Final Report

CARB Comprehensive B5/B10 Biodiesel Blends Heavy-Duty Engine Dynamometer Testing

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Disclaimer

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Abstract

The reduction of emissions from diesel engines has been one of the primary elements in obtaining air quality and greenhouse gas reduction goals within California and throughout the nation. A key element of the California Air Resources Board's (CARB's) efforts in reducing greenhouse gases over the past few years has been the implementation of the Low Carbon Fuel Standard (LCFS), the goal of which is to reduce carbon intensity of transportation fuels by 10% by 2020. This will predominantly be achieved by introducing more renewable fuels to partially replace conventional fuels for transportation applications.

Biodiesel is a renewable fuel that has the potential for diesel fuel applications, but there is a tendency for biodiesel to increase NO_x emissions, which remains an important issue with respect to implementing biodiesel within California. In order to determine whether increased levels of biodiesel use within the State of California would affect air quality, CARB conducted an extensive study on the emissions impacts of biodiesel use. The results of this study showed that B20 and higher biodiesel blends would likely increase NO_x emissions in CARB diesel fuels. The potential impact of lower level biodiesel blends, such as B5, on NO_x, on the other hand, was unclear, showing increases in some cases, but not in others. A subsequent study found increases in NO_x for a B5 soy-based and waste vegetable oil (WVO) biodiesel, but either no increases or a slight reduction for a B5 animal based biodiesel.

The goal of this study was to conduct a more comprehensive study of the emissions impacts of lower level B5 and B10 blends in CARB diesel fuel. For this study, B5 and B10 biodiesel blends with both an animal-based and a soy-based biodiesel feedstock were tested. These fuels were tested in a 2006 Cummins ISM engine and a 1991 Detroit Diesel Corporation (DDC) Series 60 Engine over the standard Federal Test Procedure (FTP), the Urban Dynamometer Driving Schedule (UDDS), and the Supplemental Emissions Test (SET).

NO_x emissions results for the testing of the 2006 Cummins ISM engine showed a statistically significant 1.0% and 1.9% increase, respectively, for the B5-soy and the B10-soy blends compared to the CARB diesel fuel for the FTP cycle, and a statistically significant increase of 3.6% for the B10-soy blend compared to the CARB diesel fuel for the UDDS. NO_x emissions for the 1991 DDC Series engine showed a statistically significant increase of 1.0% and 3.2%, respectively, for the B5-soy blend for the FTP and UDDS cycles. Similarly, the B10-soy blend showed a statistically significant increase of 1.5% and 1.3%, respectively, for the FTP and SET cycles. NO_x emissions for the animal biodiesel blends did not show the more consistent NO_x increases found for the soy biodiesel blends, with only the B10-animal blend showing a statistically significant increase of 0.7% for the FTP on the 1991 DDC engine.

Acronyms and Abbreviations

ARB ....Air Resources Board
BSFC………………………………..brake specific fuel consumption
CARB...California Air Resources Board
CE-CERT...College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CCR…………………………………California Code of Regulations
CFR ....Code of Federal Regulations
CO ....carbon monoxide
CO_2...carbon dioxide
CVS…………………………………Constant Volume Sampling
FTP...Federal Test Procedure
g/bhp-hr ....grams per brake horsepower hour
hp……………………………………horsepower
MEL ....CE-CERT's Mobile Emissions Laboratory
NMHC...non-methane hydrocarbons
NO_x ....nitrogen oxides
NO_2 ....nitrogen dioxide
LCFS...Low Carbon Fuel Standard
PM...particulate matter
QA...quality assurance
QC ....quality control
THC...total hydrocarbons
ULSD ....ultralow sulfur diesel

Executive Summary

The Low Carbon Fuel Standard (LCFS) is one of the main regulations being implemented by the California Air Resources Board (CARB) in its efforts to reduce greenhouse gases. Biodiesel is one alternative to conventional diesel fuel that could be used to partially meet the LCFS objectives however, many studies have reported emissions increases for oxides of nitrogen (NO_x) with biodiesel blends. In order to investigate the impact of biodiesel fuels on NO_x emissions, CARB, in conjunction with the University of California Riverside (UCR) and UC Davis (UCD), conducted one of the most comprehensive biofuels emissions characterization studies to date. This large study showed a definitive trend of NO_x increases for B20 and higher blends relative to a CARB diesel fuel, but the trends in NO_x emissions for the B5 blends were less clear, with increases seen in some cases, but not others. A subsequent study found increases in NO_x for low level biodiesel blends with a soy-based and waste vegetable oil (WVO) biodiesel, but either no increases or a slight reduction for low level blends with an animal-based biodiesel.

The present study expands upon the earlier CARB/UCR/UCD studies to provide more comprehensive information on the emissions impacts of lower level B5 and B10 blends in CARB diesel fuel. The results of this study will be used in conjunction with results from other associated or related studies to evaluate the emissions impacts of biodiesel use in CARB diesel fuel. For this study B5 and B10 blends were evaluated over a test sequence that is similar to that used for the emissions equivalent diesel certification procedure. Biodiesel blends included B5 and B10 blends with both an animal-based and a soy-based biodiesel feedstock. Testing was conducted in CE-CERT's heavy-duty engine dynamometer laboratory with a 2006 Cummins ISM engine and a 1991 Detroit Diesel Corporation (DDC) Series 60 Engine. The test sequence included the standard Federal Test Procedure (FTP), the Urban Dynamometer Driving Schedule (UDDS), and the Supplemental Emissions Test (SET).

Test Fuels

The test fuels included a baseline CARB diesel fuel, and B5 and B10 blends with biodiesels from two different feedstock sources. The feedstocks for the biodiesel included one soy-based and one animal-based feedstock. The CARB diesel fuel was the blendstock used for the B5/B10 fuels, and the fuel to which the B5 and B10 fuels were compared.

Test Engines

Two engines were used for this test program, including a 2006 model year Cummins ISM engine and a 1991 DDC series 60 engine. The Cummins engine was a 370 horsepower (hp), 10.8 liter, in-line, six cylinder, four-stroke diesel engine equipped with a turbocharger with a charge air cooler and exhaust gas recirculation (EGR). The 1991 DDC Series 60 engine was a 360 hp, 11.1 liter, in-line, six cylinder, four stroke diesel engine with a turbocharger with after cooler.

Test Procedure

Three test cycles were used for this program, the Federal Test Procedure (FTP), the Urban Dynamometer Driving Schedule (UDDS), and the Supplemental Emissions Test (SET). The SET cycle is a 13-mode, steady state engine dynamometer test cycle.

The test sequence for the FTP and the UDDS emissions testing was conducted using one of the hot start sequences described under title 13, California Code of Regulations (CCR), section 2282(g)(4)(c) 1.b Alternative 1. Where "R" in this case is the baseline CARB diesel fuel and "C" is the candidate biodiesel blend being tested, the test sequence used is shown in Table ES-1. This sequence was repeated over two days to provide a total of 8 replicates on both the baseline CARB diesel and the biodiesel blend.

Table ES-1. Testing Protocol for Certification Procedure

Day	Fuel Test Sequence
1	RC CR RC CR
2	RC CR RC CR

For the SET cycle, a total of 4 tests were run for each day of SET testing. This test sequence is presented in Table ES-2 for the two day sequence. This sequence was repeated over two days to provide a total of 4 replicates on both the baseline CARB diesel and the biodiesel blend.

Table ES-2. Testing Protocol for SET Cycle

Day	Fuel Test Sequence
1	RC CR
2	RC CR

The engine emissions testing was performed at UCR's Bourns College of Engineering-Center for Environmental Research and Technology's (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.

For all tests, standard emissions measurements of non-methane hydrocarbons (NMHC), total hydrocarbons (THC), carbon monoxide (CO), NO_x, particulate matter (PM), and carbon dioxide (CO_2) were performed, along with fuel consumption measurement via carbon balance. The emissions measurements were made using the standard analyzers in CE-CERT's heavy-duty Mobile Emissions Laboratory (MEL) trailer. Additional analyses were also conducted on a subset of FTP tests to evaluate the composition of the particles on a subset of tests, including organic carbon (OC) and elemental carbon (EC) via thermal optical reflectance (TOR), ions via ion chromatography, and metallic elements using the x-ray fluorescence (XRF) method. Additional analyses were also conducted to evaluate carbonyls on a subset of FTP tests.

Results

A summary of all the results for this data set is provided below. Note that the results summary focuses on results that were found to be either statistically significant or marginally statistically significant.

Figure E-1 shows the NO_x emission results for the testing of the different B5/B10 biodiesel blends on a gram per brake horsepower hour (g/bhp-hr) basis for 2006 Cummins ISM and 1991 DDC Series 60 Engine for different cycles. NO_x emissions results for the testing of the 2006 Cummins ISM engine showed a statistically significant 1.0% and 1.9% increase, respectively, for the B5-soy and the B10-soy blends compared to the CARB diesel fuel for the FTP cycle, and a statistically significant increase of 3.6% for the B10-soy blend compared to the CARB diesel fuel for the UDDS. NO_x emissions for the 1991 DDC Series 60 engine showed a statistically significant increase of 1.0% and 3.2%, respectively, for the B5-soy blend for the FTP and UDDS cycles. Similarly, the B10-soy blend showed a statistically significant increase of 1.5% and 1.3%, respectively, for the FTP and SET cycles.

NO_x emissions for the animal biodiesel blends did not show the more consistent NO_x increases found for the soy biodiesel blends, with only the B10-animal blend showing a statistically significant increase of 0.7% for the FTP on the 1991 DDC series 60 engine.

PM emissions showed consistent reductions for the biodiesel blends for both engines for the FTP and SET cycles. For the 2006 Cummins ISM engine, statistically significant reductions for PM ranged from 5.8-15.1% with all B5 and B10 biodiesel blends tested over the FTP cycle and from 6.7-14.3% for B5-, B10-animal, and B10-soy blends over the SET cycle. For the 1991 DDC Series 60 engine, statistically significant reductions in PM ranged from 7.5%-16.5% for the B5 and B10 biodiesel blends over the FTP cycle and from 6.0%-9.4% for the SET cycle. There were some inconsistencies in the PM emissions results for the UDDS cycle, with even a marginally statistically significant increase of 6.4% for the B5-soy compared to the CARB diesel fuel for the 2006 Cummins ISM engine and a 26.6% increase for the B5-soy biodiesel compared to CARB diesel fuel for the 1991 DDC Series 60 engine. This might be due to the low load nature of this cycle.

THC emissions showed a general decreasing trend for most biodiesel blends over most of the test cycles compared to the CARB diesel fuel, but these differences were only statistically significant or marginally statistically significant for the B5-soy blend for the SET cycle for the 2006 Cummins ISM engine and the B5-animal blend for the SET cycle and the B10-soy blend for the FTP for the 1991 DDC series 60 engine.

CO emissions results showed a general trend of reductions with the biodiesel blends, although these differences were not statistically significant for all biodiesel blends or cycles. The statistically significant and marginally statistically significant reductions ranged from 2.0%-7.9% for the 2006 Cummins ISM engine and 2.3%-7.3% for the 1991 DDC series 60 engine for the different biodiesel blends and cycles. There was a somewhat stronger trend of biodiesel CO reductions for the 1991 DDC series 60 engine, which showed CO reductions for nearly all biodiesel blends and cycles with the exception of some UDDS cycles, compared to the 2006 Cummins ISM engine.

BSFC results showed a general increasing trend with the biodiesel blends, although this was not seen for all biodiesel blend, cycle, and engine combinations. For the 2006 Cummins ISM engine, these BSFC increases ranged from 0.5 to 2.3%. For the 1991 DDC series 60 engine, these BSFC increases ranged from 0.7 to 3.2%. These differences can be attributed to the differences in the energy contents of the fuels. CO_2 emissions did not consistent fuel trends over the range of blends, cycles, and engines tested, with most differences not being statistically significant.

There were not any consistent fuel differences between the CARB diesel and the biodiesel blends for carbonyls. Formaldehyde and Acetaldehyde were the highest carbonyl emissions, consistent with previous studies, with some other higher molecular weight carbonyls seen at much lower levels.

The results showed some differences in the carbonaceous portion of the PM with different fuels, but not in other components. The results for the Elemental Carbon/Organic Carbon (EC/OC) were not as consistent as those for the total PM mass. Statistically significant reductions in EC were seen for the B5 animal, B10 soy and B10 animal blends for the 1991 DDC Series 60 engine, but only for the B10 animal blend for the 2006 Cummins ISM engine. For OC emissions, the only statistically significant difference found was a 20.5% increase for the B5 soy blend for the 1991 DDC Series 60 engine. The less consistent trends for EC/OC emissions could be due to the lower blend levels or due to the fewer number of samples collected. The emissions of individual elements and ions were at very low levels in comparison with the PM mass. A number of elements were found at levels above the background levels, including Na, Mg, Si, P, S, Ca, Fe, and Zn. Several ions were measureable for most of the test fuel combinations, including sulfate, nitrate, sodium, ammonium, and calcium. Neither the elements nor ions showed significant differences between the different fuels tested.

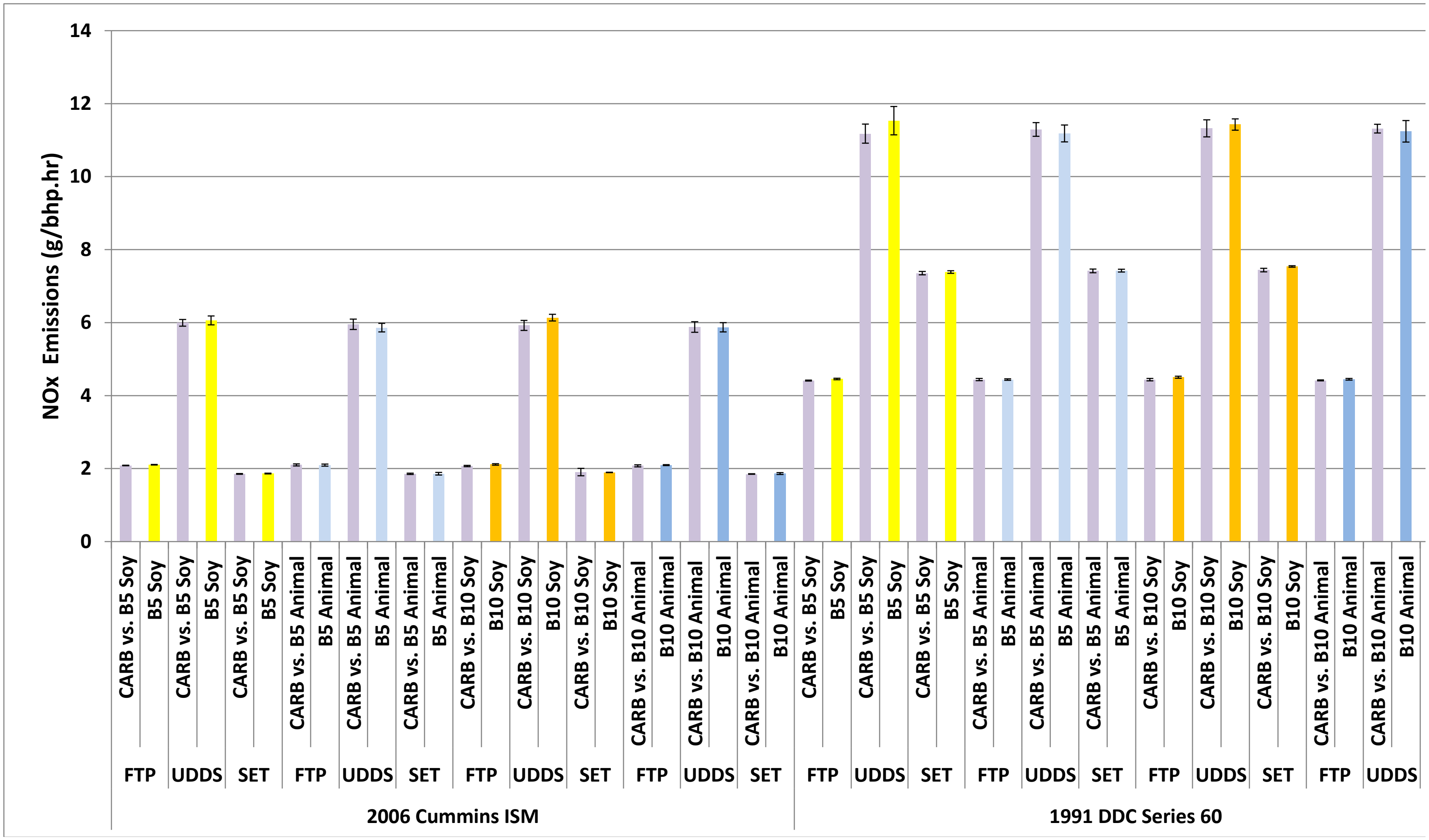

Figure E-1. Average NO_x Emission Results for B5 and B10 Soy- and Animal-based Biodiesel Blends 2006 Cummins ISM and 1991 DDC Series Engines for FTP, UDDS, and SET Cycle

1 Introduction

The California Air Resources Board (CARB) has implemented a number of programs/regulations to reduce greenhouse gas emissions in response to the AB32, the Global Warming Solutions Act. In recent years, CARB has examined renewable fuels that could potentially be introduced into the fuel market as part of its efforts to implement the Low Carbon Fuel Standard (LCFS). Biodiesel is one of the more popular renewable fuels, as a substitute for diesel fuel. Lower blends of biodiesel can be used in existing diesel engines with no or minor engine modifications. From an air quality perspective, biodiesel blends can reduce total hydrocarbon (THC), particulate matter (PM), and carbon monoxide (CO) emissions [1–6]. It can also reduce overall carbon dioxide (CO_2) emissions when a complete carbon lifecycle is considered [3,7,8]. However, biodiesel blends can increase emissions of oxides of nitrogen (NO_x) [1,2,4,7,9].

In recent years, many researchers have studied the impact of biodiesel blends on NO_x emissions [4,7,8,10–13]. These studies have often been limited, however, in terms of the number of engines and test replicates, with many studies also focusing on Federal fuels that cannot be sold in states with more stringent fuel regulations, such as California and Texas. To better investigate the impact of biodiesel fuel and blends with CARB diesel fuels on NO_x emissions and other emissions components, such as PM and toxics, CARB, in conjunction with the University of California at Riverside (UCR) and UC Davis (UCD), conducted one of the most comprehensive biofuels emissions studies to date for diesel applications. The results of this study showed that B20 and higher biodiesel blends would likely increase NO_x emissions in CARB diesel fuels. The potential impact of lower level biodiesel blends, such as B5, on NO_x, on the other hand, was unclear, showing increases in some cases, but not in others [1,2]. A subsequent study found increases in NO_x for low level biodiesel blends with a soy-based and waste vegetable oil (WVO) biodiesel, but either no increases or a slight reduction for low level blends with an animal-based biodiesel [14].

The present study expands upon the earlier CARB/UCR/UCD studies to provide more comprehensive information on the emissions impacts of lower level B5 and B10 blends in CARB diesel fuel. The results of this study will be used in conjunction with results from other associated or related studies to evaluate the emissions impacts of biodiesel use in CARB diesel fuel. For this study B5 and B10 blends were evaluated over a test sequence that is similar to that used for the emissions equivalent diesel certification procedure. Biodiesel blends included B5 and B10 blends with both an animal-based and a soy-based biodiesel feedstock. Testing was conducted in CE-CERT's heavy-duty engine dynamometer laboratory with a 2006 Cummins ISM engine and a 1991 Detroit Diesel Corporation (DDC) Series 60 Engine. The test sequence included the standard Federal Test Procedure (FTP), the Urban Dynamometer Driving Schedule (UDDS), and the Supplemental Emissions Test (SET).

