Final Report

CARB B20 Biodiesel Preliminary and Certification Testing

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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. This earlier work showed that biodiesel would likely increase NO_x emissions when used in CARB diesel at blends of B20% and above, but also showed that additives could be used to mitigate NO_x increases in biodiesel blends.

The goal of this study is to evaluate different B20 additive blends as potential emissions equivalent biodiesel fuel formulations for California. For this work, preliminary tests were performed on soy-based B20 blends with 5 different additive combinations. A full emissions equivalent certification test was then performed on one of the B20-soy additive. The results showed that although some additives provided reductions in NO_x emissions with B20 blends, none of the additives tested provided sufficient benefits in NO_x emissions to provide the level of NO_x mitigation required to pass a full emissions equivalent certification test procedure at a B20 level.

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
SIP…………………………………….State Implementation Plan
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 of the popular alternatives 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 University of California Riverside (UCR) and UC Davis (UCD), conduced one of the most comprehensive biofuels emissions characterization studies to date. The major focus of this large study was to evaluate the impact of biodiesel fuels on NO_x emissions and mitigate the NO_x emissions increases with biodiesel fuels to the extent possible. This large study showed a definitive trend of NO_x increases for B20 and higher blends relative to a CARB diesel fuel. The results also showed that the impacts of NO_x increases with biodiesel could be mitigated with combinations of blends with renewable and gas-to-liquid (GTL) fuels or with additives. The use of additives in particular has also shown some success in other studies, and could represent a viable and cost effective pathway to achieving NO_x neutral biodiesel blends.

The present study expands upon the earlier CARB/UCR/UCD study to examine the viability of certifying B20-biodiesel blends with additives under CARB's procedures for emissions equivalent diesel fuel formulations. The emissions equivalent diesel certification procedure is robust in that it requires at least twenty replicate tests on the reference and candidate fuels, depending on the test sequence selected, providing the ability to differentiate small differences in emissions. For this study, preliminary tests were performed on soy-based B20 blends with 5 different additive combinations. A full certification test was then performed on one of the B20-soy additive combinations to evaluate the viability of this strategy for implementation into the California fuel marketplace. This report provides a summary of both the preliminary and certification testing results.

Test Fuels

The reference fuel was the fuel with which the candidate fuels emissions were compared and the fuel with which the biodiesel was blended to produce candidate fuels. The reference fuel was 10% aromatic content diesel fuel meeting the CARB reference fuel specifications under 13 CCR 2282(g)(4)(C)1.b Alternative 1. A B20 biodiesel and five B20 additive blends were made by blending neat biodiesels made from soy-bean oil feedstock with the CARB reference fuel at a 20% level.

Test Engine

The engine that was used for this program was a 2006 model year Cummins ISM engine. This engine was a 370 hp, 10.8 liter, in-line, six cylinder, four-stoke diesel engine equipped with a turbocharger with a charge air cooler and exhaust gas recirculation (EGR).

Test Procedure

All testing was conducted in accordance with the Federal Test Procedure (FTP) for heavy-duty engines. The test sequence for the preliminary and certification emissions testing was conducted using one of the hot start sequences described under §114.315(c)(4)(C)(ii)(I), This test sequence is presented in Table E-1. The preliminary testing was only a day testing based on this sequence while certification testing was a five day testing with a minimum of 20 tests each on the reference and candidate fuels.

Table E-1. Testing Protocol for Certification Procedure

Day	Fuel Test Sequence
1	RC CR RC CR
2	RC CR RC CR
3	RC CR RC CR
4	RC CR RC CR
5	RC CR RC CR

The engine emissions testing was performed at the UCR's 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 via carbon balance. The emissions measurements were made using the standard analyzers in CE-CERT's heavy-duty Mobile Emissions Laboratory (MEL) trailer. The soluble organic fraction (SOF) of the PM was also determined for each test.

Results

Figure E-1 shows the NO_x emission results for the preliminary and certification testing of the different B20 additive blends on a gram per brake horsepower hour (g/bhp-hr) basis A summary of all the results is as follows:

Preliminary Testing Results:

- NO_x emissions results showed a statistically significant 1.2-5.1% increase with B20-soy with additive blends compared to the CARB reference fuel. The B20-soy 1% INNOSPEC 1 blend NO_x emissions results from the preliminary testing showed the lowest increase in of 1.2%. Therefore, this blend was selected for the certification testing.
- PM emissions results showed consistent, statistically significant reductions ranged from 15.7-24.7% with B20 with additive blends and B20-soy compared to CARB reference fuel.
- THC emissions results showed consistent 10.8-15.5% statistically significant reductions for the B20 and B20 additive blends. Only the reduction for the B20-soy 1.5% INNOSPEC 2 was not statistically significant.

- CO emissions results showed reductions ranged from 6.9-14.5% compared to CARB reference fuel for the B20-soy additive blends. The B20-soy blend CO emissions results did not show statistically significant differences in CO compared to the CARB reference fuel, however.
- CO_2 emissions results showed increases for some of the B20 additive blends, but not for others. These increases were in the range of 0.2-1.4%. BSFC results showed increases of 0.9-2.1% with B20-soy and B20-soy with additives, which were statistically significant or marginally statistically significant for all cases. The magnitude of the increases in BSFC for the B20-soy and B20-soy with additives are comparable to the differences seen in the energy contents of the different fuels tested.

