B-20	-99%	0.232	86%	0.251	-6%	0.872
	B-50	-109%	0.195	55%	0.571	-24%	0.327
	B-100	-91%	0.264	-35%	0.589	94%	0.136
Nd143(LR)	B-20	-13%	0.907	97%	0.221	40%	0.322
	B-50	-101%	0.246	18%	0.779	-45%	0.102
	B-100	-48%	0.636	30%	0.744	213%	0.238
Sm147(LR)	B-20	-75%	0.269	102%	0.149	13%	0.879
	B-50	-109%	0.125	15%	0.826	42%	0.617
	B-100	-82%	0.245	24%	0.668	56%	0.537
Eu151(LR)	B-20	482%	0.304	371%	0.005	-562%	0.421
	B-50	-45%	0.751	176%	0.193	-376%	0.620
	B-100	190%	0.616	-2%	0.984	-568%	0.474
Dy163(LR)	B-20	34%	0.777	113%	0.344	67%	0.598
	B-50	-52%	0.429	13%	0.785	157%	0.288
	B-100	12%	0.895	1%	0.983	288%	0.131
Ho165(LR)	B-20	305%	0.428	303%	0.111	62%	0.714
	B-50	-70%	0.134	138%	0.370	145%	0.505
	B-100	187%	0.601	310%	0.347	356%	0.180
Yb173(LR)	B-20	-1108%	0.286	-1277%	0.021	-18%	0.937
	B-50	-251%	0.182	-1003%	0.376	-99%	0.626
	B-100	-781%	0.307	-1224%	0.181	778%	0.273
Lu175(LR)	B-20	378%	0.348	71%	0.607	40%	0.530
	B-50	6%	0.970	130%	0.330	78%	0.277
	B-100	126%	0.691	214%	0.129	31%	0.632
W184(LR)	B-20	861%	0.362	39%	0.182	30%	0.325
	B-50	-31%	0.894	4%	0.890	13%	0.773
	B-100	24429%	0.379	94%	0.369	85%	0.432
Pt195(LR)	B-20	0%	0.985	0%	0.976	-3%	0.815
	B-50	-6%	0.872	-2%	0.821	-15%	0.205

		2000 Caterpillar C-15					
		Soy-based		Animal-based		Renewable-based	
	B-100	-66%	0.077	-39%	0.020	-1%	0.945
Tl205(LR)	B-20	-60%	0.476	42%	0.523	-41%	0.461
	B-50	-86%	0.254	70%	0.443	-49%	0.427
	B-100	-97%	0.202	25%	0.485	-23%	0.700
Pb sum	B-20	51%	0.777	11%	0.702	27%	0.328
	B-50	-29%	0.855	-56%	0.271	-15%	0.579
	B-100	35108%	0.377	44%	0.618	15%	0.755
Th232(LR)	B-20	2%	0.956	-48%	0.262	-81%	0.149
	B-50	-21%	0.632	-36%	0.400	-78%	0.161
	B-100	-57%	0.266	-71%	0.122	-83%	0.140
U238(LR)	B-20	-46%	0.590	NA	NA	NA	NA
	B-50	1838%	0.495	NA	NA	NA	NA
	B-100	-86%	0.173	NA	NA	NA	NA

Table K-2. Different Elements Percentage Differences Between the Soy-Based Biodiesel and CARB ULSD base fuel for UDDS Cycle for the MBE4000

		2007 MBE 4000 Soy-based	
		% Difference	P-values
Zn	B-20	-0.01%	0.998
	B-50	-1.11%	0.852
	B-100	-1.99%	0.681
Pb	B-20	-7.21%	0.436
	B-50	-6.19%	0.604
	B-100	-4.53%	0.647
Cr	B-20	-3.13%	0.655
	B-50	-2.48%	0.783
	B-100	-2.38%	0.752
Ir	B-20	-3.77%	0.491
	B-50	-0.26%	0.965
	B-100	-1.70%	0.766
Sn	B-20	305.43%	0.505
	B-50	93.48%	0.662
	B-100	-100.00%	0.374
Pt	B-20	-4.22%	0.416
	B-50	-1.33%	0.821
	B-100	-2.44%	0.660
As	B-20	98.68%	0.523
	B-50	40.42%	0.824
	B-100	100.32%	0.518
Ag	B-20	23.08%	0.110
	B-50	1.78%	0.752
	B-100	3.38%	0.422
Ti	B-20	-100%	0.374
	B-50	-100%	0.495
	B-100	-100%	0.374
Mn	B-20	NA	0.374
	B-50	NA	NA
	B-100	NA	NA
Fe	B-20	NA	0.374
	B-50	NA	NA
	B-100	NA	NA
Co	B-20	NA	NA
	B-50	NA	NA
	B-100	NA	0.374
Mo	B-20	NA	0.374
	B-50	NA	0.272
	B-100	NA	NA
Rh	B-20	NA	NA
	B-50	NA	0.272
	B-100	NA	NA

* Li, Be, V, Ni, Cu, Se, Rb, Sr, Zr, Nb, Ru, Pd, Cd, Sb, Te, Cs, Ba, La, Ce, Hf, Ta, W, Au. Tl, U values were under detection limit, so they are not included in the table.