2 Experimental Procedures

2.1 Test Fuels

The test fuels included a baseline CARB diesel fuel, and B5 and B10 blends with biodiesels from two different feedstock sources. The biodiesel feedstocks included one soy-based and one animal-based feedstock. The CARB diesel was an in-use diesel fuel obtained from a local supplier. The neat biodiesel fuels were obtained from BQ-9000 suppliers. The CARB diesel was the blendstock used for the B5/B10 fuels, and the fuel to which the B5 and B10 fuels were compared.

The CARB diesel fuel was tested for D975 properties, plus additional properties of interest. The properties for the CARB diesel fuel are provided in Table 2-1. In addition to the primary fuel analyses, additional tests were also conducted for C/H/O content via ASTM D5291 and heating value via ASTM D240. Triplicate analyses were performed on a subset of properties that were of greater interest in characterizing the fuel, such as cetane number, density, and aromatic content.

Table 2-1. Properties of CARB Diesel

Property	ASTM Test Method	Units	Results
API Gravity	ASTM D4052	API	38.8
Specific Gravity	ASTM D4052		0.831
Total Aromatics	ASTM D5186	vol%	22.6
Cetane number	ASTM D613		53.4
Heating Value	ASTM D240	BTU/lb	19773
Carbon Unit per Energy		Carbon lbs. /BTU	4.36×10^{-5}
Carbon	ASTM D5291	wt%	86.17
Hydrogen	ASTM D5291	wt%	13.63
Distillation, IBP	D 86	^{o}F	349.8
5%			404.8
10%			429.1
15%			447.9
20%			462.6
30%			490.1
40%			514.4
50%			536.8
60%			558
70%			578.5
80%			602.3
90%			634.8
95%			659.9
Distillation - EP			680.7
Recovery		mL	98.3
Residue			1.4
Loss			0.3
Flash Point	ASTM D93	^{o}F	163
Water and Sediment	ASTM D2709	% Vol.	< 0.02
Viscosity, 40 ^{o}C	ASTM D445	mm^2/s	3.069
Sulfur	ASTM D5453	ppm wt	7.8

The baseline neat biodiesel fuels were tested for ASTM D6751 properties. The specifications and properties for the two neat biodiesel fuels are provided in Table 2-2. Additional analyses for the biodiesel fuels included C/H/O content via ASTM D5291 and heating value via ASTM D240. Triplicate analyses were performed for cetane number and density.

Table 2-2. Properties of Soy-based and Animal-based Biodiesels

Property	ASTM Test Method	Units	Specification	Animal	Soy
API Gravity@60°F	ASTM D4052			30.3	28.5
Specific Gravity @60°F	ASTM D4052			0.875	0.885
Cetane Number	ASTM D613		47 min.	58.0	49.1*/44.9**
Heating value	ASTM D240	BTU/lb		17172	17128
Carbon Unit per Energy		Lbs. carbon/BTU		4.45×10^{-5}	4.50×10^{-5}
Carbon	ASTM D5291	wt%		76.34	77
Hydrogen	ASTM D5291	wt%		12.31	11.8
Oxidation Stability	EN15751	hours	3 hour minimum	21.6	16.4
Free Glycerin	ASTM D6584	% mass	0.02 max.	0.010	<0.005
Total Glycerin	ASTM D6584	% mass	0.240 max.	0.072	<0.005
Monoglycerides	ASTM D6584	% mass	Report	0.220	0.112
Diglycerides	ASTM D6584	% mass	Report	<0.05	<0.05
Triglycerides	ASTM D6584	% mass	0.050 max.	<0.05	<0.05
Flash Point	ASTM D93	^{o}C	130 min.	165	160
Water and Sediment	ASTM D2709	% Vol.	0.05 max.	< 0.02	< 0.02
Kinematic Viscosity, 40^{o}C	ASTM D445	mm^2/s	1.9 – 6.0	4.714	4.097
Ash	ASTM D482	% mass		<0.001	<0.001
Sulfur	ASTM D5453	ppm	15 max.	5.4	0.7
Copper Strip Corrosion	ASTM D130		No. 3 max.	1A	1A
Pour Point	ASTM D97	^{o}C		12	1
Acid Number	ASTM D664	0.3 max.	Mg KOH/g	0.41	0.19
Phosphorous content	ASTM D4951	% mass	0.001 max.	<5	<5
Calcium	ASTM D7111			<100ppb	<100ppb
Potassium,				1.725ppm	1.839ppm
Magnesium				<100ppb	<100ppb
Sodium				<1ppm	<1ppm

*Producers Certificate of Analysis; **Analysis by outside laboratory

The biodiesel blends were blended at the B5 and B10 levels for both the soy-based and animal-based blends. The B5/B10 fuels were blended volumetrically using the CARB reference fuel as the base diesel fuel. The B5/B10 fuels were tested for D975 properties, plus other properties that might be of relevance for the blends. The fuel analysis results are provided in Table 2-3. Triplicate analyses were performed for cetane number and density.

Table 2-3. Properties of the B5/B10 Soy-based and Animal-based Blends

Property	ASTM Test Method	Units	B5 Animal	B5 Soy	B10 Animal	B10 Soy
API Gravity@60°F	ASTM D4052		38.2	38.3	38.0	37.8
Specific Gravity @60°F	ASTM D4052		0.834	0.834	0.835	0.836
Cetane Number	ASTM D613		56.3	52.9	57.1	53.4
Heating value	ASTM D240	BTU/lb	19590	19609	19480	19509
Carbon Unit per Energy		Carbon lbs. /BTU	4.36×10^{-5}	4.33×10^{-5}	4.37×10^{-5}	4.37×10^{-5}
Biodiesel content	ASTM D7371		5.3	5.2	9.9	9.8
Carbon	ASTM D5291	wt%	85.44	84.87	85.04	85.17
Hydrogen	ASTM D5291	wt%	13.56	13.53	13.5	13.49
Flash Point	ASTM D93	^oC	76	76	75	73
Water and Sediment	ASTM D2709	% Vol.	< 0.02	< 0.02	< 0.02	< 0.02
Kinematic Viscosity, 40^{o}C	ASTM D445	mm^2/s	3.131	3.105	3.178	3.147
Sulfated Ash	ASTM D874	% mass	<0.001	<0.001	<0.001	<0.001
Sulfur	ASTM D5453	ppm	7.5	7.6	7.9	6.5
Copper Strip Corrosion	ASTM D130		1A	1A	1A	1A
Lubricity	ASTM D6079	Microns	201	319	214	183
Pour Point	ASTM D97	^oC	-6	-6	-6	-6
Acid Number	ASTM D664	Mg KOH/g	<0.05	<0.05	<0.05	<0.05
Ramsbottom Carb. Res.	ASTM D524	% mass	0.04	0.06	0.06	0.04

2.2 Test Engine

Two engines were used for this test program, including a 2006 model year Cummins ISM engine and a 1991 Detroit Diesel Corporation (DDC) series 60 engine. The 2006 Cummins ISM represents the last generation of diesel engine technology that did not require aftertreatment. The 1991 DDC Series 60 engine is the engine that has traditionally been used for the emissions equivalent diesel certification procedure. The specifications of these engines are provided in Table 2-4.

Table 2-4. Test Engine Specifications

Engine Manufacturer	Cummins, Inc.	Detroit Diesel Corp.
Engine Model	ISM 370	Series 60
Model Year	2006	1991
Engine Family Name	6CEXH0661MAT	MDD11.1FZA2
Engine Type	In-line 6 cylinder, 4 stroke	In-line 6 cylinder, 4 stroke
Displacement (L)	10.8	11.1
Power Rating (hp)	370 @ 2100 rpm	360 @ 1800 rpm
Fuel Type	Diesel	Diesel
Induction	Turbocharger w/ charge air cooler	Turbocharger with after cooler

2.3 Test Matrix and Test Sequence

Testing for each fuel/blend pair was conducted separately for each test cycle. A total of four fuel comparisons were made for each engine and cycle. This included the comparisons of the CARB diesel with B5-soy, B10-soy, B5-animal, and B10 animal.

Three test cycles were used for this program, the Federal Test Procedure (FTP), the Urban Dynamometer Driving Schedule (UDDS), and the Supplemental Emissions Test (SET). The SET cycle is a 13-mode, steady state engine dynamometer test cycle. These cycles are described in Appendix A.

The test sequence for the FTP and the UDDS emissions testing was conducted using one of the hot start sequences described under title 13, California Code of Regulations (CCR), section 2282(g)(4)(c) 1.b Alternative 1. Where "R" in this study is the baseline CARB diesel fuel and "C" is the candidate biodiesel blend being tested [15]. This test sequence is shown in Table 2-5. This sequence was repeated over two days to provide a total of 8 replicates on both the baseline CARB diesel and the biodiesel blend.

Table 2-5. Testing Protocol for FTP and UDDS

Day	Fuel Test Sequence
1	RC CR RC CR
2	RC CR RC CR

Since the SET cycle is longer than the FTP, fewer tests were conducted each day. A total of 4 tests were run for each day of SET testing. This test sequence is presented in Table 2-6 for the two day sequence. Although fewer replicates are being conducted on the SET cycle, this cycle contains 13 different steady state segments, which provides additional levels of replication for statistical comparisons. This sequence was repeated over two days to provide a total of 4 replicates on both the baseline CARB diesel and the biodiesel blend.

Table 2-6. Testing Protocol for SET Cycle

Day	Fuel Test Sequence
1	RC CR
2	RC CR

An engine map was conducted at the beginning of each test day on the CARB diesel fuel. This provided consistent preconditioning for each test day. The engine map on the CARB diesel fuel for the first day for a given test fuel comparison was used for all subsequent emissions testing on both the reference and candidate fuels.

2.4 Emissions Testing

The engine dynamometer emissions testing was performed in UCR's Bourns College of Engineering-Center for Environmental Research and Technology's (CE-CERT's) heavy-duty engine dynamometer laboratory. This laboratory is equipped with a 600-hp General Electric DC electric engine dynamometer.

For all tests, standard emissions measurements of total hydrocarbons (THC), non-methane hydrocarbons (NMHC), CO, NO_x, PM, and CO_2 were made for each test. Fuel consumption was determined from these emissions measurements via carbon balance using the densities and carbon weight fractions from the fuel analysis. 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 B, with more details on the MEL provided in Cocker et al. (2004a,b) [16,17].

In addition to the standard measurements for PM mass, additional PM samples for a subset of tests were collected for additional chemical analyses. These analyses will include organic carbon (OC) and elemental carbon (EC) via thermal optical reflectance (TOR), ions via ion chromatography (IC) analysis, and metallic elements using the x-ray fluorescence (XRF) method as per EPA IO-3 by an outside laboratory. These analyses were only conducted for the FTP testing on any given fuel, and only in triplicate for each test fuel combination.

Additional samples were also collected for analysis of carbonyl species on a subset of tests. Samples for carbonyl analysis were collected onto 2,4-dinitrophenylhydrazine (DNPH) coated silica cartridges (Waters Corp., Milford, MA). Speciation measurements for carbonyl groups, such as aldehydes and ketones, were carried out using a High Performance Liquid Chromatography (HPLC). These analyses were only conducted for the FTP testing on any given fuel, and only in triplicate for each test fuel combination.

3 Heavy-duty Engine Dynamometer Testing Results

The results of the engine dynamometer testing for each pollutant and fuel consumption are summarized in this section. The results presented in the figures represent the average of all test runs performed on that fuel for the specific engine and cycle. The error bars represent one standard deviation on the average value. The tables show the average emission values, the percentage differences for the different biodiesel fuels compared to the CARB diesel fuel, and the associated p-values for statistical comparisons using a 2-tailed, 2-sample, equal-variance t-test. Each B5/B10 biodiesel blend was compared against the CARB diesel fuel tests conducted over the two day test sequence on that particular B5 or B10 blend. The CARB diesel fuel values for the individual comparisons are denoted in the figures as "CARB vs. Blend Name". The statistical analyses provide information on the statistical significance of the different individual findings. This section focuses predominantly on results that were found to be either statistically significant or marginally statistically significant. For the discussion in this report, results are considered to be statistically significant for p values ≤ 0.05, meaning that the probability that the compared emissions are the same is less than or equal to 5 percent. These values are shown in bold in the Tables below. Results were considered marginally statistically significant for $0.05 \leq p$ values<0.1.

3.1 NO_x Emissions

The NO_x emission results on a gram per brake horsepower hour (g/bhp-hr) basis for the testing of the different B5 and B10 biodiesel blends for the 2006 Cummins ISM and 1991 DDC Series 60 engines for different test cycles are presented in Figure 3-1. Table 3-1 shows the average emission values and percentage differences for the different fuels and cycles, along with the associated p-values for statistical comparisons using a t-test. Table 3-2 shows the average emission values and percentage differences for the 13 modes of the SET cycle, along with the associated p-values for statistical comparisons using a t-test.

NO_x emissions results for the testing of the 2006 Cummins ISM engine showed a statistically significant 1.0% and 1.9% increase, respectively, for the B5-soy and the B10-soy blends compared to the CARB diesel fuel for the FTP cycle. For the UDDS cycle for this engine, only the B10-soy blend showed a statistically significant increase of 3.6% compared to the CARB diesel fuel, whereas the differences for the B5-soy blend were not statistically significant. Looking at all the different test cycles results for the 2006 Cummins ISM engine, none of the differences seen in NO_x emissions for the B5/B10 animal-based fuels compared to the CARB diesel fuel were statistically significant.

For the 1991 DDC Series 60 engine, the B5-soy blend showed a statistically significant increase of 1.0% and 3.2%, respectively, for the FTP and UDDS cycles. Similarly, the B10-soy blend showed a statistically significant increase of 1.5% and 1.3%, respectively, for the FTP and SET cycles. The B10-animal blend showed a statistically significant increase of 0.7% for the FTP, but the B10-animal blend did not show statistically significant differences for the other cycles. The B5-animal blend did not show any statistically significant differences for NO_x for any of the three cycles.

Some statistically significant differences were also found for individual modes of the SET cycle, as shown in Table 3-1, even though the overall SET emissions differences were statistically significant only for the B10-soy blend for the 1991 DDC series 60 engine. Table 3-2 shows that some statistically significant increases were found, ranging from 1.6-4.4%, respectively, for the B5-soy and B10-soy blends for the 2006 Cummins ISM engine. B10-animal showed a 3.1% marginally statistically significant reduction for the 2006 Cummins ISM engine for mode 1, which is the idle mode. For the 1991 DDC series 60 engine, statistically significant and marginally statistically significant increases for the biodiesel blends ranged from 1.0 to 2.9% for different modes.

Previous studies have shown a tendency for biodiesel blends to increase NO_x emissions compared to regular diesel fuel, although this trend is not seen in many studies and can depend on the blend level, test engine, the base test fuel and the biodiesel fuel, number of replicates, and other factors [1,2,4,7]. Fuel density, cetane number, fuel chemical composition (carbon chain length and number of double bonds), and combustion chemistry and stoichiometry are some of the factors that can contribute to increases in NO_x emissions when biodiesel is used, as discussed in greater detail in the literature [1,2,4,6,7,18–24]. The magnitude of the NO_x emissions increases can also change with the biodiesel feedstock, with more saturated feedstocks, such as animal tallow, often showing smaller or no increases [2,6,8].

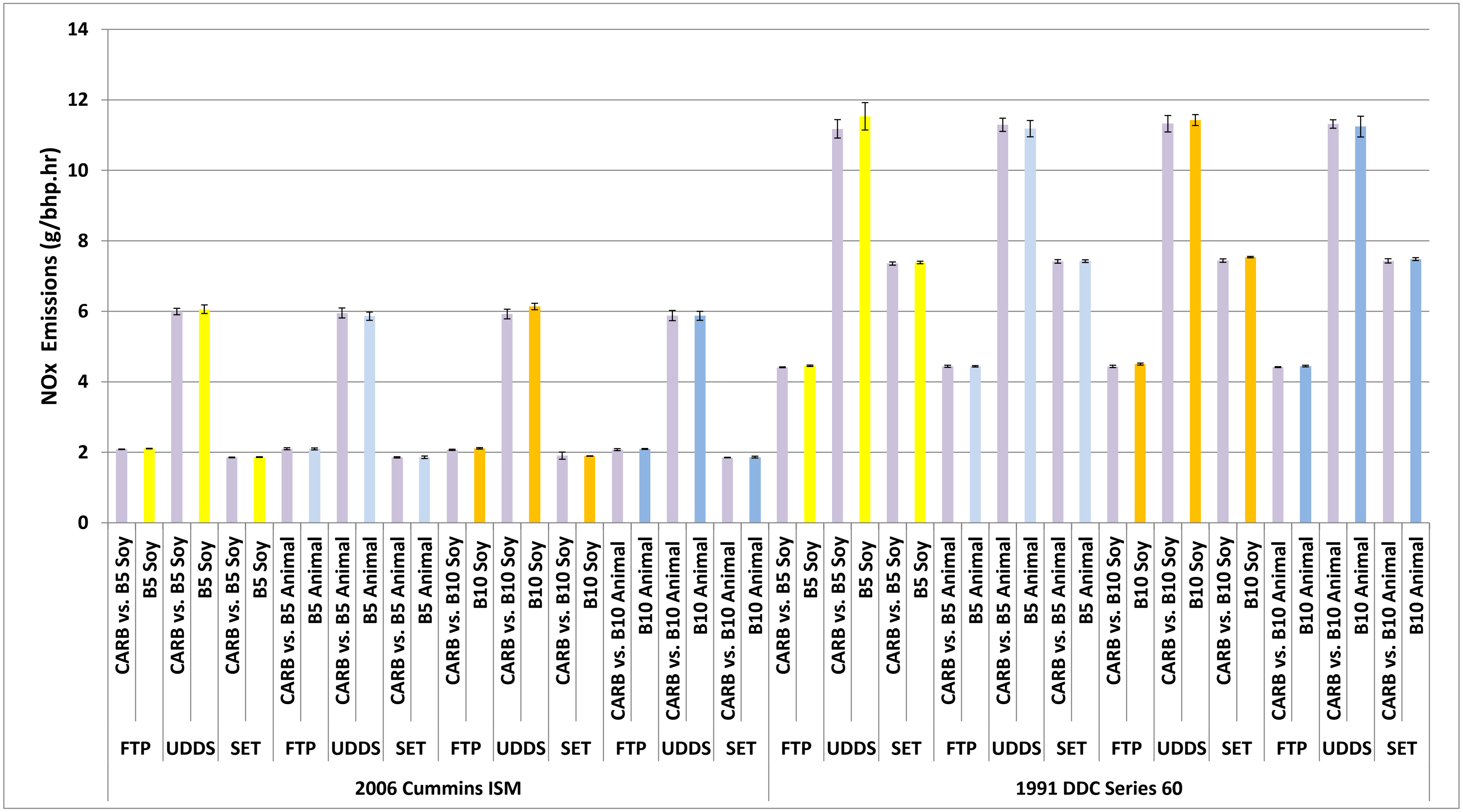

Figure 3-1.Average NO_x Emission Results for B5 and B10 Soy- and Animal-based Biodiesel Blends 2006 Cummins ISM and 1991 DDC Series Engines for FTP, UDDS, and SET Cycle