Certification Testing Results:

- Certification testing was performed on B20-soy 1.0% INNOSPEC 1 for the 2006 Cummins ISM engine over the FTP cycle.
- B20-soy 1.0% INNOSPEC 1 blend NO_x emissions results showed a 2.5% statistically significant increase. Therefore, this blend did not pass the NO_x emissions criteria of the certification testing.
- PM emission results showed a statistically significant reduction of 20.6% with the B20-soy 1.0% INNOSPEC 1.
- THC emissions results showed a statistically significant 16.8% reduction with the B20-soy 1.0% INNOSPEC 1.
- CO emissions results showed a statistically significant 15.9 reduction with the B20-soy 1.0% INNOSPEC 1
- CO_2 emissions and BSFC results showed slight increases of 0.3% and 1.2%, respectively, with the B20-soy 1.0% INNOSPEC 1. The increase in BSFC was statistically significant, while the CO_2 emissions increase was marginally statistically significant.
- The B20-soy 1.0% INNOSPEC 1 blend failed the full certification test procedure based on NO_x emissions.

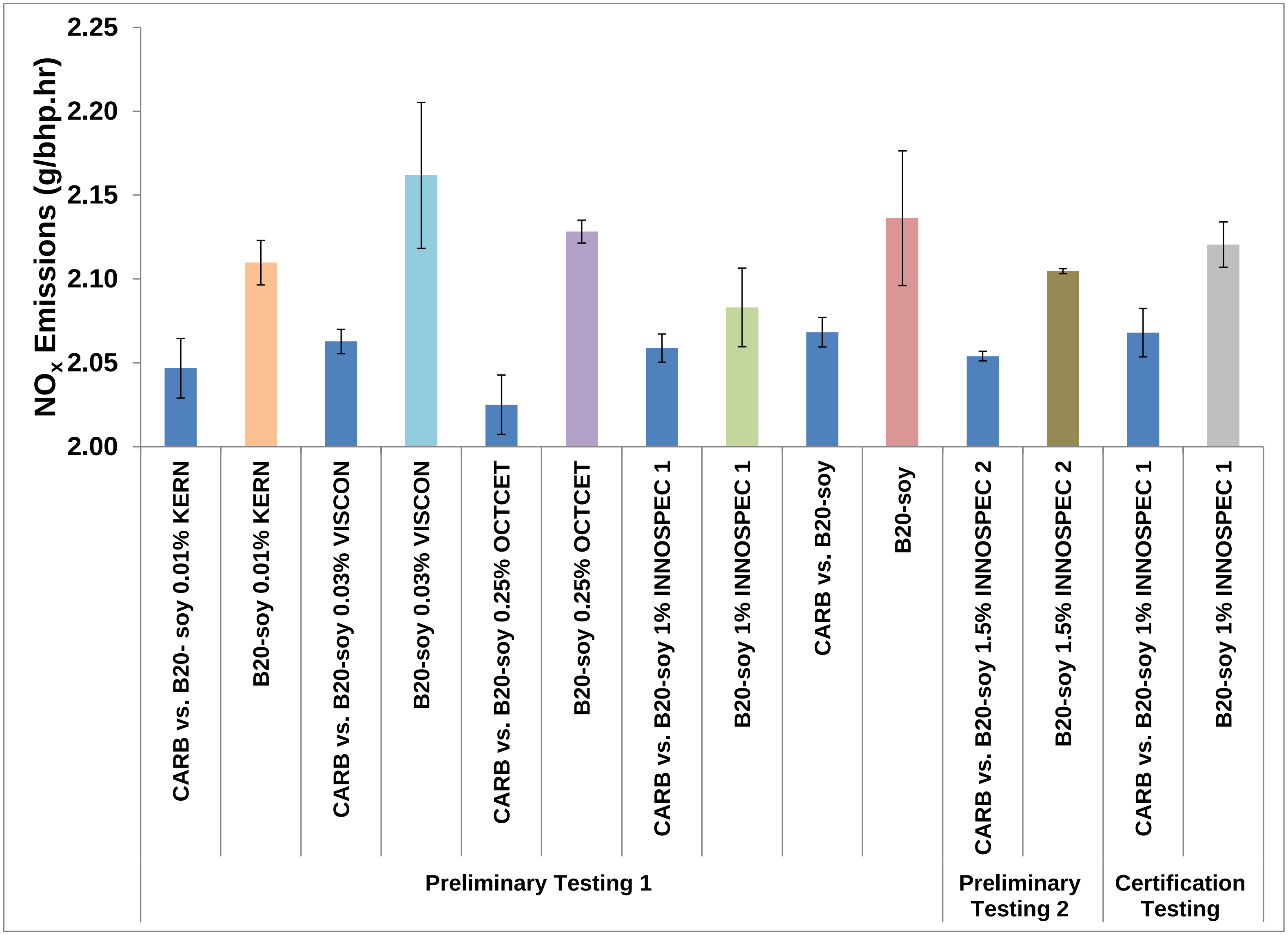

Figure E-1. Average NO_x Emission Results for the Preliminary and Certification Testing

1 Introduction

The California Air Resources Board (CARB) has developed a number of programs 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, which can be a good substitute for diesel fuel. 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]. This is a concern, especially in California, since allowing emissions to increase or "backslide" above those levels implemented through the regulatory process could require a modification of the State Implementation Plan (SIP).