Table 3-1. NO_x (g/bhp-hr) Percentage Differences Between the Biodiesel Blends and the CARB Reference Fuel for the 2006 Cummins ISM and 1991 DDC Series 60 Engines

	Test Cycle	Fuel Type			
			Ave. (g/bhp.hr)	% Diff vs. CARB	P-values
2006 Cummins ISM	FTP	CARB vs. B5 Soy	2.086		
		B5 Soy	2.107	**1.0%**	**0.000**
	UDDS	CARB vs. B5 Soy	5.994		
		B5 Soy	6.059	1.1%	0.227
	SET	CARB vs. B5 Soy	1.853		
		B5 Soy	1.864	0.6%	0.162
	FTP	CARB vs. B5 Animal	2.101		
		B5 Animal	2.094	-0.3%	0.615
	UDDS	CARB vs. B5 Animal	5.954		
		B5 Animal	5.861	-1.6%	0.165
	SET	CARB vs. B5 Animal	1.857		
		B5 Animal	1.860	0.1%	0.909
	FTP	CARB vs. B10 Soy	2.072		
		B10 Soy	2.112	**1.9%**	**0.000**
	UDDS	CARB vs. B10 Soy	5.924		
		B10 Soy	6.136	**3.6%**	**0.003**
	SET	CARB vs. B10 Soy	1.906		
		B10 Soy	1.896	-0.5%	0.858
	FTP	CARB vs. B10 Animal	2.077		
		B10 Animal	2.095	0.8%	0.125
	UDDS	CARB vs. B10 Animal	5.880		
		B10 Animal	5.872	-0.1%	0.910
	SET	CARB vs. B10 Animal	1.851		
		B10 Animal	1.863	0.6%	0.401
1991 DDC Series 60	FTP	CARB vs. B5 Soy	4.411		
		B5 Soy	4.456	**1.0%**	**0.000**
	UDDS	CARB vs. B5 Soy	11.178		
		B5 Soy	11.532	**3.2%**	**0.050**
	SET	CARB vs. B5 Soy	7.356		
		B5 Soy	7.386	0.4%	0.363
	FTP	CARB vs. B5 Animal	4.438		
		B5 Animal	4.441	0.1%	0.813
	UDDS	CARB vs. B5 Animal	11.294		
		B5 Animal	11.182	-1.0%	0.306
	SET	CARB vs. B5 Animal	7.416		
		B5 Animal	7.426	0.1%	0.771
	FTP	CARB vs. B10 Soy	4.437		
		B10 Soy	4.504	**1.5%**	**0.008**
	UDDS	CARB vs. B10 Soy	11.322		
		B10 Soy	11.428	0.9%	0.298

	SET	CARB vs. B10 Soy	7.440		
		B10 Soy	7.540	**1.3%**	**0.008**
	FTP	CARB vs. B10 Animal	4.415		
		B10 Animal	4.447	**0.7%**	**0.003**
	UDDS	CARB vs. B10 Animal	11.314		
		B10 Animal	11.243	-0.6%	0.535
	SET	CARB vs. B10 Animal	7.433		
		B10 Animal	7.485	0.7%	0.209

Table 3-2. NO_x (g/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for 2006 Cummins ISM and 1991 DDC Series 60 and Different Modes of SET Cycle

		Average								Percentage Difference				P-value			
	Mode	CARB vs. B5 Soy	B5 Soy	CARB vs. B5 Animal	B5 Animal	CARB vs. B10 Soy	B10 Soy	CARB vs. B10 Animal	B10 Animal	CARB vs. B5 Soy	CARB vs. B5 Animal	CARB vs. B10 Soy	CARB vs. B10 Animal	CARB vs. B5 Soy	CARB vs. B5 Animal	CARB vs. B10 Soy	CARB vs. B10 Animal
2006 Cummins ISM	1+14*	5.549	5.639	5.501	5.441	5.601	5.692	5.515	5.346	1.6%	-1.1%	**1.6%**	-3.1%	0.085	0.333	**0.016**	0.059
	2	1.659	1.646	1.635	1.670	1.925	1.701	1.629	1.645	-0.8%	2.1%	-11.6%	1.0%	0.764	0.363	0.493	0.601
	3	1.874	1.887	1.980	1.988	1.999	1.963	1.972	1.876	0.7%	0.4%	-1.8%	-4.9%	0.667	0.958	0.764	0.424
	4	1.942	2.012	1.939	1.973	2.202	2.013	1.919	1.979	**3.6%**	1.7%	-8.6%	3.1%	**0.002**	0.138	0.457	0.183
	5	1.598	1.658	1.640	1.635	1.646	1.677	1.595	1.625	**3.8%**	-0.3%	1.8%	1.9%	**0.001**	0.724	0.539	0.287
	6	2.115	2.120	2.153	2.139	2.132	2.167	2.119	2.140	0.2%	-0.6%	1.6%	1.0%	0.823	0.749	0.265	0.297
	7	1.380	1.411	1.374	1.376	1.409	1.452	1.351	1.384	2.3%	0.2%	3.0%	2.4%	0.131	0.904	0.102	0.378
	8	2.099	2.084	2.099	2.099	2.128	2.108	2.114	2.103	-0.7%	0.0%	-0.9%	-0.5%	0.473	0.989	0.564	0.461
	9	1.720	1.720	1.723	1.704	1.708	1.741	1.735	1.722	0.0%	-1.1%	**1.9%**	-0.7%	0.985	0.524	**0.041**	0.389
	10	1.493	1.495	1.463	1.476	1.472	1.511	1.484	1.487	0.1%	0.8%	**2.6%**	0.2%	0.936	0.426	**0.016**	0.854
	11	1.550	1.553	1.532	1.538	1.525	1.591	1.547	1.536	0.2%	0.4%	**4.4%**	-0.7%	0.871	0.816	**0.007**	0.454
	12	1.691	1.718	1.700	1.705	1.695	1.750	1.695	1.720	**1.6%**	0.3%	**3.2%**	1.5%	**0.032**	0.687	**0.014**	0.260
	13	2.015	2.072	2.027	2.021	2.035	2.102	2.015	2.048	**2.8%**	-0.3%	**3.3%**	1.6%	**0.004**	0.737	**0.023**	0.379
1991 DDC Series 60	1+14	7.514	7.577	7.370	7.419	7.330	7.433	7.287	7.285	0.8%	0.7%	1.4%	0.0%	0.552	0.632	0.166	0.988
	2	4.097	4.082	4.081	4.108	4.161	4.164	4.085	4.140	-0.4%	0.7%	0.1%	**1.3%**	0.353	0.303	0.897	**0.005**
	3	10.730	11.040	10.837	11.204	10.989	10.927	10.749	10.925	**2.9%**	3.4%	-0.6%	1.6%	**0.007**	0.011	0.309	0.065
	4	6.121	6.227	6.256	6.307	6.286	6.328	6.254	6.257	1.7%	0.8%	0.7%	0.1%	0.056	0.475	0.386	0.940
	5	9.000	8.903	8.991	9.120	9.044	8.945	8.962	9.110	-1.1%	1.4%	-1.1%	**1.7%**	0.511	0.139	0.113	**0.014**
	6	6.500	6.525	6.571	6.679	6.557	6.582	6.581	6.656	0.4%	**1.6%**	0.4%	**1.1%**	0.278	**0.000**	0.323	**0.044**
	7	9.689	9.812	9.802	9.971	9.743	9.802	9.707	9.915	**1.3%**	**1.7%**	0.6%	**2.1%**	**0.025**	**0.017**	0.202	**0.001**
	8	6.880	6.917	6.968	7.086	6.966	6.993	6.991	7.060	**0.5%**	**1.7%**	0.4%	**1.0%**	**0.039**	**0.010**	0.127	**0.047**
	9	8.287	8.402	8.402	8.553	8.406	8.434	8.426	8.523	1.4%	**1.8%**	0.3%	**1.2%**	0.060	**0.005**	0.390	**0.047**
	10	6.584	6.535	6.710	6.681	6.604	6.538	6.669	6.619	-0.7%	-0.4%	-1.0%	-0.8%	0.625	0.812	0.398	0.643
	11	9.947	9.999	10.044	10.118	9.989	9.979	9.980	10.003	0.5%	0.7%	-0.1%	0.2%	0.605	0.535	0.947	0.675
	12	7.674	7.655	0.325	0.325	0.322	0.322	0.323	0.326	-0.1%	0.2%	0.0%	0.9%	0.873	0.734	0.965	0.225
	13	11.532	11.587	0.373	0.378	0.372	0.373	0.374	0.375	0.4%	1.5%	0.3%	0.4%	0.583	0.082	0.519	0.506

*Mode 1+14, which is a summation of the emissions results for mode 1 and mode 14, is reported in g and Modes 2-13 are reported in g/bhp.hr

3.2 PM Emissions

The PM emission results for the testing of the different B5 and B10 blends for the 2006 Cummins ISM and 1991 DDC Series 60 engines for different test cycles are presented in Figure 3-2 on a g/bhp-hr basis. Table 3-3 shows the average emission values and percentage differences for the different fuels, along with the associated p-values for statistical comparisons using a t-test. For the 2006 Cummins ISM engine, PM emissions results showed consistent, statistically significant reductions ranging from 5.8-15.1% with all B5 and B10 biodiesel blends tested over the FTP cycle. Statistically significant reductions in PM emissions ranging from 6.7-14.3% were seen for the biodiesel blends over the SET cycle. There were some inconsistencies in the PM emissions results for the UDDS cycle, with a marginally statistically significant increase of 6.4% for the B5-soy compared to the CARB diesel fuel for the 2006 Cummins ISM engine. This might be due to the low load nature of this cycle.

The same trend was seen for the 1991 DDC Series 60 engine with the statistically significant reductions ranging from 7.5%-16.5% for the B5 and B10 biodiesel blends over the FTP cycle. All the biodiesel blends showed either statistically significant or marginally statistically significant reductions in PM emissions for the SET cycle, which ranged from 6.0%-9.4% compared to CARB diesel fuel. Like the newer engine, PM results for the 1991 DDC series 60 engine showed some inconsistences for the UDDS cycle. None of the differences seen in PM emissions for the 1991 DDC Series 60 engine for the UDDS were statistically significant, except for the B5-soy biodiesel which showed a 26.6% increase compared to CARB diesel fuel.

Previous studies have shown consistent reductions in PM with biodiesel blends, which is generally attributed to the presence of oxygen in the biodiesel , which aids the soot oxidation process by reducing locally fuel-rich regions and limit soot nucleation early during the formation process [2,4–6,12,13,18–20]. In addition to fuel-bound oxygen, the absence of aromatic and polyaromatic compounds in biodiesel fuels, that are generally considered to act as soot precursors, contributed to PM mass reductions.

Table 3-3. PM (g/bhp-hr) Percentage Differences Between the Biodiesel Blends and the CARB Reference Fuel for the 2006 Cummins ISM and 1991 DDC Series 60 Engines

	Test Cycle	Fuel Type			
			Ave. (g/bhp.hr)	% Diff vs. CARB	P-values
2006 Cummins ISM	FTP	CARB vs. B5 Soy	0.0681		
		B5 Soy	0.0641	**-5.8%**	**0.000**
	UDDS	CARB vs. B5 Soy	0.1075		
		B5 Soy	0.1143	6.4%	0.100
	SET	CARB vs. B5 Soy	0.0379		
		B5 Soy	0.0353	**-6.7%**	**0.022**
	FTP	CARB vs. B5 Animal	0.0687		
		B5 Animal	0.0642	**-6.5%**	**0.000**
	UDDS	CARB vs. B5 Animal	0.0579		
		B5 Animal	0.0585	1.0%	0.770
	SET	CARB vs. B5 Animal	0.0383		
		B5 Animal	0.0349	**-8.8%**	**0.002**
	FTP	CARB vs. B10 Soy	0.0686		
		B10 Soy	0.0606	**-11.6%**	**0.000**
	UDDS	CARB vs. B10 Soy	0.1093		
		B10 Soy	0.1148	5.0%	0.245
	SET	CARB vs. B10 Soy	0.0389		
		B10 Soy	0.0334	**-14.3%**	**0.009**
	FTP	CARB vs. B10 Animal	0.0682		
		B10 Animal	0.0578	**-15.1%**	**0.000**
	UDDS	CARB vs. B10 Animal	0.0529		
		B10 Animal	0.0548	-1.1%	0.898
	SET	CARB vs. B10 Animal	0.0375		
		B10 Animal	0.0329	**-12.0%**	**0.000**
1991 DDC Series 60	FTP	CARB vs. B5 Soy	0.0648		
		B5 Soy	0.0600	**-7.5%**	**0.001**
	UDDS	CARB vs. B5 Soy	0.0317		
		B5 Soy	0.0401	**26.6%**	**0.018**
	SET	CARB vs. B5 Soy	0.0204		
		B5 Soy	0.0188	-8.2%	0.085
	FTP	CARB vs. B5 Animal	0.0636		
		B5 Animal	0.0575	**-9.5%**	**0.000**
	UDDS	CARB vs. B5 Animal	0.0344		
		B5 Animal	0.0354	3.1%	0.760
	SET	CARB vs. B5 Animal	0.0200		
		B5 Animal	0.0188	**-6.0%**	**0.028**
	FTP	CARB vs. B10 Soy	0.0656		
		B10 Soy	0.0547	**-16.5%**	**0.000**
	UDDS	CARB vs. B10 Soy	0.0362		
		B10 Soy	0.0348	-3.8%	0.714

	SET	CARB vs. B10 Soy	0.0211		
		B10 Soy	0.0191	-9.2%	0.076
	FTP	CARB vs. B10 Animal	0.0630		
		B10 Animal	0.0543	**-13.8%**	**0.000**
	UDDS	CARB vs. B10 Animal	0.0295		
		B10 Animal	0.0295	0.0%	1.000
	SET	CARB vs. B10 Animal	0.0207		
		B10 Animal	0.0187	**-9.4%**	**0.008**

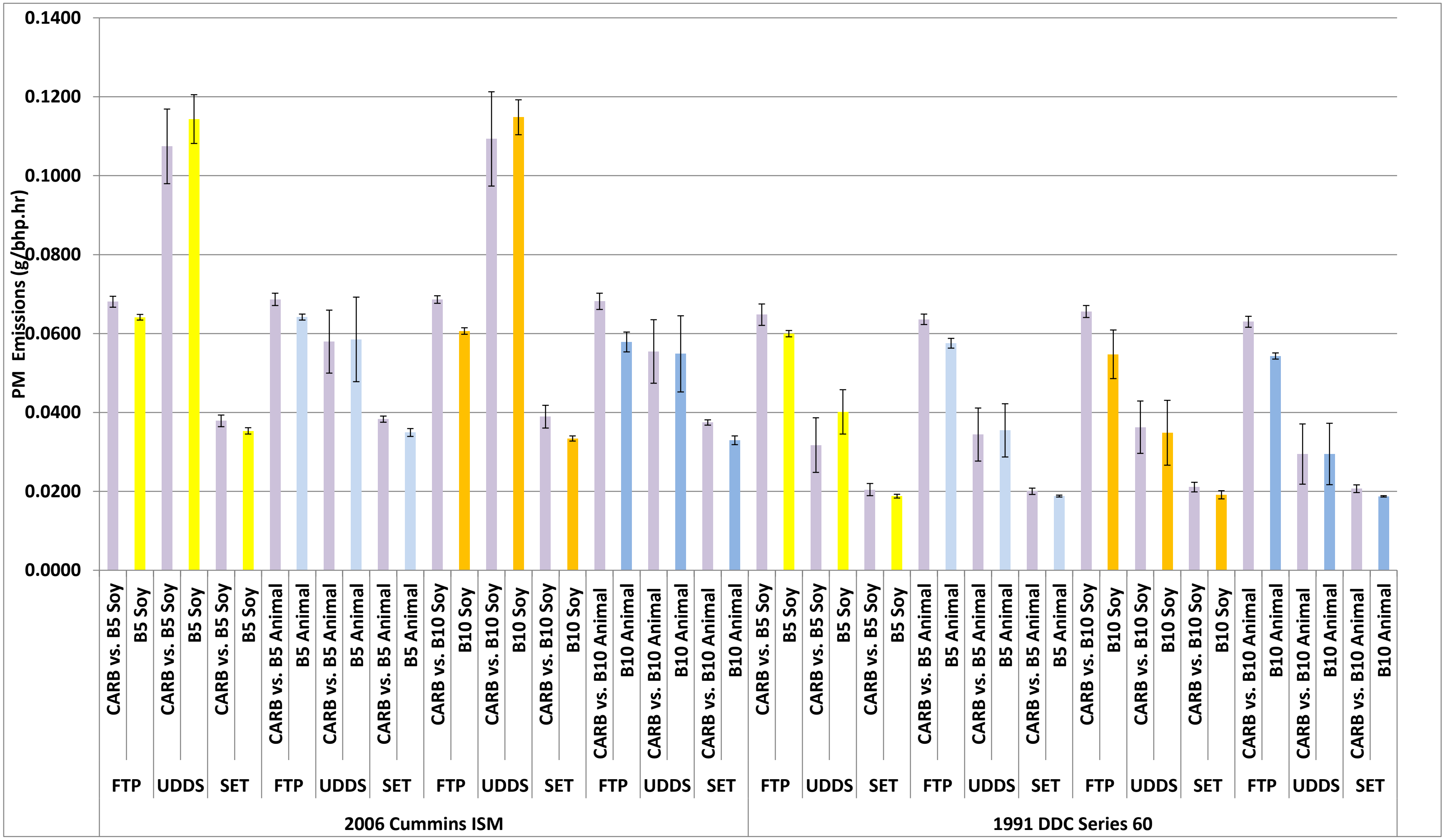

Figure 3-2. Average PM Emission Results for B5 and B10 Soy- and Animal-based Biodiesel Blends 2006 Cummins ISM and 1991 DDC Series Engines for FTP, UDDS, and SET Cycle

3.3 THC Emissions

The THC emission results for the testing of the different B5 and B10 biodiesel blends for the 2006 Cummins ISM and 1991 DDC Series 60 engines on different test cycles are presented in Figure 3-3 on a g/bhp-hr basis. Table 3-4 shows the percentage differences and the average emission values for the different fuels, along with the associated p-values for statistical comparisons using a t-test. Table 3-5 shows the average emission values and percentage differences for the 13 modes of the SET cycle, along with the associated p-values for statistical comparisons using a t-test. Although THC emissions showed a general decreasing trend for most biodiesel blends over most of the test cycles compared to the CARB diesel fuel, these differences were only statistically significant or marginally statistically significant for the B5-soy blend for the SET cycle for the 2006 Cummins ISM engine and the B5-animal and B10-animal blends for the SET cycle and the B10-soy blend for the FTP for the 1991 DDC series 60 engine. Looking at the differences seen in THC emissions for the biodiesel blends compared to the CARB diesel fuel over different modes of SET cycle, some statistically significant and marginally statistically significant reductions were seen, ranging 0.1 to 28.4% over the two engines and the range of blends tested.

The observation of reduced THC emissions for biodiesel blends is consistent with the results seen in other studies [1,4,6,21–23]. The reduction in THC emissions with biodiesel blends can be attributed to the presence of oxygen in the biodiesel, which contributes to more complete combustion when biodiesel blends are used [4–7,25-26].

Table 3-4. THC (g/bhp-hr) Percentage Differences Between the Biodiesel Blends and the CARB Reference Fuel for the 2006 Cummins ISM and 1991 DDC Series 60 Engines

	Test Cycle	Fuel Type			
			Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
2006 Cummins ISM	FTP	CARB vs. B5 Soy	0.167		
		B5 Soy	0.165	-0.8%	0.797
	UDDS	CARB vs. B5 Soy	0.440		
		B5 Soy	0.433	-1.7%	0.553
	SET	CARB vs. B5 Soy	0.069		
		B5 Soy	0.062	**-9.8%**	**0.046**
	FTP	CARB vs. B5 Animal	0.175		
		B5 Animal	0.173	-1.1%	0.684
	UDDS	CARB vs. B5 Animal	0.413		
		B5 Animal	0.408	-1.4%	0.489
	SET	CARB vs. B5 Animal	0.070		
		B5 Animal	0.066	-5.4%	0.372
	FTP	CARB vs. B10 Soy	0.157		
		B10 Soy	0.154	-2.1%	0.463
	UDDS	CARB vs. B10 Soy	0.451		
		B10 Soy	0.436	-3.3%	0.288
	SET	CARB vs. B10 Soy	0.068		
		B10 Soy	0.064	-6.2%	0.383
	FTP	CARB vs. B10 Animal	0.184		
		B10 Animal	0.172	-6.7%	0.133
	UDDS	CARB vs. B10 Animal	0.441		
		B10 Animal	0.446	1.0%	0.778
	SET	CARB vs. B10 Animal	0.067		
		B10 Animal	0.066	-2.2%	0.679
1991 DDC Series 60	FTP	CARB vs. B5 Soy	0.056		
		B5 Soy	0.055	-0.9%	0.497
	UDDS	CARB vs. B5 Soy	0.206		
		B5 Soy	0.212	3.0%	0.138
	SET	CARB vs. B5 Soy	0.024		
		B5 Soy	0.024	-2.1%	0.356
	FTP	CARB vs. B5 Animal	0.053		
		B5 Animal	0.051	-2.4%	0.503
	UDDS	CARB vs. B5 Animal	0.203		
		B5 Animal	0.203	0.2%	0.962
	SET	CARB vs. B5 Animal	0.024		
		B5 Animal	0.023	**-4.2%**	**0.050**
	FTP	CARB vs. B10 Soy	0.054		
		B10 Soy	0.052	<u>-3.7%</u>	<u>0.065</u>
	UDDS	CARB vs. B10 Soy	0.205		
		B10 Soy	0.217	5.5%	0.399
	SET	CARB vs. B10 Soy	0.025		

		B10 Soy	0.022	-11.0%	0.307
	FTP	CARB vs. B10 Animal	0.052		
		B10 Animal	0.049	-4.7%	0.120
	UDDS	CARB vs. B10 Animal	0.206		
		B10 Animal	0.204	-1.3%	0.531
	SET	CARB vs. B10 Animal	0.023		
		B10 Animal	0.022	**-5.4%**	**0.040**

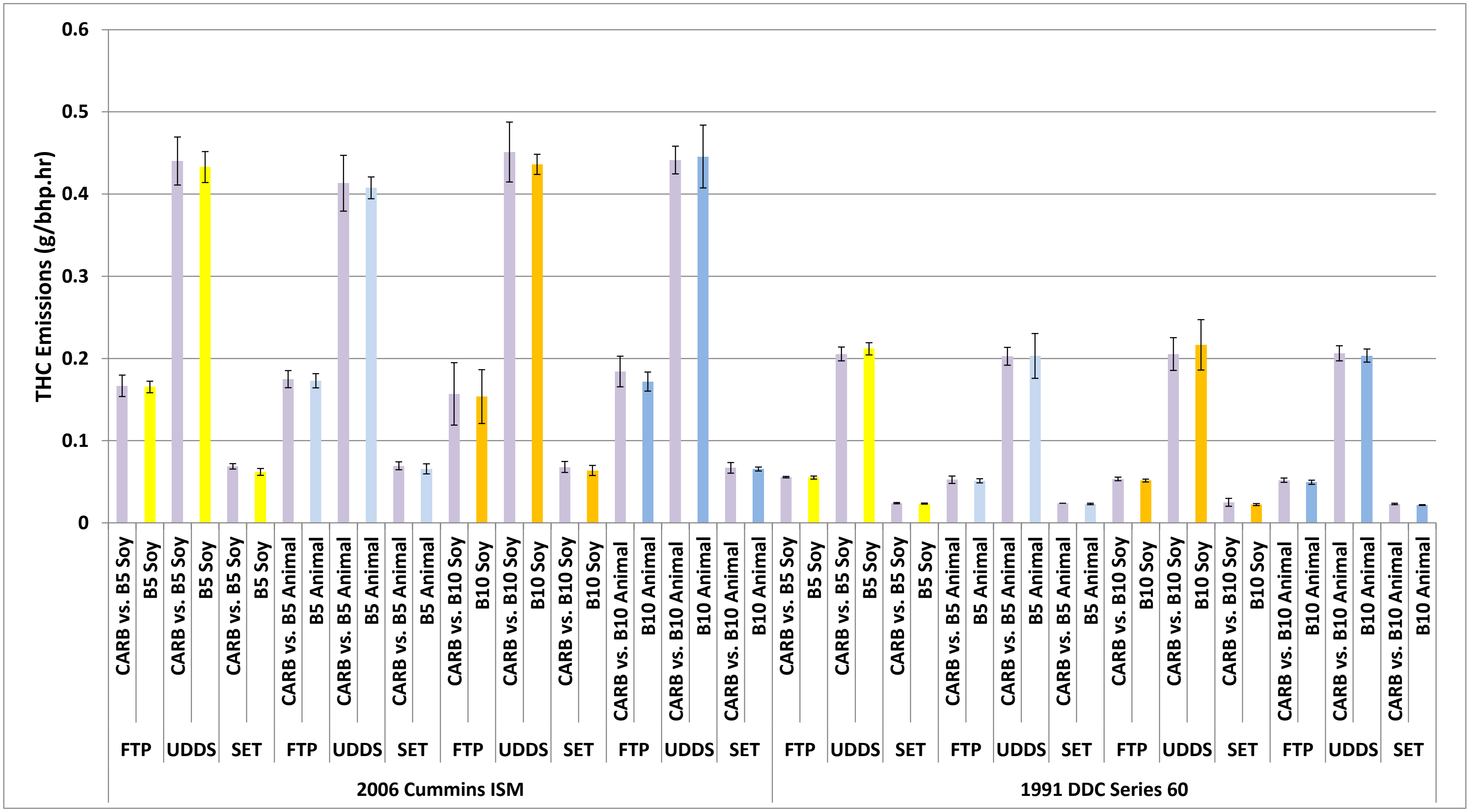

Figure 3-3. Average THC Emission Results for B5 and B10 Soy- and Animal-based Biodiesel Blends 2006 Cummins ISM and 1991 DDC Series Engines for FTP, UDDS, and SET Cycle

Table 3-5. THC (g/bhp-hr) Percentage Differences Between the Biodiesel Blends and the CARB Reference Fuel for the 2006 Cummins ISM and 1991 DDC Series 60 Engines

		Average								Percentage Difference				P-value			
	Mode	CARB vs. B5 Soy	B5 Soy	CARB vs. B5 Animal	B5 Animal	CARB vs. B10 Soy	B10 Soy	CARB vs. B10 Animal	B10 Animal	CARB vs. B5 Soy	CARB vs. B5 Animal	CARB vs. B10 Soy	CARB vs. B10 Animal	CARB vs. B5 Soy	CARB vs. B5 Animal	CARB vs. B10 Soy	CARB vs. B10 Animal
2006 Cummins ISM	1+14	0.440	0.315	0.391	0.344	0.400	0.380	0.387	0.384	-28.4%	-11.9%	-4.9%	-0.8%	0.067	0.620	0.845	0.958
	2	0.050	0.047	0.050	0.050	0.052	0.049	0.049	0.049	-5.8%	0.9%	-5.3%	0.7%	0.219	0.838	0.368	0.894
	3	0.050	0.037	0.046	0.045	0.044	0.043	0.046	0.053	-26.1%	-1.7%	-2.4%	14.8%	0.157	0.942	0.939	0.506
	4	0.050	0.044	0.049	0.048	0.049	0.047	0.048	0.047	-10.7%	-3.3%	-3.6%	-2.8%	0.148	0.666	0.687	0.711
	5	0.043	0.034	0.044	0.040	0.039	0.037	0.040	0.040	-19.8%	-8.7%	-5.5%	-0.3%	0.122	0.545	0.737	0.980
	6	0.061	0.059	0.062	0.060	0.061	0.060	0.060	0.060	-3.4%	-3.7%	-3.1%	-0.6%	0.198	0.284	0.220	0.785
	7	0.081	0.067	0.094	0.078	0.080	0.073	0.079	0.079	-17.7%	-16.3%	-9.5%	0.3%	0.053	0.262	0.519	0.977
	8	0.056	0.051	0.059	0.054	0.055	0.051	0.056	0.052	-7.9%	-7.9%	-7.7%	-6.7%	0.107	0.177	0.219	0.244
	9	0.053	0.046	0.052	0.050	0.052	0.047	0.052	0.050	**-14.0%**	-3.2%	-9.6%	-3.8%	**0.042**	0.670	0.354	0.595
	10	0.083	0.080	0.084	0.082	0.084	0.080	0.083	0.081	**-4.0%**	-3.0%	-4.1%	-2.8%	**0.029**	0.115	0.112	0.280
	11	0.150	0.139	0.152	0.151	0.151	0.142	0.152	0.149	**-7.7%**	-0.5%	-5.7%	-2.5%	**0.048**	0.943	0.501	0.682
	12	0.064	0.058	0.064	0.061	0.066	0.057	0.063	0.059	**-9.2%**	-4.2%	-12.9%	-7.1%	**0.015**	0.383	0.065	0.101
	13	0.098	0.089	0.097	0.095	0.100	0.090	0.097	0.092	**-9.3%**	-1.8%	-10.5%	-5.7%	**0.016**	0.767	0.207	0.277
1991 DDC Series 60	1+14	0.148	0.159	0.171	0.160	0.162	0.154	0.152	0.147	**7.5%**	-6.2%	-5.0%	-3.8%	**0.001**	0.720	0.228	0.147
	2	0.027	0.027	0.026	0.025	0.028	0.027	0.025	0.025	-1.1%	-2.3%	-2.4%	**-2.9%**	0.789	0.716	0.646	**0.025**
	3	0.037	0.039	0.037	0.038	0.041	0.039	0.036	0.036	4.5%	3.8%	**-7.0%**	**-0.4%**	0.253	0.681	**0.030**	**0.036**
	4	0.016	0.016	0.017	0.015	0.017	0.016	0.016	0.015	0.6%	-9.9%	-5.2%	**-4.4%**	0.878	0.388	0.230	**0.015**
	5	0.020	0.020	0.022	0.019	0.021	0.020	0.019	0.019	-0.9%	-11.7%	-8.0%	**-0.1%**	0.852	0.513	0.069	**0.019**
	6	0.025	0.024	0.024	0.023	0.024	0.023	0.023	0.022	-4.3%	-6.1%	-5.3%	**-2.9%**	0.189	0.414	0.019	**0.022**
	7	0.034	0.034	0.038	0.033	0.036	0.034	0.033	0.032	-0.5%	-14.1%	**-5.6%**	**-2.2%**	0.837	0.363	**0.050**	**0.032**
	8	0.021	0.021	0.021	0.018	0.020	0.020	0.020	0.019	-1.6%	-12.2%	-3.9%	**-5.0%**	0.613	0.253	0.114	**0.019**
	9	0.019	0.019	0.022	0.019	0.020	0.019	0.020	0.019	-0.4%	-15.1%	-2.6%	**-4.3%**	0.840	0.325	0.230	**0.019**
	10	0.015	0.015	0.016	0.014	0.015	0.015	0.015	0.014	-2.4%	-9.9%	-2.6%	**-3.8%**	0.558	0.288	0.461	**0.014**
	11	0.039	0.038	0.044	0.038	0.040	0.036	0.038	0.035	-1.6%	-14.2%	**-10.6%**	**-6.2%**	0.632	0.303	**0.020**	**0.035**
	12	0.016	0.016	0.017	0.015	0.017	0.016	0.016	0.015	-0.4%	-13.6%	**-5.9%**	**-4.3%**	0.909	0.260	**0.001**	**0.015**
	13	0.030	0.029	0.034	0.028	0.030	0.028	0.029	0.028	-0.7%	-17.0%	-4.9%	**-5.1%**	0.832	0.181	0.225	**0.028**

*Mode 1+14, which is a summation of the emissions results for mode 1 and mode 14, is reported in g and Modes 2-13 are reported in g/bhp.hr

3.4 CO Emissions

The CO emission results for the testing of the different B5 and B10 blends for the 2006 Cummins ISM and 1991 DDC Series 60 engines for different test cycles are presented in Figure 3-4 on a g/bhp-hr basis. Table 3-6 shows the average emission values and percentage differences for the different fuels, along with the associated p-values for statistical comparisons using a t-test. Table 3-7 shows the average emission values and percentage differences for the 13 modes of the SET cycle, along with the associated p-values for statistical comparisons using a t-test. CO emissions results showed a general trend of reductions with the biodiesel blends, although these differences were not statistically significant for all biodiesel blends or cycles. The statistically significant and marginally statistically significant reductions ranged from 2.0%-7.9% for the 2006 Cummins ISM engine and 2.3%-7.3% for the 1991 DDC engine for the different biodiesel blends and cycles. There was a somewhat stronger trend of biodiesel CO reductions for the 1991 DDC engine, which showed CO reductions for nearly all biodiesel blends and cycles with the exception of some UDDS cycles, compared to the 2006 Cummins engine. Reductions were also seen for individual modes of the SET cycle for both engines, with most of the statistically significant reductions being on the order of 12% or less, and with one statistically significant increase seen for the B5 soy for the idle mode for the 1991 DDC Series 60 engine.

Previous studies have generally showed reductions in CO for biodiesel blends, with greater reductions found for higher level blends [4,6,7,24]. Similar testing on another 2006 Cummins ISM in the major CARB/UCR/UCD study, however, did not show strong effects for a soy based biodiesel blends ranging up to 100%, although CO emissions benefits were seen for biodiesel blends with an animal-based feedstock [1].

Table 3-6. CO (g/bhp-hr) Percentage Differences Between the Biodiesel Blends and the CARB Reference Fuel for the 2006 Cummins ISM and 1991 DDC Series 60 Engines

	Test Cycle	Fuel Type			
			Ave. (g/bhp.hr)	% Diff vs. CARB	P-values
2006 Cummins ISM	FTP	CARB vs. B5 Soy	0.678		
		B5 Soy	0.672	-0.9%	0.288
	UDDS	CARB vs. B5 Soy	1.933		
		B5 Soy	1.959	1.3%	0.513
	SET	CARB vs. B5 Soy	0.361		
		B5 Soy	0.353	-2.1%	0.127
	FTP	CARB vs. B5 Animal	0.699		
		B5 Animal	0.679	<u>-2.8%</u>	<u>0.070</u>
	UDDS	CARB vs. B5 Animal	1.901		
		B5 Animal	1.887	-0.8%	0.720
	SET	CARB vs. B5 Animal	0.358		
		B5 Animal	0.344	**-4.1%**	**0.010**
	FTP	CARB vs. B10 Soy	0.689		
		B10 Soy	0.675	**-2.0%**	**0.001**
	UDDS	CARB vs. B10 Soy	1.915		
		B10 Soy	1.972	3.0%	0.274
	SET	CARB vs. B10 Soy	0.353		
		B10 Soy	0.340	-3.6%	0.173
	FTP	CARB vs. B10 Animal	0.684		
		B10 Animal	0.645	**-5.7%**	**0.000**
	UDDS	CARB vs. B10 Animal	1.879		
		B10 Animal	1.730	**-7.9%**	**0.000**
	SET	CARB vs. B10 Animal	0.365		
		B10 Animal	0.337	**-7.5%**	**0.001**
1991 DDC Series 60	FTP	CARB vs. B5 Soy	1.592		
		B5 Soy	1.540	**-3.3%**	**0.003**
	UDDS	CARB vs. B5 Soy	1.970		
		B5 Soy	2.078	**5.5%**	**0.029**
	SET	CARB vs. B5 Soy	1.543		
		B5 Soy	1.507	<u>-2.3%</u>	<u>0.055</u>
	FTP	CARB vs. B5 Animal	1.529		
		B5 Animal	1.443	**-5.6%**	**0.000**
	UDDS	CARB vs. B5 Animal	1.996		
		B5 Animal	1.891	**-5.3%**	**0.050**
	SET	CARB vs. B5 Animal	1.488		
		B5 Animal	1.450	**-2.6%**	**0.013**
	FTP	CARB vs. B10 Soy	1.518		
		B10 Soy	1.439	**-5.2%**	**0.000**
	UDDS	CARB vs. B10 Soy	2.002		
		B10 Soy	2.012	0.5%	0.799
	SET	CARB vs. B10 Soy	1.561		

		B10 Soy	1.468	**-6.0%**	**0.008**
	FTP	CARB vs. B10 Animal	1.548		
		B10 Animal	1.436	**-7.3%**	**0.000**
	UDDS	CARB vs. B10 Animal	1.968		
		B10 Animal	1.898	**-3.6%**	**0.048**
	SET	CARB vs. B10 Animal	1.552		
		B10 Animal	1.442	**-7.1%**	**0.002**

Table 3-7. CO (g/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for 2006 Cummins ISM and Different Modes of SET Cycle