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 results also showed that the impacts of NO_x increases with biodiesel could be mitigated with combinations of blends with renewable and gas-to-liquid (GTL) fuels or with additives [1,2]. The use of additives, in particular, has also shown some success in other studies, and could represent a viable and cost effective pathway to achieving NO_x neutral biodiesel blends.

The present study expands upon the earlier CARB/UCR/UCD study to examine the viability of certifying B20 biodiesel blends with different additives under CARB's procedures for emissions equivalent diesel fuel formulations. The emissions equivalent diesel certification procedure is robust in that it requires at least twenty replicate tests, depending on the test sequence selected, on the reference and candidate fuels, providing the ability to differentiate small differences in emissions. For this study, preliminary tests were performed on soy-based B20 blends with 5 different additive combinations. A full certification test was then performed on one of the B20-soy additive combinations to evaluate the viability of this strategy for implementation into the California fuel marketplace.

2 Experimental Procedures

2.1 Test Fuels

The reference fuel was the fuel with which the candidate fuels emissions were compared and the fuel with which the biodiesel was blended to produce candidate fuels. The reference fuel was a 10% aromatic content diesel fuel meeting the CARB reference fuel specifications under title 13, California Code of Regulations (CCR), section 2282(g)(3). For this study two different batches of reference fuel from the same suppliers were used. The specifications and properties of these two reference fuels are provided in NA= Not Available

Table 2-2 and NA= Not Available

Table 2-2. 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 on the first batch of CARB reference fuel.

Table 2-1. Properties of CARB Reference Fuel

Property	ASTM Test Method	Units	Specification		Batch 1 Results	Batch 2 Results
Distillation, IBP	D 86	^oF	340	420	354	359
5%					404	400
10%			400	490	416	414
20%					440	438
30%					464	460
40%					483	478
50%			470	560	497	493
60%					509	508
70%					523	524
80%					541	543
90%			550	610	565	568
95%					587	588
Distillation - EP			580	660	608	605
Recovery		vol%			98.0	98.3
Residue					1.3	1.3
Loss					0.7	0.4
Gravity	ASTM D4052	API	33	39	37.2	38
Specific Gravity	ASTM D4052		0.83	0.86	0.839	0.836
Cloud Point	ASTM D2500	^oF			-26	-22
Flash Point	ASTM D93	^oF	130		172	172
Viscosity, 40 ^oC	ASTM D445	cSt	2.0	4.1	2.5	2.5
Sulfur	ASTM D5453	ppm wt		15	4.7	None Detected
Nitrogen	ASTM D4629	Ppm		10	None Detected	None Detected
Total Aromatics	ASTM D5186	vol%		10	9	9
Polycyclic Aromatics	ASTM D5186	vol%		1.4	None Detected	0.3
Cetane number	ASTM D613		48		53.1	48.4
High Frequency Recip. Rig	ASTM D6079	microns		520	290	210
Carbon	ASTM D5291	wt%			85.80	NA
Hydrogen	ASTM D5291	wt%			13.61	NA
Heating Value	ASTM D240	BTU/lb			19689	NA
Carbon per Unit Energy		Carbon lbs. /BTU			$4.36x10^{-5}$	NA

NA= Not Available

Table 2-2. Properties of Soy-based Biodiesel

Property	ASTM Test Method	Units	Specification	Soy
Flash Point	ASTM D93	^oC	130 min.	159
Water and Sediment	ASTM D2709	% Vol.	0.05 max.	0.000
Kinematic Viscosity, 40^oC	ASTM D445	mm^2/s	1.9 – 6.0	4.220*
Sulfated Ash	ASTM D874	% mass	0.02	<0.01*
Sulfur	ASTM D5453	Ppm	15 max.	1.1
Copper Strip Corrision	ASTM D130		No. 3 max.	1a*
Cetane Number	ASTM D613		47 min.	49.2
Cloud Point	ASTM D2500	^oC	Report	0
Carbon Residue	ASTM D4530	% mass	0.05 max.	<0.02*
Acid Number	ASTM D664	Mg KOH/g	0.5 max.	0.26
Free Glycerin	ASTM D6584	% mass	0.02 max.	0.003
Total Glycerin	ASTM D6584	% mass	0.240 max.	0.106
Monoglycerides	ASTM D6584	% mass	Report	0.342
Diglycerides	ASTM D6584	% mass	Report	0.124
Triglycerides	ASTM D6584	% mass	0.050 max.	0.000
Visual inspection	ASTM D4176	1-6	2 max.	1
Phosphorous content	ASTM D4951	% mass	0.001 max.	<0.0001*
Distillation at 90% Recovered	ASTM D1160	^oC	360 max.	341*
Sodium/Potassium, combined	EN14538	ppm (µg/g)	5 max.	<5.0*
Calcium/Magnesium, combined	EN14538	ppm (µg/g)	5 max.	<2.0*
Oxidation Stability	EN15751	Hours	3 min.	4
Cold Soak Filtration	ASTM D7501	Seconds	360 max.	72
Moisture	ASTM D6304	%mass		190
Methanol Content	EN14110	%mass	0.2 max.	
Heating value	ASTM D240	BTU/lb		17140
API Gravity@60°F	ASTM D4052			28.43
Specific Gravity @60°F	ASTM D4052			0.8848
Carbon	ASTM D5291	wt%		77.10
Hydrogen	ASTM D5291	wt%		11.85
Carbon per Unit Energy		Lbs. Carbon/BTU		$4.50x10^{-5}$

* Are based on the most recent fuel specification testing

Biodiesel was blended at a B20 level for this test program. A soy-based biodiesel was the base biodiesel used for all testing. The properties of the soy-based biodiesel are provided in NA= Not Available

Table 2-2. The B20 fuels were blended volumetrically using the CARB reference fuel as the base diesel fuel. A total of 5 additives were used with the B20 blends, including additives labeled Kern, Viscon, Octcet, and Innospec, with Innospec providing two additive variations. The B20 additive formulations were blended in drums for the preliminary testing. A single B20 additive batch was used for each of the full emissions equivalent certification tests. The first batch of reference fuel was used for the Kern and Octcet preliminary B20-additive testing. The second batch of reference fuel was used for all the remaining preliminary tests and the full emissions equivalent certification testing. The B20 soy-based blends are denoted B20-soy throughout this report. Although fuel analyses were not performed for the B20-soy blends, a table of estimated properties for a limited number of fuel specifications is included in Table 2-3, based on arithmetic averages of the corresponding properties for the CARB reference fuel and the soy-based B100 based on their relative fractions in the blend.

Table 2-3. Properties of B20-Soy Blend

Property	ASTM Test Method	Units	Results
Heating value	ASTM D240	BTU/lb	19200
API Gravity@60°F	ASTM D4052		35.4
Specific Gravity @60°F	ASTM D4052		0.85
Carbon	ASTM D5291	wt%	84.1
Hydrogen	ASTM D5291	wt%	13.3
Carbon Unit per Energy		Carbon lbs. /BTU	$4.39x10^{-5}$

*B20-soy properties are the arithmetic averages of the properties for the B100-soy and CARB reference fuels

2.2 Test Engine

The engine that was used for this program was a 2006 model year Cummins ISM engine. The specifications of the engine are provided in Table 2-4.

Table 2-4. Test Engine Specifications

Engine Manufacturer	Cummins, Inc.
Engine Model	ISM 370
Model Year	2006
Engine Family Name	6CEXH0661MAT
Engine Type	In-line 6 cylinder, 4 stroke
Displacement (liter)	10.8
Power Rating (hp)	370 @ 2100 rpm
Fuel Type	Diesel
Induction/exhaust	Turbocharger with charge air cooler with EGR

2.3 Test Matrix and Test Sequence

The testing was conducted in two different segments. First, preliminary or scoping testing was conducted on the B20-soy biodiesel blends with 5 different additives and on the B20-soy biodiesel without an additive for comparison. Full certification testing was then performed with a B20 blend with one of the additives tested in the preliminary testing.

All testing was conducted in accordance with the Federal Test Procedure (FTP) for heavy-duty engines [14]. The testing for the preliminary and certification emissions testing was conducted using one of the hot start sequences described under 13 CCR 2282(g)(4)(C)1.b Alternative 1. Where "R" is the reference fuel and "C" is the candidate fuel, the test sequence was performed as follows:

(I) Alternative 1: RC CR RC CR Continuing in the same order for a given calendar day until a minimum of twenty individual hot start exhaust emission tests are completed with each fuel.

This test sequence for the certification testing is presented in

Table 2-5. For the preliminary testing, only a single day using this sequence was conducted for each candidate B20 additive blend. For one of the additive combinations, a shorter sequence with 3 tests on the CARB reference fuel followed by 3 tests on the B20-soy biodiesel blend with the additive. For the certification testing, this sequence was performed over at least five days until a minimum of 20 tests each on the reference and candidate fuels were obtained, with an equal number of morning and afternoon tests. For this test sequence, the first four tests in a day were termed morning tests, while the last four tests in a day were considered afternoon tests.

Table 2-5. Testing Protocol for Certification Procedure

Day	Fuel Test Sequence
1	RC CR RC CR
2	RC CR RC CR
3	RC CR RC CR
4	RC CR RC CR
5	RC CR RC CR

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

2.4 Emissions Testing

The engine emissions testing was performed in UCR’s 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 THC, CO, NO_x, PM, and CO_2 were made. 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 A, with more details on the MEL provided in Cocker et al. (2004a,b) [15,16]. Also, information on the quality assurance/quality control (QA/QC) procedures used for the MEL is provided in Appendix B.

3 Preliminary and Certification Engine Testing Results

The results of preliminary and certification engine dynamometer testing for each emission component are summarized in this section. The results presented in the figures represent the average of all test runs done on that fuel. 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 reference fuel, and the associated p-values for statistical comparisons using a 2-tailed, 2-sample, equal-variance t-test. The statistical analyses provide information on the statistical significance of the different findings. 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. These values are underlined in the tables. The pass/fail criteria for certification test is based on additional statistical analysis for NO_x, PM, and SOF. More detailed results for the NO_x, PM, and SOF for the certification testing, and the corresponding statistical analysis for the certification test criteria, are provided in Appendix C.