		Average								Percentage Difference				P-value			
	Mode	CARB vs. B5 Soy	B5 Soy	CARB vs. B5 Animal	B5 Animal	CARB vs. B10 Soy	B10 Soy	CARB vs. B10 Animal	B10 Animal	CARB vs. B5 Soy	CARB vs. B5 Animal	CARB vs. B10 Soy	CARB vs. B10 Animal	CARB vs. B5 Soy	CARB vs. B5 Animal	CARB vs. B10 Soy	CARB vs. B10 Animal
2006 Cummins ISM	1+14	2.714	2.562	1.693	2.156	2.378	2.575	2.661	2.052	-5.6%	27.3%	8.3%	-22.9%	0.623	0.411	0.208	0.090
	2	0.439	0.469	0.458	0.431	0.429	0.414	0.465	0.435	6.9%	-5.9%	-3.5%	-6.5%	0.440	0.334	0.807	0.372
	3	0.481	0.462	0.415	0.463	0.472	0.469	0.492	0.463	**-3.9%**	11.4%	-0.5%	-5.9%	**0.012**	0.541	0.887	0.064
	4	0.272	0.255	0.248	0.257	0.253	0.254	0.277	0.250	**-6.5%**	3.4%	0.6%	-9.7%	**0.007**	0.692	0.924	0.004
	5	0.276	0.264	0.314	0.266	0.270	0.263	0.284	0.267	**-4.4%**	-15.4%	-2.6%	-6.0%	**0.010**	0.296	0.424	0.075
	6	0.299	0.287	0.305	0.280	0.292	0.270	0.300	0.273	**-4.1%**	-8.1%	**-7.3%**	**-9.1%**	**0.011**	0.108	**0.004**	**0.000**
	7	0.637	0.621	0.807	0.621	0.623	0.612	0.652	0.616	-2.6%	-23.1%	-1.8%	-5.4%	0.229	0.295	0.350	0.190
	8	0.192	0.188	0.215	0.184	0.186	0.181	0.191	0.179	-2.3%	-14.6%	-2.8%	**-6.3%**	0.161	0.236	0.273	**0.000**
	9	0.209	0.205	0.182	0.203	0.206	0.200	0.208	0.201	-2.0%	11.6%	**-2.6%**	**-3.6%**	0.296	0.437	**0.030**	**0.007**
	10	0.383	0.365	0.373	0.362	0.390	0.354	0.380	0.349	**-4.7%**	-2.9%	**-9.3%**	**-8.1%**	**0.003**	0.483	**0.000**	**0.000**
	11	0.952	0.949	0.920	0.954	0.957	0.955	0.968	0.939	-0.4%	3.7%	-0.2%	-3.0%	0.657	0.579	0.928	0.349
	12	0.235	0.229	0.220	0.228	0.233	0.223	0.234	0.224	**-2.4%**	3.4%	**-4.3%**	**-4.4%**	**0.017**	0.629	**0.000**	**0.001**
	13	0.466	0.463	0.444	0.464	0.473	0.462	0.473	0.458	-0.6%	4.4%	**-2.4%**	-3.1%	0.465	0.639	**0.038**	0.326
1991 DDC Series 60 Engine	1+14	1.689	1.955	1.840	1.655	1.860	1.711	1.798	1.678	**15.8%**	-10.0%	-8.0%	-6.7%	**0.018**	0.297	0.252	0.532
	2	10.176	9.989	10.490	10.076	9.775	9.716	10.363	9.810	-1.8%	-3.9%	-0.6%	-5.3%	0.346	0.120	0.724	0.049
	3	0.502	0.507	0.477	0.446	0.486	0.465	0.469	0.434	1.0%	-6.4%	-4.3%	**-7.3%**	0.736	0.157	0.252	**0.085**
	4	1.867	1.713	1.767	1.734	1.669	1.573	1.831	1.679	**-8.3%**	-1.9%	-5.8%	-8.3%	**0.050**	0.655	0.117	0.118
	5	0.551	0.517	0.499	0.474	0.501	0.479	0.510	0.484	-6.2%	-5.0%	-4.2%	-5.2%	0.125	0.287	0.316	0.255
	6	1.764	1.678	1.751	1.594	1.711	1.633	1.752	1.558	**-4.9%**	**-9.0%**	**-4.6%**	**-11.1%**	**0.000**	**0.001**	**0.001**	**0.000**
	7	0.330	0.329	0.333	0.319	0.334	0.337	0.331	0.316	-0.5%	-4.0%	0.9%	-4.4%	0.757	0.257	0.675	0.125
	8	0.840	0.803	0.844	0.766	0.807	0.765	0.862	0.763	**-4.4%**	**-9.3%**	**-5.2%**	**-11.5%**	**0.006**	**0.000**	**0.000**	**0.004**
	9	0.296	0.290	0.290	0.272	0.292	0.282	0.290	0.272	-2.0%	**-6.4%**	-3.2%	**-6.2%**	0.135	**0.037**	0.154	**0.020**
	10	0.344	0.333	0.341	0.309	0.344	0.331	0.339	0.307	-3.2%	**-9.2%**	-3.7%	**-9.4%**	0.235	**0.011**	0.075	**0.003**
	11	0.323	0.329	0.338	0.331	0.349	0.326	0.340	0.324	1.8%	-2.1%	-6.4%	**-4.7%**	0.474	0.415	0.123	**0.001**
	12	0.229	0.222	0.230	0.216	0.234	0.212	0.238	0.216	-2.8%	**-6.2%**	**-9.3%**	**-9.1%**	0.299	**0.013**	**0.012**	**0.014**
	13	0.241	0.240	0.250	0.229	0.243	0.235	0.247	0.233	-0.5%	**-8.3%**	-3.6%	**-5.6%**	0.853	**0.006**	0.204	**0.016**

*Mode 1+14, which is a summation of the emissions results for mode 1 and mode 14, is reported in g and Modes 2-13 are reported in g/bhp.hr

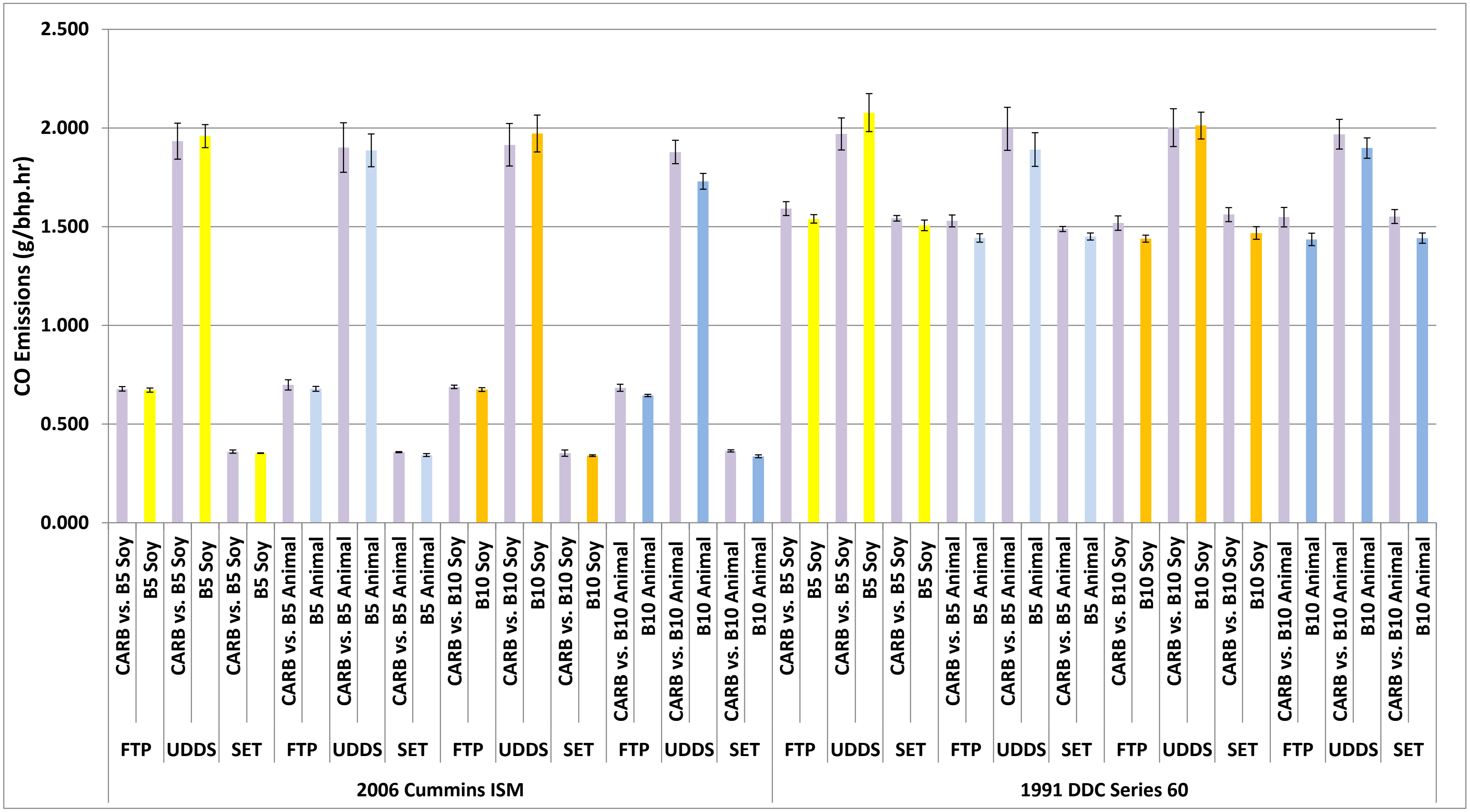

Figure 3-4. Average CO Emission Results for B5 and B10 Soy- and Animal-based Biodiesel Blends 2006 Cummins ISM and 1991 DDC Series Engines for FTP, UDDS, and SET Cycle

3.5 CO_2 Emissions

The CO_2 emission results for the testing of the different B5 and B10 biodiesel blends for the 2006 Cummins ISM and 1991 DDC Series engines for different test cycles are presented in Figure 3-5 on a g/bhp-hr basis. Table 3-8 shows the average emissions values and percentage differences for the different fuels, along with the associated p-values for statistical comparisons using a t-test. Table 3-9 shows the average emission values and percentage differences for the 13 modes of the SET cycle, along with the associated p-values for statistical comparisons using a t-test.

CO_2 emissions did not show consistent fuel trends over the range of blends, cycles, and engines tested, with nearly all differences not being statistically significant. Other studies have shown increases in exhaust CO_2 emissions with biodiesel, which could be related to the generally higher carbon content per unit of energy for biodiesel compared to typical diesel fuel [4,6,7,24–26]. For the present study, the differences in the carbon content per unit energy between the CARB reference fuel are very minor, however, as shown in Table 2-1 and Table 2-3, due to the relatively low blend levels.

Table 3-8. CO_2 (g/bhp-hr) Percentage Differences Between the Biodiesel Blends and the CARB Reference Fuel for the 2006 Cummins ISM and 1991 DDC Series 60 Engines

	Test Cycle	Fuel Type			
			Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
2006 Cummins ISM	FTP	CARB vs. B5 Soy	623.9		
		B5 Soy	624.6	0.1%	0.532
	UDDS	CARB vs. B5 Soy	797.8		
		B5 Soy	800.4	0.3%	0.583
	SET	CARB vs. B5 Soy	530.6		
		B5 Soy	528.5	-0.4%	0.018
	FTP	CARB vs. B5 Animal	630.1		
		B5 Animal	630.0	-0.0%	0.943
	UDDS	CARB vs. B5 Animal	785.0		
		B5 Animal	788.0	0.4%	0.788
	SET	CARB vs. B5 Animal	530.6		
		B5 Animal	528.7	-0.4%	0.298
	FTP	CARB vs. B10 Soy	623.8		
		B10 Soy	624.3	0.1%	0.680
	UDDS	CARB vs. B10 Soy	790.5		
		B10 Soy	804.0	1.7%	0.125
	SET	CARB vs. B10 Soy	530.2		
		B10 Soy	532.3	0.4%	0.223
	FTP	CARB vs. B10 Animal	627.9		
		B10 Animal	628.7	0.1%	0.707
	UDDS	CARB vs. B10 Animal	788.6		
		B10 Animal	796.4	1.0%	0.216
	SET	CARB vs. B10 Animal	531.4		
		B10 Animal	530.0	-0.3%	0.415
1991 DDC Series 60	FTP	CARB vs. B5 Soy	547.3		
		B5 Soy	547.1	-0.0%	0.890
	UDDS	CARB vs. B5 Soy	677.7		
		B5 Soy	691.0	**2.0%**	**0.024**
	SET	CARB vs. B5 Soy	472.8		
		B5 Soy	472.0	-0.2%	0.433
	FTP	CARB vs. B5 Animal	542.3		
		B5 Animal	541.6	-0.1%	0.749
	UDDS	CARB vs. B5 Animal	676.5		
		B5 Animal	674.7	-0.3%	0.748
	SET	CARB vs. B5 Animal	471.8		
		B5 Animal	470.2	-0.3%	0.238
	FTP	CARB vs. B10 Soy	545.1		
		B10 Soy	546.1	0.5%	0.313
	UDDS	CARB vs. B10 Soy	674.3		
		B10 Soy	681.6	1.1%	0.398
	SET	CARB vs. B10 Soy	474.1		

		B10 Soy	476.4	0.5%	0.231
	FTP	CARB vs. B10 Animal	543.6		
		B10 Animal	544.1	0.1%	0.502
	UDDS	CARB vs. B10 Animal	681.0		
		B10 Animal	682.8	0.3%	0.703
	SET	CARB vs. B10 Animal	474.6		
		B10 Animal	476.8	0.5%	0.107

Table 3-9. CO_2 (g/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for 2006 Cummins ISM and Different Modes of SET Cycle

		Average								Percentage Difference				P-value			
	Mode	CARB vs. B5 Soy	B5 Soy	CARB vs. B5 Animal	B5 Animal	CARB vs. B10 Soy	B10 Soy	CARB vs. B10 Animal	B10 Animal	CARB vs. B5 Soy	CARB vs. B5 Animal	CARB vs. B10 Soy	CARB vs. B10 Animal	CARB vs. B5 Soy	CARB vs. B5 Animal	CARB vs. B10 Soy	CARB vs. B10 Animal
2006 Cummins ISM	1+14	407.5	410.5	396.0	399.4	401.5	405.4	407.8	396.1	0.7%	0.9%	1.0%	-2.9%	0.710	0.666	0.141	0.089
	2	526.1	518.5	524.7	523.5	520.3	524.7	525.4	520.4	-1.4%	-0.2%	0.8%	-1.0%	0.126	0.992	0.266	0.286
	3	545.5	541.5	550.4	542.5	546.2	553.6	549.1	546.2	-0.7%	-1.4%	1.4%	-0.5%	0.396	0.106	0.127	0.502
	4	514.0	510.3	514.7	514.2	513.2	516.4	516.5	513.6	**-0.7%**	-0.1%	0.6%	-0.6%	**0.008**	0.792	0.428	0.196
	5	516.0	515.7	519.3	516.3	516.8	520.9	519.7	516.9	-0.1%	-0.6%	**0.8%**	**-0.5%**	0.861	0.265	**0.027**	**0.049**
	6	503.6	503.0	503.7	502.3	504.5	505.6	505.3	504.7	-0.1%	-0.3%	0.2%	-0.1%	0.551	0.391	0.501	0.751
	7	567.9	565.8	567.1	563.9	569.1	571.7	563.9	569.0	-0.4%	-0.6%	0.5%	0.9%	0.399	0.414	0.458	0.075
	8	493.1	493.4	494.9	493.1	494.2	495.6	494.8	492.8	0.0%	-0.4%	0.3%	-0.4%	0.858	0.295	0.662	0.186
	9	513.9	513.2	513.1	511.8	513.3	516.5	515.9	515.2	-0.1%	-0.3%	0.6%	-0.1%	0.504	0.452	0.145	0.783
	10	519.1	517.9	518.1	516.2	519.5	519.5	519.1	517.9	**-0.2%**	-0.4%	0.0%	-0.2%	**0.036**	0.107	0.970	0.455
	11	619.4	616.6	617.0	619.2	613.5	620.4	618.7	618.3	-0.5%	0.4%	1.1%	-0.1%	0.543	0.585	0.069	0.949
	12	523.4	522.3	523.8	522.1	524.1	525.6	523.8	523.6	-0.2%	-0.3%	0.3%	0.0%	0.515	0.322	0.479	0.934
	13	729.1	730.2	729.0	725.6	735.8	731.8	729.8	728.3	0.1%	-0.5%	-0.5%	-0.2%	0.548	0.350	0.159	0.721
1991 DDC Series 60	1+14	344.1	350.7	319.1	337.1	334.06	340.34	328.7	341.7	1.9%	5.6%	1.9%	4.0%	0.338	0.372	0.444	0.153
	2	500.1	495.2	495.7	500.3	496.11	494.55	496.4	499.1	**-1.0%**	0.9%	-0.3%	0.5%	**0.046**	0.197	0.491	0.459
	3	526.2	527.5	523.0	527.5	530.27	522.64	521.7	528.6	0.2%	0.9%	-1.4%	1.3%	0.756	0.536	0.197	0.371
	4	487.4	486.5	488.1	491.9	486.80	484.06	489.1	488.4	-0.2%	0.8%	-0.6%	-0.2%	0.685	0.312	0.060	0.798
	5	497.4	486.2	491.4	492.5	490.48	483.43	488.2	500.8	-2.3%	0.2%	-1.4%	**2.6%**	0.084	0.825	0.057	**0.044**
	6	451.0	449.8	452.8	455.7	449.95	448.41	453.4	455.2	-0.3%	0.6%	-0.3%	0.4%	0.362	0.091	0.110	0.364
	7	498.9	499.4	500.4	502.0	498.13	497.89	496.9	505.4	0.1%	0.3%	0.0%	1.7%	0.872	0.762	0.868	0.068
	8	454.8	453.4	456.4	458.5	454.26	452.53	456.5	457.9	-0.3%	0.5%	-0.4%	0.3%	0.086	0.232	0.063	0.298
	9	460.2	461.6	463.5	463.6	462.03	460.41	463.9	466.5	0.3%	0.0%	-0.4%	0.5%	0.569	0.963	0.249	0.097
	10	439.2	439.7	441.9	444.8	439.20	438.73	443.1	444.0	0.1%	0.7%	-0.1%	0.2%	0.636	0.091	0.544	0.556
	11	501.9	501.7	503.8	502.7	500.64	499.35	502.4	503.8	-0.1%	-0.2%	-0.3%	0.3%	0.933	0.871	0.746	0.690
	12	443.6	442.9	446.5	449.4	443.76	433.80	448.9	447.9	-0.2%	0.6%	-2.2%	-0.2%	0.630	0.098	0.374	0.585
	13	600.0	600.3	599.2	603.3	593.65	596.43	599.9	600.4	0.1%	0.7%	0.5%	0.1%	0.923	0.573	0.577	0.937

*Mode 1+14, which is a summation of the emissions results for mode 1 and mode 14, is reported in g and Modes 2-13 are reported in g/bhp.hr

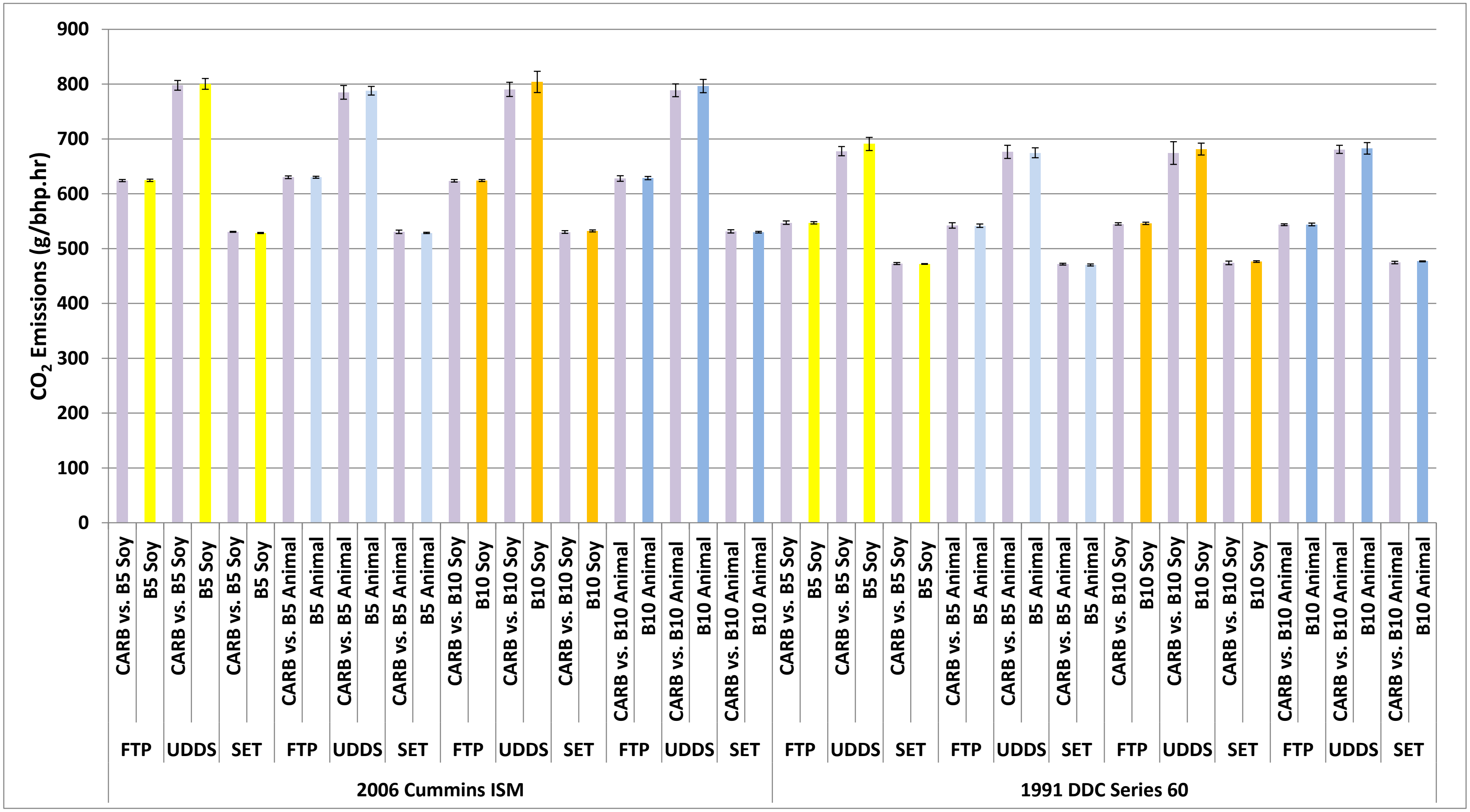

Figure 3-5. Average CO_2 Emission Results for B5 and B10 Soy- and Animal-based Biodiesel Blends 2006 Cummins ISM and 1991 DDC Series Engines for FTP, UDDS, and SET Cycle

3.6 Brake Specific Fuel Consumption

The brake specific fuel consumption (BSFC) results for the testing of the different B5 and B10 biodiesel blends for the 2006 Cummins ISM and 1991 DDC Series engines for different test cycles are presented in Figure 3-6 on a gallons/bhp-hr. The brake specific fuel consumption was calculated via the carbon balance method. Table 3-10 shows the average BSFC values and percentage differences for the different fuels, along with the associated p-values for statistical comparisons using a t-test.

BSFC results showed a general increasing trend with the biodiesel blends, although this was not seen for all biodiesel blend, cycle, and engine combinations. For the 2006 Cummins engine, these BSFC increases ranged from 0.5 to 2.3%. For the 1991 DDC engine, these BSFC increases ranged from 0.7 to 3.2%. These results are directionally consistent with the results of previous studies [4,6,7,24–26]. The increases in BSFC were comparable to the difference in the energy content between the CARB diesel fuel and B5 and B10 blends, as shown in Table 2-1 and Table 2-3, which are on the order of 0.9% for the B5 blends and 1.4% for the B10 blends.

Table 3-10. BSFC (gal/bhp-hr) Percentage Differences Between the Biodiesel Blends and the CARB Reference Fuel for the 2006 Cummins ISM and 1991 DDC Series 60 Engines

	Test Cycle	Fuel Type			
			Ave. (gal./ bhp.hr)	% Diff vs. CARB	P-values
2006 Cummins ISM	FTP	CARB vs. B5 Soy	0.0631		
		B5 Soy	0.0639	**1.3%**	**0.000**
	UDDS	CARB vs. B5 Soy	0.0809		
		B5 Soy	0.0821	**1.5%**	**0.016**
	SET	CARB vs. B5 Soy	0.0536		
		B5 Soy	0.0540	**0.8%**	**0.001**
	FTP	CARB vs. B5 Animal	0.0637		
		B5 Animal	0.0640	**0.5%**	**0.007**
	UDDS	CARB vs. B5 Animal	0.0796		
		B5 Animal	0.0803	0.9%	0.295
	SET	CARB vs. B5 Animal	0.0536		
		B5 Animal	0.0537	0.2%	0.605
	FTP	CARB vs. B10 Soy	0.0630		
		B10 Soy	0.0635	**0.7%**	**0.010**
	UDDS	CARB vs. B10 Soy	0.0801		
		B10 Soy	0.0820	**2.3%**	**0.046**
	SET	CARB vs. B10 Soy	0.0535		
		B10 Soy	0.0540	**1.0%**	**0.016**
	FTP	CARB vs. B10 Animal	0.0635		
		B10 Animal	0.0641	**1.0%**	**0.011**
	UDDS	CARB vs. B10 Animal	0.0799		
		B10 Animal	0.0814	**1.8%**	**0.032**
	SET	CARB vs. B10 Animal	0.0537		
		B10 Animal	0.0540	0.6%	0.112
1991 DDC Series 60	FTP	CARB vs. B5 Soy	0.0554		
		B5 Soy	0.0561	**1.2%**	**0.000**
	UDDS	CARB vs. B5 Soy	0.0687		
		B5 Soy	0.0709	**3.2%**	**0.001**
	SET	CARB vs. B5 Soy	0.0479		
		B5 Soy	0.0484	**1.0%**	**0.003**
	FTP	CARB vs. B5 Animal	0.0549		
		B5 Animal	0.0551	0.4%	0.321
	UDDS	CARB vs. B5 Animal	0.0686		
		B5 Animal	0.0688	0.3%	0.741
	SET	CARB vs. B5 Animal	0.0478		
		B5 Animal	0.0479	0.2%	0.456
	FTP	CARB vs. B10 Soy	0.0552		
		B10 Soy	0.0556	**0.7%**	**0.001**
	UDDS	CARB vs. B10 Soy	0.0684		
		B10 Soy	0.0695	1.7%	0.199
	SET	CARB vs. B10 Soy	0.0480		

		B10 Soy	0.0485	**1.0%**	**0.030**
	FTP	CARB vs. B10 Animal	0.0551		
		B10 Animal	0.0556	**0.9%**	**0.000**
	UDDS	CARB vs. B10 Animal	0.0690		
		B10 Animal	0.0698	1.1%	0.128
	SET	CARB vs. B10 Animal	0.0481		
		B10 Animal	0.0486	**1.1%**	**0.004**

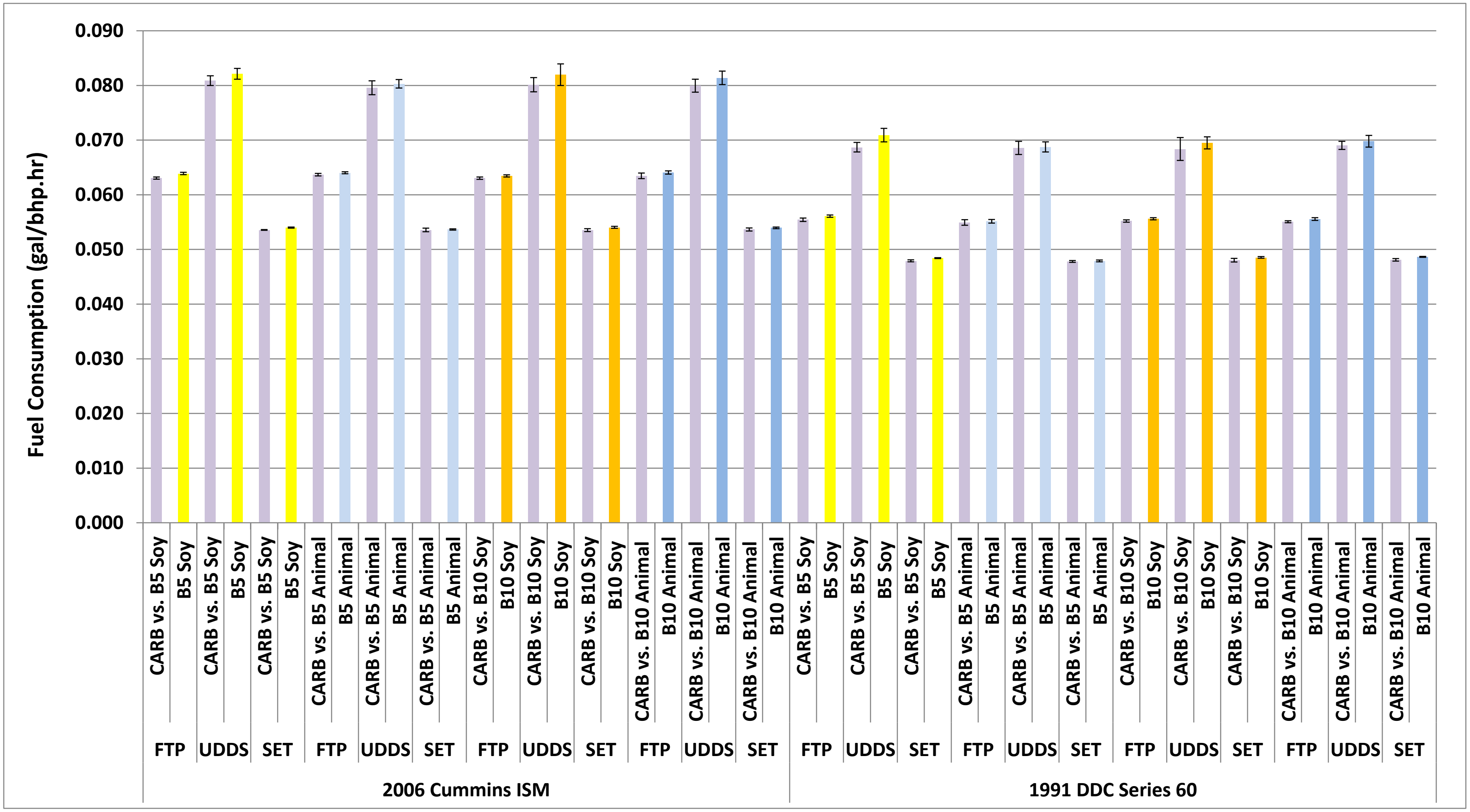

Figure 3-6. Average Brake Specific Fuel Consumption Results for B5 and B10 Soy- and Animal-based Biodiesel Blends 2006 Cummins ISM and 1991 DDC Series Engines for FTP, UDDS, and SET Cycle

3.7 EC/OC

The Elemental Carbon (EC) and Organic Carbon (OC) results for the testing of the different B5 and B10 biodiesel blends for the 2006 Cummins ISM and 1991 DDC Series engines for the FTP cycle are presented in Figure 3-7 on a g/bhp-hr. Note that these data are presented without subtracting the background. Instead the tunnel backgrounds collected for the testing on each engine are presented in the graph, due to the large OC artifact. Table 3-11 shows the average EC/OC values and percentage differences for the different fuels. The results for the EC/OC were not as consistent as those for the total PM mass. Statistically significant reductions in EC were seen for the B5 animal, B10 soy and B10 animal blends for the 1991 DDC Series 60 engine, but only for the B10 animal blend for the 2006 Cummins engine. For OC emissions, the only statistically significant difference found was a 20.5% increase for the B5 soy blend for the 1991 DDC Series 60 engine. The less consistent trends for EC/OC emissions could potentially be attributed to the lower blend levels used in this study as compared to earlier studies. Fewer numbers of samples were also collected for the EC/OC analyses as well, which could make it more difficult to quantify statistical changes for small percentage differences.

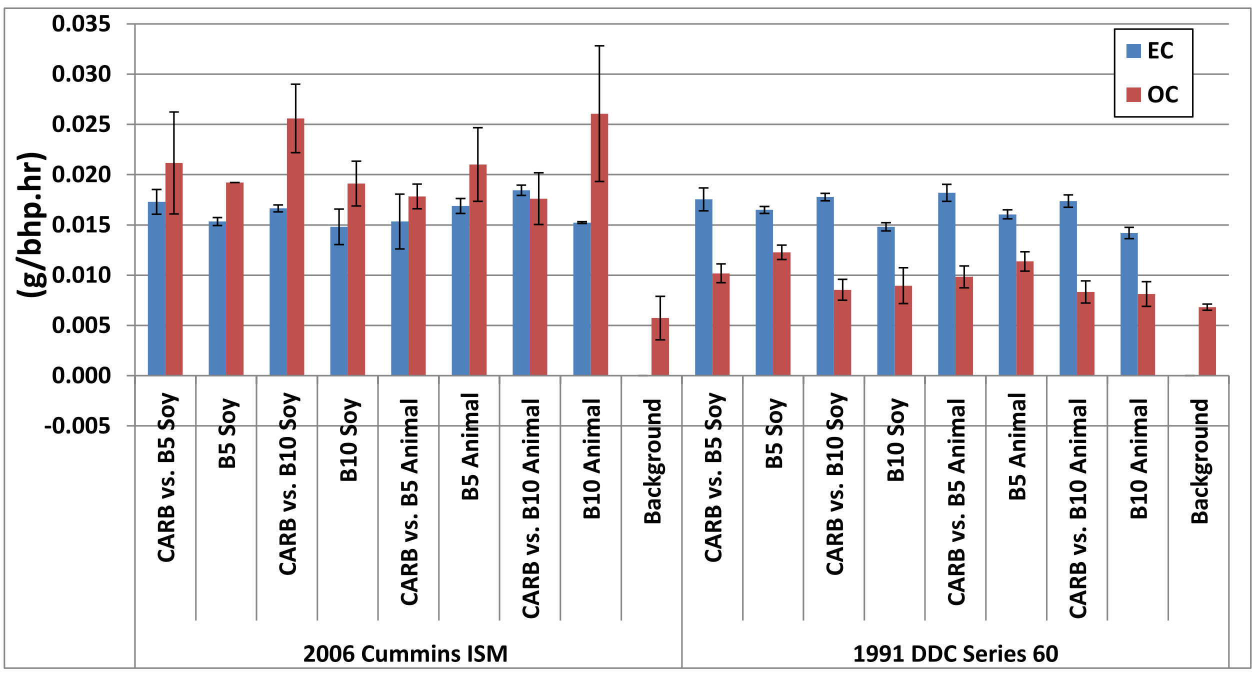

Figure 3-7. Average EC/OC Results for B5 and B10 Soy- and Animal-based Biodiesel Blends 2006 Cummins ISM and the FTP Cycle

Table 3-11. EC/OC (g/bhp-hr) Percentage Differences Between the Biodiesel Blends and the CARB Reference Fuel for the 2006 Cummins ISM and 1991 DDC Series 60 Engines

		Ave. (g/bhp.hr)		% Diff vs. CARB		P-value vs. CARB	
		EC	OC	EC	OC	EC	OC
2006 Cummins ISM	CARB vs. B5 Soy	0.0173	0.0212				
	B5 Soy	0.0153	0.0192	-11.3%	-9.2%	0.166	0.642
	CARB vs. B10 Soy	0.0167	0.0256				
	B10 Soy	0.0148	0.0191	-11.1%	-25.3%	0.283	0.152
	CARB vs. B5 Animal	0.0153	0.0178				
	B5 Animal	0.0169	0.0210	10.1%	17.8%	0.518	0.364
	CARB vs. B10 Animal	0.0184	0.0176				
	B10 Animal	0.0152	0.0261	**-17.5%**	48.0%	0.012	0.240
1991 DDC Series 60	CARB vs. B5 Soy	0.0175	0.0102				
	B5 Soy	0.0165	0.0123	-6.0%	**20.5%**	0.202	0.038
	CARB vs. B10 Soy	0.0178	0.0085				
	B10 Soy	0.0148	0.0089	**-16.6%**	4.8%	0.001	0.747
	CARB vs. B5 Animal	0.0182	0.0098				
	B5 Animal	0.0161	0.0114	**-11.8%**	15.6%	0.018	0.142
	CARB vs. B10 Animal	0.0174	0.0083				
	B10 Animal	0.0142	0.0081	**-18.3%**	-2.5%	0.003	0.838

3.8 Carbonyl Emissions

The carbonyl emissions results for the testing of the different B5 and B10 biodiesel blends for the 2006 Cummins ISM and 1991 DDC Series 60 engines for the FTP cycle are presented, respectively, in Figure 3-8 and Figure 3-9 on a mg/bhp-hr basis. Table 3-12 shows the average of different carbonyls values and percentage differences for the different fuels, along with the associated p-values for statistical comparisons using a t-test. Consistent with previous studies, formaldehyde and acetaldehyde were the dominant aldehydes in the exhaust with some other higher molecular weight carbonyls seen at much lower levels. There were not any consistent fuel differences between the CARB diesel and the biodiesel blends.

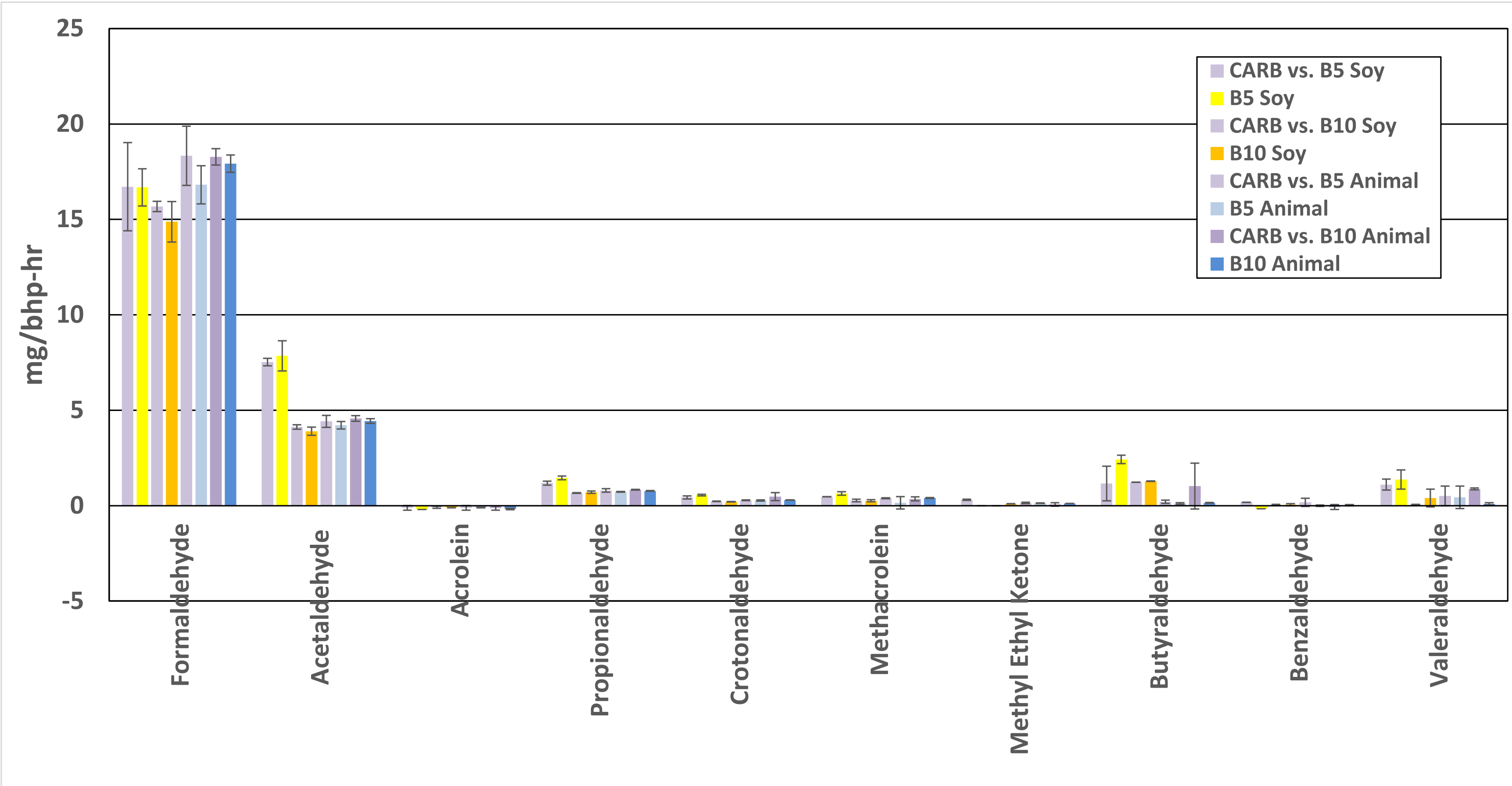

Figure 3-8. Average Carbonyl Emissions Results for B5 and B10 Soy- and Animal-based Biodiesel Blends 2006 Cummins ISM for the FTP Cycle