3.1 NO_x Emissions

The NO_x emission results for the preliminary and certification testing of the different B20 additive blends are presented in Figure 3-1 on a gram per brake horsepower hour (g/bhp-hr) basis. A B20-soy baseline test was also included to provide a baseline for comparisons. The additives are denoted by the company that produces them along with the concentration of additive used. For Innospec, two different additives were used during the preliminary testing, as noted in the figure by adding numbers to the end of the name of the company. Each potential B20-soy additive blend was compared against the CARB reference fuel tests conducted during the day that particular additive test was conducted, except for the full certification test, where the CARB reference fuel tests were averaged over all tests conducted during the certification procedure. The CARB reference fuel values for the individual comparisons are denoted in the figures as "CARB vs. Blend Name". The B20-soy 1% INNOSPEC 1 blend was selected for the actual certification testing on the basis of the preliminary test results. The certification emissions testing results for the B20-soy 1.0% INNOSPEC 1 blend showed a 2.5% statistically significant increase in NO_x emissions, however. Therefore, the B20-soy 1% INNOSPEC 1 blend did not pass NO_x emissions criteria of the certification testing.

Table 3-1 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.

NO_x emissions results for the preliminary testing showed a statistically significant 1.2-5.1% increase with B20-soy with additive blends compared to the CARB reference fuel. In comparison, NO_x emissions results for the B20 soy blend without additives showed an increase of approximately 3.3%. The B20-soy 1% INNOSPEC 1 blend from the preliminary testing showed the lowest increase in NO_x emissions (1.2%) compared to the other B20-soy with additive blends, which was only marginally statistically significant. The B20-soy 1% INNOSPEC 1 blend was also the only additive blend that showed a marginally statistically significant reduction in NO_x emissions compared to the B20-soy based biodiesel without additives. It should be noted that the CARB reference fuel showed a day to day variability of approximately 2% in NO_x emissions, so these data cannot be taken as a definitive comparison of the performance between the individual additives themselves.

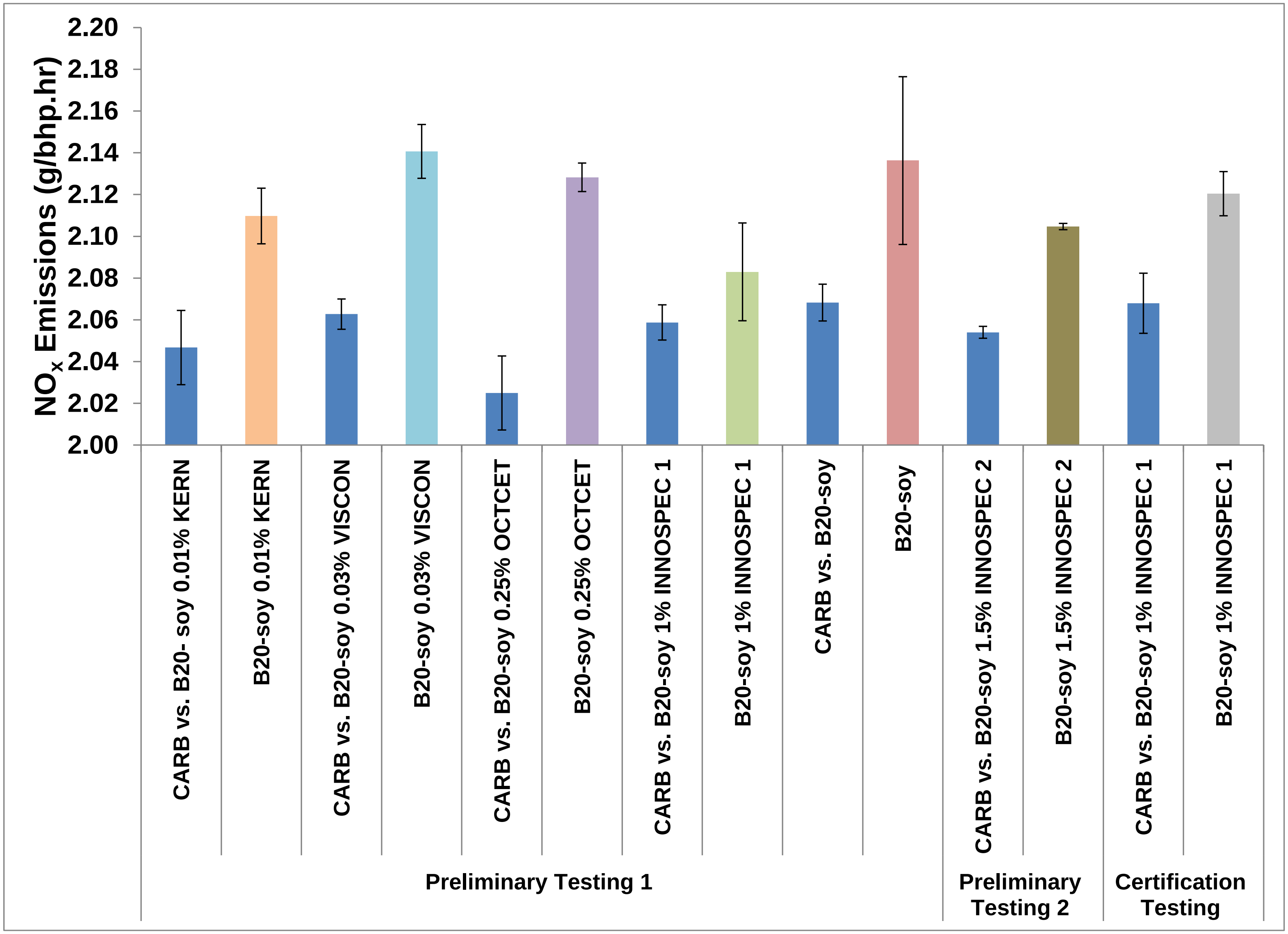

Figure 3-1.Average NO_x Emission Results for the Preliminary and Certification Testing

The B20-soy 1% INNOSPEC 1 blend was selected for the actual certification testing on the basis of the preliminary test results. The certification emissions testing results for the B20-soy 1.0% INNOSPEC 1 blend showed a 2.5% statistically significant increase in NO_x emissions, however. Therefore, the B20-soy 1% INNOSPEC 1 blend did not pass NO_x emissions criteria of the certification testing.

Table 3-1. NO_x (g/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for the Preliminary and Certification Testing

	Fuel Type			
		Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
Preliminary Testing 1	CARB vs. B20- soy 0.01% KERN	2.05		
	B20-soy 0.01% KERN	2.11	3.1%	**0.000**
	CARB vs. B20-soy 0.03% VISCON	2.06		
	B20-soy 0.03% VISCON	2.14	3.8%	**0.000**
	CARB vs. B20-soy 0.25% OCTCET	2.03		
	B20-soy 0.25% OCTCET	2.13	5.1%	**0.000**
	CARB vs. B20-soy 1% INNOSPEC 1	2.06		
	B20-soy 1% INNOSPEC 1	2.08	1.2%	0.100
	CARB vs. B20-soy	2.07		
	B20-soy	2.14	3.3%	**0.016**
Preliminary Testing 2	CARB vs. B20-soy 1.5% INNOSPEC 2	2.05		
	B20-soy 1.5% INNOSPEC 2	2.10	2.5%	**0.000**
Certification Testing	CARB vs. B20-soy 1% INNOSPEC 1	2.07		
	B20-soy 1% INNOSPEC 1	2.12	2.5%	**0.000**

Several previous studies have shown that NO_x neutral biodiesel blends can be obtained using additive blends with either DTBP or 2-EHN. Some of these earlier studies used older engines or non-CARB-like base fuels, however, which would make them less comparable with the present study [13,17]. The results for main CARB/UCR/UCD study were mixed for different additives tested on a 2006 Cummins ISM engine, with a 1% ditertiary butyl peroxide (DTBP) additive blend showing NO_x neutrality for B20 and lower blends, while other tests using an 2-ethyl hexyl nitrate (2-EHN) additive blend were not successful even at blend levels as low as 5% [1,2].

3.2 PM Emissions

The PM emission results for the preliminary testing are presented in Figure 3-2 on a g/bhp-hr basis. Table 3-2 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. PM emissions results showed consistent, statistically significant reductions ranging from 15.7-24.7% with B20 with additive blends and B20-soy compared to CARB reference fuel for both preliminary and certification testing. For the certification test, the reduction in PM emissions was 20.6% for the B20-soy 1.0% INNOSPEC 1 blend. The B20-soy 1% INNOSPEC 1 blend passed the PM emissions criteria of the certification testing.

Previous studies have shown reductions in PM with biodiesel blends, which is generally attributed to the presence of oxygen in the biodiesel and its impact on reducing excessively rich zones during combustion [2,4–6,12,13,17–19]. In other studies, adding additives to biodiesel blends has generally not shown significant additional benefits with respect to PM, similar to the present study [1,13,17–19].

Table 3-2. PM (g/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for the Preliminary and Certification Testing

	Fuel Type			
		Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
Preliminary Testing 1	CARB vs. B20- soy 0.01% KERN	0.064		
	B20-soy 0.01% KERN	0.050	-21.3%	**0.000**
	CARB vs. B20-soy 0.03% VISCON	0.063		
	B20-soy 0.03% VISCON	0.048	-22.8%	**0.000**
	CARB vs. B20-soy 0.25% OCTCET	0.067		
	B20-soy 0.25% OCTCET	0.051	-24.7%	**0.000**
	CARB vs. B20-soy 1% INNOSPEC 1	0.065		
	B20-soy 1% INNOSPEC 1	0.053	-18.0%	**0.000**
	CARB vs. B20-soy	0.062		
	B20-soy	0.050	-20.7%	**0.001**
Preliminary Testing 2	CARB vs. B20-soy 1.5% INNOSPEC 2	0.064		
	B20-soy 1.5% INNOSPEC 2	0.054	-15.7%	**0.000**
Certification Testing	CARB vs. B20-soy 1% INNOSPEC 1	0.066		
	B20-soy 1% INNOSPEC 1	0.052	-20.6%	**0.000**