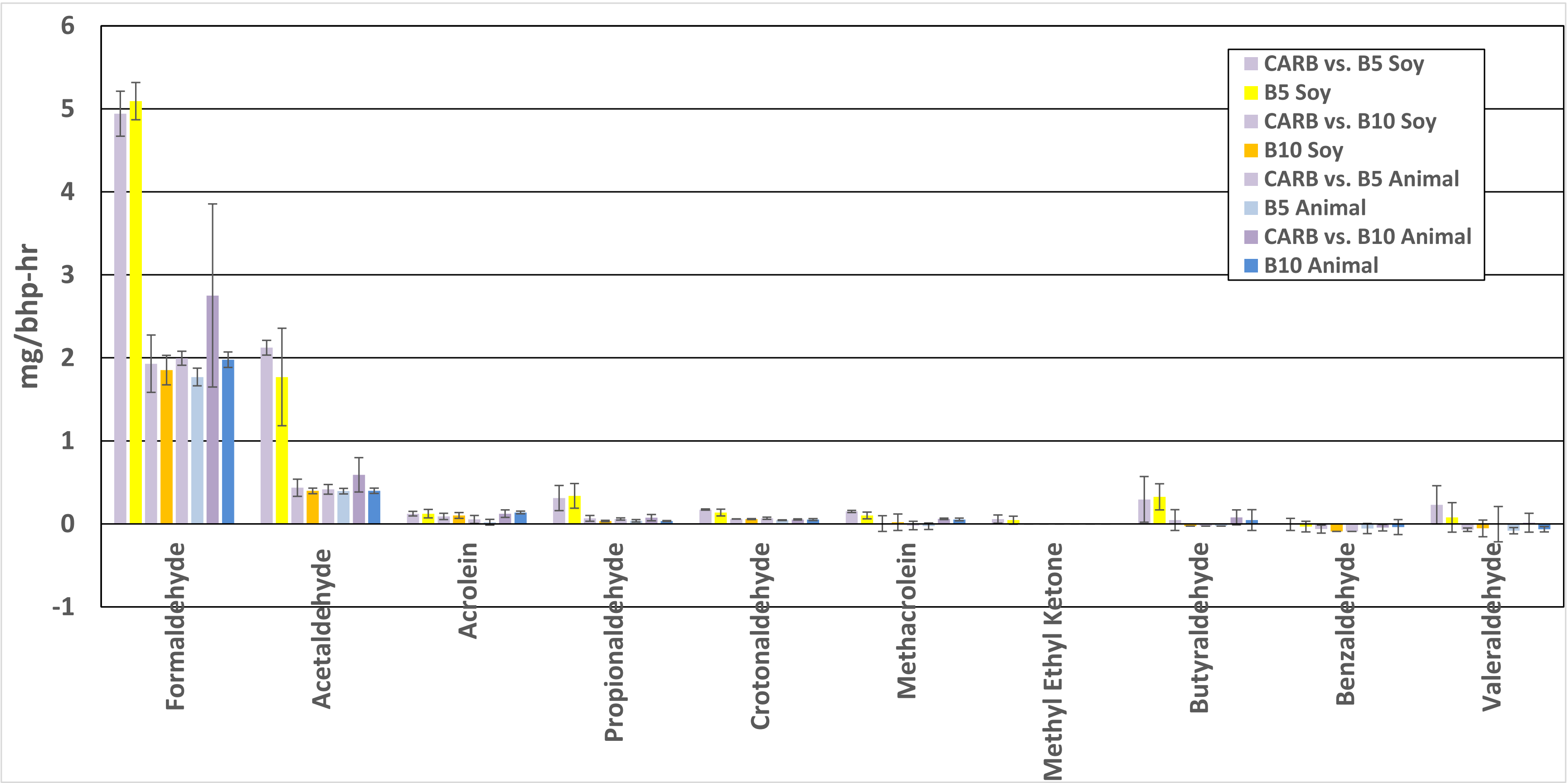

Figure 3-9.Average Carbonyl Emissions Results for B5 and B10 Soy- and Animal-based Biodiesel Blends 1991 DDC Series 60 for the FTP Cycle

Table 3-12. Carbonyl (mg/bhp-hr) Percentage Differences Between the Biodiesel Blends and the CARB Reference Fuel for the 2006 Cummins ISM and 1991 DDC Series 60 Engines

			Formaldehyde	Acetaldehyde	Acrolein	Propionaldehyde	Crotonaldehyde	Methacrolein	Methyl Ethyl Ketone	Butyraldehyde	Benzaldehyde	Valeraldehyde
2006 Cummins ISM	**Average (mg/bhp-hr)**	CARB vs. B5 Soy	16.713	7.521	-0.116	1.181	0.436	0.467	0.304	1.164	0.177	1.103
		B5 Soy	16.680	7.852	-0.204	1.454	0.556	0.638	0.000	2.421	-0.163	1.369
		CARB vs. B10 Soy	15.680	4.125	-0.080	0.666	0.229	0.272	0.000	1.230	0.041	0.062
		B10 Soy	14.879	3.901	-0.106	0.703	0.206	0.259	0.099	1.286	0.052	0.401
		CARB vs. B5 Animal	18.336	4.418	-0.117	0.798	0.284	0.394	0.138	0.208	0.174	0.512
		B5 Animal	16.814	4.214	-0.098	0.725	0.275	0.150	0.130	0.117	0.001	0.436
		CARB vs. B10 Animal	18.281	4.568	-0.127	0.832	0.475	0.352	0.066	1.021	-0.072	0.883
		B10 Animal	17.920	4.433	-0.179	0.770	0.296	0.402	0.116	0.148	0.022	0.095
	% Diff vs. CARB	B5 Soy	-0.2%	4.4%	75.7%	23.1%	27.3%	36.6%	-100.0%	108.1%	**-192.5%**	24.1%
		B10 Soy	-5.1%	-5.4%	33.4%	5.6%	-10.0%	-4.7%	-	**4.5%**	25.6%	544.0%
		B5 Animal	-8.3%	-4.6%	-16.2%	-9.1%	-3.0%	-61.9%	-5.9%	-44.1%	-99.4%	-14.8%
		B10 Animal	-2.0%	-2.9%	41.1%	-7.4%	-37.6%	14.1%	77.1%	-85.5%	-131.4%	**-89.2%**
	P-value vs. CARB	B5 Soy	0.987	0.623	0.426	0.116	0.208	0.128	**-**	0.198	**0.000**	0.580
		B10 Soy	0.410	0.327	0.572	0.496	0.214	0.863	**-**	**0.025**	0.818	0.409
		B5 Animal	0.364	0.518	0.848	0.406	0.740	0.401	0.784	0.315	0.373	0.904
		B10 Animal	0.501	0.424	0.591	0.086	0.354	0.576	0.521	0.412	0.426	**0.005**
1991 DDC Series 60	**Average (mg/bhp-hr)**	CARB vs. B5 Soy	4.942	2.122	0.123	0.311	0.173	0.150	0.057	0.295	-0.007	0.230
		B5 Soy	5.094	1.769	0.123	0.338	0.136	0.102	0.046	0.327	-0.033	0.079
		CARB vs. B10 Soy	1.930	0.436	0.090	0.066	0.059	0.005	0.000	0.047	-0.062	-0.071
		B10 Soy	1.852	0.398	0.103	0.035	0.058	0.020	0.000	-0.026	-0.090	-0.054
		CARB vs. B5 Animal	1.996	0.415	0.054	0.059	0.068	-0.021	0.000	-0.026	-0.090	-0.003
		B5 Animal	1.769	0.395	0.020	0.037	0.046	-0.028	0.000	-0.026	-0.055	-0.083
		CARB vs. B10 Animal	2.750	0.591	0.123	0.076	0.053	0.060	0.000	0.078	-0.045	0.015
		B10 Animal	1.978	0.400	0.137	0.034	0.051	0.053	0.000	0.046	-0.038	-0.065
	% Diff vs. CARB	B5 Soy	-16.9%	568.4%	85.0%	-2.8%	466.7%	197.0%	-3.7%	-43.0%	-13.6%	-22.9%
		B10 Soy	-48.2%	-68.1%	-11.2%	-74.8%	173.9%	4.2%	-	-99.9%	-99.0%	408.4%
		B5 Animal	27.4%	-43.5%	-27.4%	22.4%	**-67.0%**	-23.4%	-	434.6%	72518.1%	-82.2%
		B10 Animal	-91.6%	-84.5%	-64.1%	-87.8%	57.2%	87.4%	-	36.6%	133.9%	-71.0%
	P-value vs. CARB	B5 Soy	0.496	0.362	0.995	0.842	0.197	0.123	0.780	0.872	0.667	0.420
		B10 Soy	0.796	0.663	0.735	0.333	0.754	0.872	-	0.495	0.495	0.785
		B5 Animal	0.484	0.549	0.083	0.270	**0.012**	0.615	-	0.374	0.882	0.640
		B10 Animal	0.294	0.187	0.634	0.132	0.806	0.546	-	0.734	0.900	0.311

3.9 Trace Elements and Metals

The individual element emissions results for the testing of the different B5 and B10 biodiesel blends for the 2006 Cummins ISM engine for the FTP cycle are presented in this section. Table 3-13 shows the average of different element values in µg/bhp-hr and percentage differences for the different fuels. In Table 3-13 percentage differences that statistically significant are bolded, while those that are marginally statistically significant are underlined. These elements were found at very low levels in comparison with the PM mass. A number of elements were found at levels above the background levels, including Na, Mg, Si, P, S, Ca, Fe, and Zn. For the metals, low level emissions can result from engine wear or metal compounds collected in lubrication oil that can be re-entrained into the cylinder and then oxidized during combustion [27]. The dominant metals included divalent transition metals (Zn), alkaline earth metals (Mg and Ca), and redox active transition metals (Fe). The first two metal categories, primarily originate from the lubricant oil and its additive package components. Fe is a product of engine wear, but can also be sourced from the fuel itself. In addition to iron, chromium (Cr) and nickel (Ni), which are also redox active transition metals, were found in the diesel and biodiesel exhaust particles, but in lesser concentrations. Redox active transition metals can help stimulate the generation of hydroxyl radicals by Fenton-type reactions, causing extensive oxidative damage to cellular macromolecules [28]. The elements did not show significant differences between the different fuels tested. For Cr, the use of B5 and B10 blends showed some decreases relative to CARB diesel, with the exception of B10 Soy. On the other hand, Cu emissions showed increases with biodiesel blends, with the exception of B10 Animal.

Table 3-13. Elements (µg/bhp-hr) Percentage Differences Between the Biodiesel Blends and the CARB Reference Fuel for the 2006 Cummins ISM

	Average (µg/bhp-hr)								% Difference			
	CARB vs. B5 Soy	B5 Soy	CARB vs. B10 Soy	B10 Soy	CARB vs. B5 Animal	B5 Animal	CARB vs. B10 Animal	B10 Animal	CARB vs. B5 Soy	CARB vs. B10 Soy	CARB vs. B5 Animal	CARB vs. B10 Animal
Na	245.97	180.09	34.11	237.68	223.92	261.55	101.66	-18.79	-26.8%	596.7%	14.4%	-118.5%
Mg	43.05	3.87	14.30	28.95	33.17	33.92	26.47	3.45	**-91.0%**	102.4%	2.2%	-87.0%
Al	4.90	-2.73	0.94	4.46	-0.97	4.63	-3.10	-3.40	-155.6%	375.0%	120.9%	9.6%
Si	146.49	134.22	234.65	187.62	246.23	255.49	157.98	233.52	-8.4%	**-20.0%**	3.6%	47.8%
P	41.74	48.30	37.89	30.66	34.55	28.40	30.49	25.52	15.7%	-19.1%	-21.6%	-16.3%
S	41.36	42.34	35.15	36.42	40.12	40.96	42.68	37.45	2.4%	3.6%	2.1%	-12.2%
Cl	9.64	4.63	5.66	3.74	6.19	2.36	6.69	3.03	-52.0%	-34.0%	-162.7%	-54.7%
K	3.39	1.62	5.22	5.73	2.07	3.25	1.41	1.34	-52.3%	9.8%	36.3%	-5.0%
Ca	37.25	38.40	31.42	34.10	25.93	30.17	25.92	24.64	3.1%	8.5%	14.0%	-5.0%
Ti	0.15	-0.07	0.67	0.82	0.08	0.38	-0.07	-0.07	-143.2%	22.3%	78.0%	0.1%
V	0.01	0.01	-0.21	-0.06	-0.21	0.09	1.19	0.52	-1.6%	-72.4%	340.8%	-56.1%
Cr	3.18	0.24	0.74	2.06	1.34	0.38	4.94	2.37	-92.6%	176.9%	-255.0%	-52.0%
Mn	0.00	1.17	0.07	0.51	0.00	1.40	0.00	0.00	-	617.2%	100.0%	-
Fe	8.74	12.57	34.63	74.10	10.73	15.27	13.30	12.44	43.8%	**114.0%**	29.7%	-6.5%
Co	0.00	0.00	0.00	0.00	0.00	0.29	0.00	0.00	-	-	100.0%	-
Ni	-0.14	0.23	0.37	1.26	-0.14	0.67	0.74	0.68	-260.7%	236.2%	121.0%	-9.3%
Cu	0.02	0.75	0.46	1.19	0.02	0.97	2.23	1.28	4303.9%	159.4%	98.2%	-42.8%
Zn	48.68	49.92	36.51	36.82	30.06	30.18	30.34	29.00	2.5%	0.9%	0.4%	-4.4%
Ga	1.33	1.18	0.67	0.74	2.15	0.30	0.74	0.89	-11.4%	11.5%	-622.9%	20.3%
Ge	-0.07	-0.07	0.00	-0.07	-0.07	-0.07	-0.07	0.08	-0.6%	-1521.6%	-0.1%	-224.0%
As	0.39	0.38	-0.35	0.24	0.98	0.83	0.76	0.68	-1.5%	-168.9%	-18.1%	-10.3%
Se	0.69	0.46	0.91	0.03	1.35	0.47	0.77	1.20	-32.5%	-96.8%	-186.2%	57.4%
Br	0.65	0.65	0.95	0.43	0.95	1.10	0.73	1.47	0.0%	-54.7%	12.9%	101.1%
Rb	-0.20	0.02	-0.20	0.09	0.02	-0.20	0.98	-0.27	-110.1%	-144.9%	109.3%	-128.1%
Sr	0.60	0.22	-0.14	0.37	0.60	0.30	0.60	0.89	-62.4%	-367.3%	-97.1%	49.2%
Y	-0.18	1.58	0.85	1.95	1.00	2.03	-0.26	0.93	-992.4%	129.9%	50.6%	-462.8%
Zr	-1.09	-1.23	-0.79	-0.50	-0.06	-1.23	0.90	-1.24	12.5%	-37.1%	**95.5%**	-237.3%
Mo	6.27	5.50	2.80	3.53	5.16	3.47	5.09	2.30	-12.3%	26.0%	-48.9%	-54.9%
Pd	-0.75	-0.68	0.79	1.16	-0.75	2.64	0.43	-0.53	-10.1%	46.9%	128.7%	-225.4%
Ag	-1.49	-2.58	-2.81	-2.74	-0.91	0.35	-0.39	2.34	72.9%	-2.7%	362.4%	-706.8%
Cd	-1.65	-1.20	-1.65	-1.57	-0.69	0.49	1.36	3.00	-27.2%	-4.5%	240.8%	120.0%
In	2.06	-1.77	2.05	-3.01	3.54	-0.67	-3.03	-3.03	-185.9%	-247.0%	629.7%	0.1%
Sn	-0.72	0.48	-9.26	-2.87	-9.14	-8.83	-6.85	-7.97	-166.9%	-69.0%	-3.5%	16.2%
Sb	-0.27	4.40	-0.27	5.01	0.91	0.24	0.98	2.01	-1705.3%	-1932.8%	-276.4%	105.4%
Ba	3.11	3.03	3.91	0.32	2.44	0.32	1.64	-0.49	-2.4%	-91.9%	-671.3%	-129.9%
La	2.98	1.50	2.61	0.40	2.25	2.76	0.55	2.76	-49.8%	-84.5%	18.6%	403.1%
Hg	0.00	0.00	0.00	0.00	0.00	3.25	0.00	0.00	-	-	100.0%	-
Pb	3.25	1.41	5.15	2.36	1.27	2.07	2.96	1.78	-56.5%	-54.2%	38.9%	-39.7%

3.10 Ions

The individual ions emissions results for the testing of the different B5 and B10 biodiesel blends for the 2006 Cummins ISM engine for the FTP cycle are presented in this section. Table 3-14 shows the average of different ions values in µg/bhp-hr and percentage differences for the different fuels. The ions were found at very low levels in comparison with the PM mass. Several ions were measureable for most of the test fuel combinations, including sulfate, nitrate, sodium, ammonium, and calcium. Sulfate emissions could be attributed to sulfur from either the fuel or the lubricant. The nitrate emissions could be formed during combustion under high NO_x conditions. There were no consistent fuel trends for the different ions, however.

Table 3-14. Ions (µg/bhp-hr) Percentage Differences Between the Biodiesel Blends and the CARB Reference Fuel for the 2006 Cummins ISM

	Average (µg/bhp-hr)								% Difference			
	CARB vs. B5 Soy	B5 Soy	CARB vs. B10 Soy	B10 Soy	CARB vs. B5 Animal	B5 Animal	CARB vs. B10 Animal	B10 Animal	CARB vs. B5 Soy	CARB vs. B10 Soy	CARB vs. B5 Animal	CARB vs. B10 Animal
Fluoride	0.125	-0.459	0.313	-0.214	-0.537	1.050	0.761	0.158	-467.5%	-168.3%	-295.7%	-79.3%
Chloride	-0.404	-1.285	-1.453	-1.539	-0.756	-0.730	-0.989	-0.964	218.0%	5.9%	-3.5%	-2.6%
Nitrite	-0.204	-0.585	-0.431	-0.475	-0.634	0.494	1.795	1.407	186.3%	10.3%	-177.9%	-21.6%
Sulfate	1.518	0.972	3.872	1.798	1.989	0.779	0.980	1.479	-36.0%	-53.6%	-60.8%	50.9%
Nitrate	4.996	4.642	6.090	2.856	3.322	12.636	-0.874	1.304	-7.1%	-53.1%	280.4%	-249.2%
Sodium	2.366	25.228	-1.500	4.874	3.267	2.252	2.185	-0.403	966.4%	-424.9%	-31.1%	-118.4%
Ammonium	7.893	9.910	6.720	5.165	14.906	6.765	8.319	8.521	25.5%	-23.1%	-54.6%	2.4%
Potassium	0.132	1.066	-0.060	0.210	3.448	0.451	-0.103	1.596	710.7%	-449.5%	-86.9%	-1653.2%
Magnesium	0.044	-	0.000	0.466	1.437	-0.005	0.392	0.952	-	274527.0%	-100.3%	142.6%
Calcium	3.857	2.384	14.123	0.723	4.326	4.500	1.318	4.250	-38.2%	-94.9%	4.0%	222.6%

4 Summary

This goal of this study was to more comprehensively study the impact of B5/B10 biodiesel blends with CARB diesel fuel on different emissions. The results of this study will be used in conjunction with results from other associated or related studies to evaluate the emissions impacts of biodiesel use in CARB diesel fuel. For this purpose, two different biodiesel feedstocks (soybean oil and animal tallow biodiesels) were blended with a CARB diesel fuel at 5% and 10% levels. Testing was conducted in CE-CERT's heavy-duty engine dynamometer laboratory with a 2006 Cummins ISM engine and a 1991 Detroit Diesel Corporation (DDC) Series 60 Engine. The test sequence included the standard Federal Test Procedure (FTP), the Urban Dynamometer Driving Schedule (UDDS), and the Supplemental Emissions Test (SET).