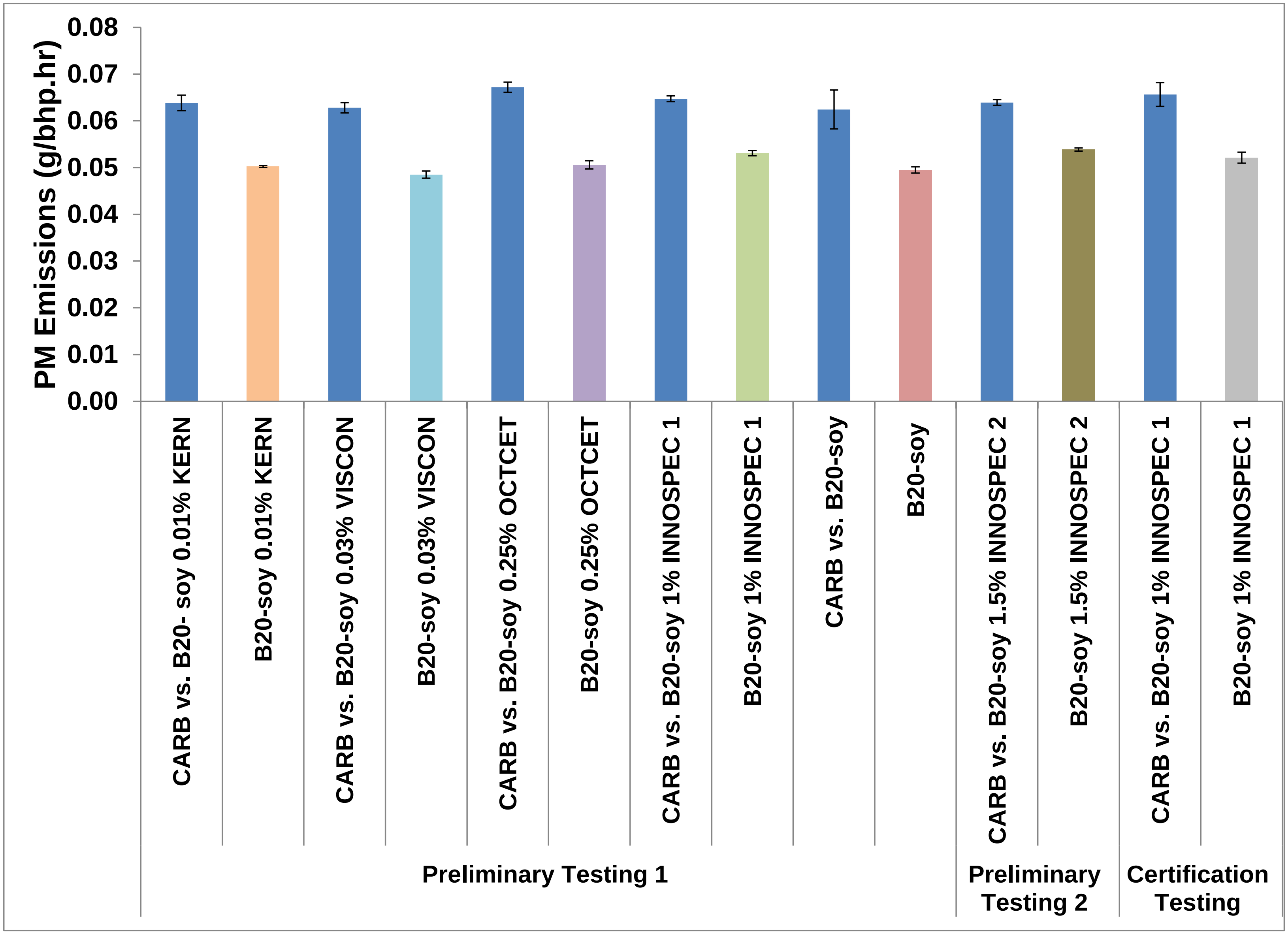

Figure 3-2. Average PM Emission Results for the Preliminary and Certification Testing

3.3 THC Emissions

The THC emission results for the preliminary and certification testing are presented in Figure 3-3 for the FTP cycle on a g/bhp-hr basis. has generally either shown modest additional benefits or no significant additional benefits with respect to THC [1,13,17–19].

Table 3-3 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. THC emissions results for both the preliminary and certification testing showed consistent 10.8-16.8% statistically significant reductions for the B20 and B20 additive blends. Only the reduction in THC emissions results for B20-soy 1.5% INNOSPEC 2 compared to CARB reference fuel, was not statistically significant, which might be due to the limited number of tests that were performed for this specific blend. For the certification test, the reduction in THC emissions was 16.8% for the B20-soy 1.0% INNOSPEC 1 blend. It should be noted that THC emissions are not part of the pass/fail criteria for the full certification test.

The observation of reduced THC emissions for biodiesel and biodiesel additive blends is consistent with the results seen in other studies [1,4,6,20–22]. The previous CARB/UCR/UCD study showed that additives in conjunction with B20 blends provided greater reductions in THC emissions compared to the B20-soy baseline fuel alone [1]. The same trend was also seen for the B20-soy additive blends for the present study, showing either equal or greater reductions in THC emissions compared to the B20-soy blend. In other studies, adding additives to biodiesel blends has generally either shown modest additional benefits or no significant additional benefits with respect to THC [1,13,17–19].