A summary of all the results for this data set is provided below. Note that the results summary focuses on results that were found to be either statistically significant or marginally statistically significant.

- NO_x emissions results for the testing of the 2006 Cummins ISM engine showed a statistically significant 1.0% and 1.9% increase, respectively, for the B5-soy and the B10-soy blends compared to the CARB diesel fuel for the FTP cycle, and a statistically significant increase of 3.6% for the B10-soy blend compared to the CARB diesel fuel for the UDDS.
- NO_x emissions results for the 1991 DDC Series 60 engine showed a statistically significant increase of 1.0% and 3.2%, respectively, for the B5-soy blend for the FTP and UDDS cycles. Similarly, the B10-soy blend showed a statistically significant increase of 1.5% and 1.3%, respectively, for the FTP and SET cycles.
- NO_x emissions results for the animal biodiesel blends did not show the more consistent NO_x increases found for the soy biodiesel blends, with only the B10-animal blend showing a statistically significant increase of 0.7% for the FTP on the 1991 DDC engine.
- PM emissions results showed consistent reductions for the biodiesel blends for both engines for the FTP and SET cycles. For the 2006 Cummins ISM engine, statistically significant reductions for PM ranged from 5.8-15.1% with all B5 and B10 biodiesel blends tested over the FTP cycle and from 6.7-14.3% for B5 and B10 blends over the SET cycle. For the 1991 DDC Series 60 engine, statistically significant reductions in PM ranged from 7.5%-16.5% for the B5 and B10 biodiesel blends over the FTP cycle and from 6.0%-9.4% for the SET cycle. There were some inconsistencies in the PM emissions results for the UDDS cycle, with a marginally statistically significant increase of 6.4% for the B5-soy compared to the CARB diesel fuel for the 2006 Cummins engine and a 26.6% increase for the B5-soy biodiesel compared to CARB diesel fuel for the 1991 DDC Series 60 engine. This might be due to the low load nature of this cycle.
- THC emissions results showed a general decreasing trend for most biodiesel blends over most of the test cycles compared to the CARB diesel fuel, but these differences were only statistically significant or marginally statistically significant for the B5-soy blend for the SET cycle for the 2006 Cummins ISM engine and the B5-animal blend for the SET cycle and the B10-soy blend for the FTP for the 1991 DDC Series 60 engine.
- CO emissions results showed a general trend of reductions with the biodiesel blends, although these differences were not statistically significant for all biodiesel blends or

cycles. The statistically significant and marginally statistically significant reductions ranged from 2.0%-7.9% for the 2006 Cummins ISM engine and 2.3%-7.3% for the 1991 DDC Series 60 engine for the different biodiesel blends and cycles. There was a somewhat stronger trend of biodiesel CO reductions for the 1991 DDC Series 60 engine, which showed CO reductions for nearly all biodiesel blends and cycles with the exception of some UDDS cycles, compared to the 2006 Cummins ISM engine.

- CO_2 emissions results did not show consistent fuel trends over the range of blends, cycles, and engines tested, with most differences not being statistically significant.
- BSFC results showed a general increasing trend with the biodiesel blends, although this was not seen for all biodiesel blend, cycle, and engine combinations. For the 2006 Cummins ISM engine, these BSFC increases ranged from 0.5 to 2.3%. For the 1991 DDC Series 60 engine, these BSFC increases ranged from 0.7 to 3.2%. These differences can be attributed to the differences in the energy contents of the fuels.
- The results for the EC/OC were not as consistent as those for the total PM mass. Statistically significant reductions in EC were seen for the B5 animal, B10 soy and B10 animal blends for the 1991 DDC Series 60 engine, but only for the B10 animal blend for the 2006 Cummins ISM engine. For OC emissions, the only statistically significant difference found was a 20.5% increase for the B5 soy blend for the 1991 DDC Series 60 engine. The less consistent trends for EC/OC emissions could be due to the lower blend levels or fewer number of samples collected.
- There were not any consistent fuel differences between the CARB diesel and the biodiesel blends for carbonyls. Formaldehyde and Acetaldehyde showed the highest carbonyl emissions, consistent with previous studies, with some other higher molecular weight carbonyls seen at much lower levels.
- The emissions of individual elements were found at very low levels in comparison with the PM mass. A number of elements were found at levels above the background levels, including Na, Mg, Si, P, S, Ca, Fe, and Zn. The elements did not show significant differences between the different fuels tested.
- The ions were found at very low levels in comparison with the PM mass. Several ions were measureable for most of the test fuel combinations, including sulfate, nitrate, sodium, ammonium, and calcium. There were no consistent fuel trends for the different ions, however.

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Appendix A: Test Cycles

The FTP cycle consists of four phases, including (1) New York Non Freeway (NYNF) phase typical of light urban traffic with frequent stops and starts, (2) Los Angeles Non Freeway (LANF) phase typical of crowded urban traffic with few stops, (3) Los Angeles Freeway (LAFY) phase simulating crowded expressway traffic in Los Angeles, followed by (4) a repetition of the first NYNF phase. The variation of normalized speed and torque with time is shown in Figure A-1.

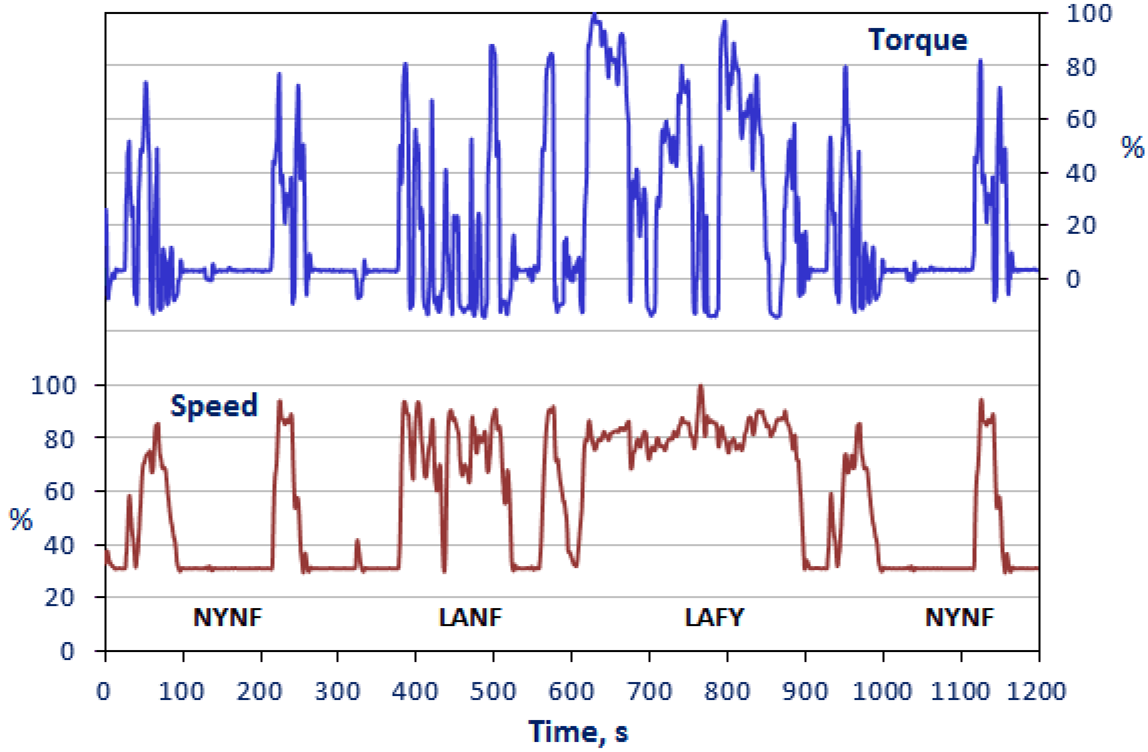

Figure A-1. FTP Engine Dynamometer Test Cycle

- **Reference : Emissions Test Cycle, Engine Dynamometer FTP Transient Cycle, Diesel Net, Available at http://www.dieselnet.com/standards/cycles/ftp_trans.php**

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 engine dynamometer cycle is developed from engine data (engine RPM and torque) collected from a typical truck while it is operated over the UDDS on a chassis dynamometer.

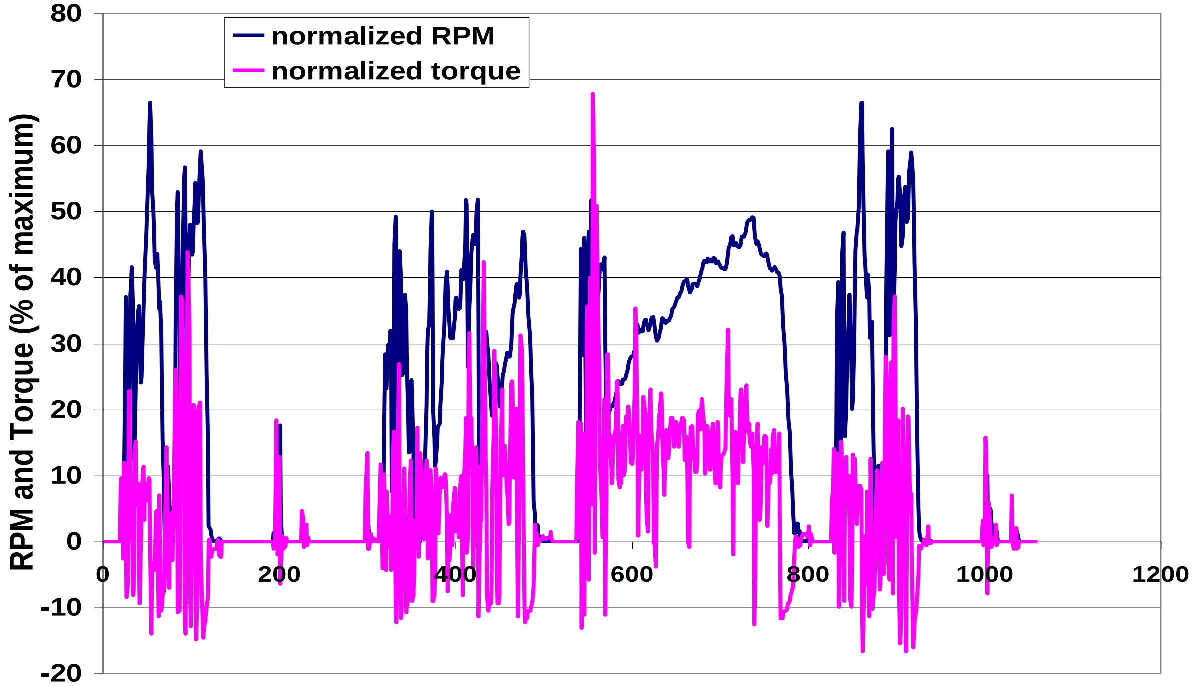

Figure A-2. UDDS Engine Dynamometer Test Cycle

Reference: Durbin TD, Miller JW, Johnson K, Hajbabaei M, Kado NY, Kobayashi R, et al. Final Report for the CE-CERT Engine Testing Portion for the CARB Assessment of the Emissions from the Use of Biodiesel as a Motor Vehicle Fuel in California "Biodiesel Characterization and NOx Mitigation Study". Final Report Prepared for CARB, October; 2011.

The Supplemental Emissions Test (SET) is a 13-mode steady-state engine dynamometer test. Figure A-3 summarizes the ramped modal used, as specified in §86.1362-2007. Speeds A, B and C are defined as specified in 40 CFR 1065.

RMC mode	Time in mode (seconds)	Engine speed [1,2]	Torque (percent) [2,3]
1a Steady-state	170	Warm Idle	0
1b Transition	20	Linear Transition	Linear Transition
2a Steady-state	170	A	100
2b Transition	20	A	Linear Transition
3a Steady-state	102	A	25
3b Transition	20	A	Linear Transition
4a Steady-state	100	A	75
4b Transition	20	A	Linear Transition
5a Steady-state	103	A	50
5b Transition	20	Linear Transition	Linear Transition
6a Steady-state	194	B	100
6b Transition	20	B	Linear Transition
7a Steady-state	219	B	25
7b Transition	20	B	Linear Transition
8a Steady-state	220	B	75
8b Transition	20	B	Linear Transition
9a Steady-state	219	B	50
9b Transition	20	Linear Transition	Linear Transition
10a Steady-state	171	C	100
10b Transition	20	C	Linear Transition
11a Steady-state	102	C	25
11b Transition	20	C	Linear Transition
12a Steady-state	100	C	75
12b Transition	20	C	Linear Transition
13a Steady-state	102	C	50
13b Transition	20	Linear Transition	Linear Transition
14 Steady-state	168	Warm Idle	0

[1] Speed terms are defined in 40 CFR part 1065.
[2] Advance from one mode to the next within a 20-second transition phase. During the transition phase, command a linear progression from the speed or torque setting of the current mode to the speed or torque setting of the next mode.
[3] The percent torque is relative to maximum torque at the commanded engine speed.

Figure A-3. Supplemental Emissions Test (SET) Test Cycle
Reference: Emissions Test Cycle, Heavy-Duty Supplemental Emissions Test (SET) Cycle, Diesel Net, Available at https://www.dieselnet.com/standards/cycles/set.php

Appendix B: Laboratory Resources

CE-CERT Mobile Emissions Laboratory

Controlling emissions from heavy-duty diesel engines is a major priority for the regulatory community and industry. To assist with this effort, CE-CERT has worked with regulatory agencies, engine manufacturers, exhaust aftertreatment companies, fuel companies, and vehicle end users over the past year and a half to understand the scope of the diesel exhaust issue and articulate a research program designed to improve our understanding of the problem and potential solutions. CE-CERT also has developed new research capabilities, including a unique emissions measurement laboratory and an enhanced environmental modeling group. Together, these resources can shed important light on critical emissions issues and contribute to efficient, effective environmental strategies and to greater industry/government/academic cooperation. This program plan describes the technical vision and contemplated approach for achieving these objectives.

CE-CERT has constructed an emissions laboratory contained within a 53-foot truck trailer, designed to make laboratory-quality emissions measurements of heavy-duty trucks under actual operating conditions (Figure B-1).

The laboratory contains a dilution tunnel, analyzers for gaseous emissions, and ports for particulate measurements. Although much of the system is custom-designed, the laboratory was designed to conform as closely as possible to Code of Federal Regulations requirements for gaseous and particulate emissions measurement. The laboratory is designed to operate as a class 8 tractor is pulling it over the road (or on a closed track over a repeatable cycle); it is not a roadside testing laboratory. It also is used to measure emissions from heavy-duty stationary engines, such as pipeline pumps and backup generators, as they operate under actual loads.

With laboratory development and validation nearly complete, CE-CERT intends to embark on a research program to explore the following topics:

- “Real world” emissions of gaseous and particulate pollutants from on-road heavy-duty engines.
- The effects of alternative diesel fuel formulations, alternative fuels, alternative powertrains, and emission control technologies on emissions and energy consumption.
- The effects of driving cycles on emissions.
- Modal emissions modeling for heavy-duty trucks.

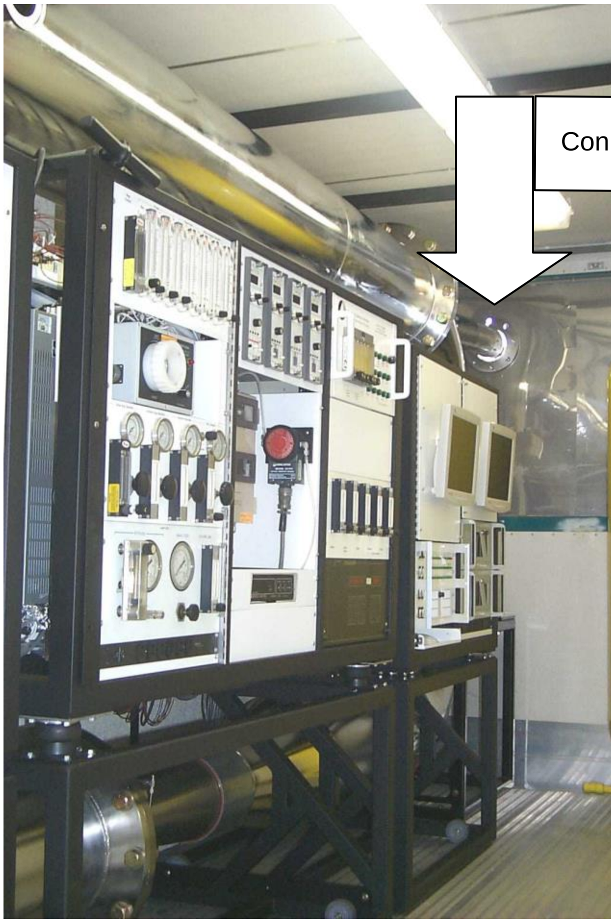

Figure B-1.

Left: Trailer laboratory interior, looking forward. Dilution tunnel travels beneath, forward of, and above analytical instruments. Connector at the front captures emissions as the truck pulls the trailer.

Above: Trailer laboratory in operation at the California Speedway.

CE-CERT Heavy-Duty Engine Dynamometer Test Facility

CE-CERT's Heavy-Duty Engine Dynamometer Test Facility is designed for a variety of applications including verification of diesel aftertreatment devices, certification of alternative diesel fuels, and fundamental research in diesel emissions and advanced diesel technologies. The engine dynamometer facility components were provided as a turnkey system by Dyne Systems of Wisconsin. CE-CERT's Mobile Emissions Laboratory (MEL) is used directly in conjunction with this facility for certification type emissions measurements.

The test cell is equipped with a 600 horsepower (hp) GE DC electric engine dynamometer that was obtained from the EPA's National Vehicle and Fuels Emission Laboratory in Ann Arbor, MI. The dynamometer is capable of testing approximately 85% of the engines used in on-road applications, and will primarily be used for engines in the 300 to 600 hp range. A charge air conditioning system was obtained from Dyno Air of North Carolina to provide temperature/ humidity control for the engine intake air, with an accuracy of ±2°C from the setpoint.

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Figure B-2. Picture of CE-CERT's Heavy-Duty Engine Dynamometer Facility