Table 3-3. THC (g/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for the Preliminary and Certification Testing

	Fuel Type			
		Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
Preliminary Testing 1	CARB vs. B20- soy 0.01% KERN	0.34		
	B20-soy 0.01% KERN	0.30	-12.3%	**0.012**
	CARB vs. B20-soy 0.03% VISCON	0.35		
	B20-soy 0.03% VISCON	0.31	-9.9%	**0.028**
	CARB vs. B20-soy 0.25% OCTCET	0.35		
	B20-soy 0.25% OCTCET	0.31	-13.7%	**0.002**
	CARB vs. B20-soy 1% INNOSPEC 1	0.34		
	B20-soy 1% INNOSPEC 1	0.29	-15.5%	**0.000**
	CARB vs. B20-soy	0.35		
	B20-soy	0.31	-10.8%	**0.008**
Preliminary Testing 2	CARB vs. B20-soy 1.5% INNOSPEC 2	0.31		
	B20-soy 1.5% INNOSPEC 2	0.28	-10.9%	0.337
Certification Testing	CARB vs. B20-soy 1% INNOSPEC 1	0.33		
	B20-soy 1% INNOSPEC 1	0.28	-16.8%	**0.000**

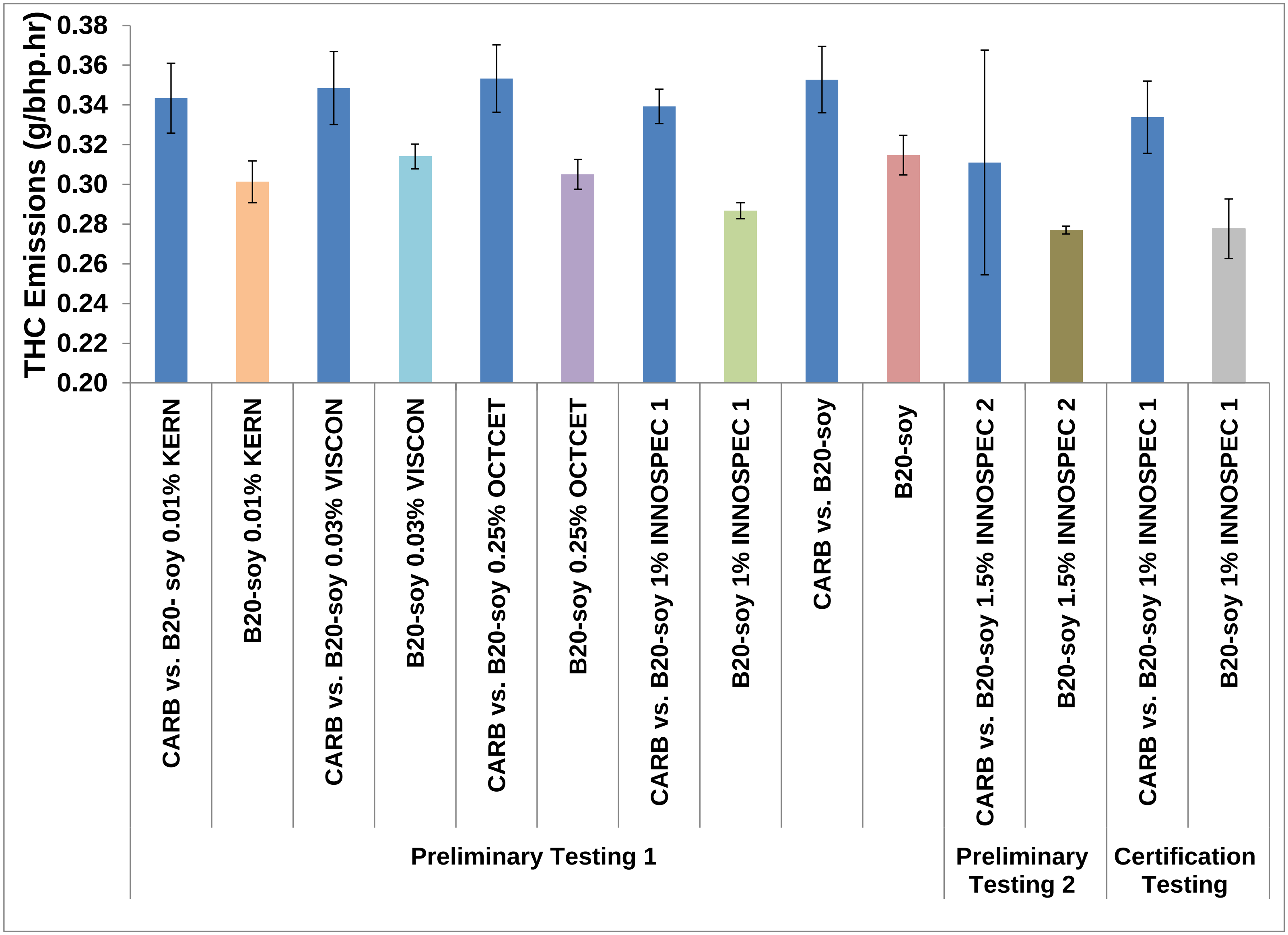

Figure 3-3. Average THC Emission Results the Preliminary and Certification Testing

3.4 CO Emissions

The CO emission results for the preliminary and certification testing are presented in Figure 3-4 on a g/bhp-hr basis. Table 3-4 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. CO emissions results showed consistent trends of reductions over all the B20 additive fuel blends. These reductions ranged from 6.9-15.9% compared to CARB reference fuel for both the preliminary and certification testing. The B20-soy blend CO emissions results did not show statistically significant differences compared to the CARB reference fuel, however. For the certification test, the reduction in CO emissions was 15.9% for the B20-soy 1.0% INNOSPEC 1 blend. It should be noted that CO emissions are not part of the pass/fail criteria for the full certification test.

Previous studies have generally showed reductions in CO for biodiesel blends, with greater reductions found for higher level blends [4,6,7,23]. 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]. The earlier CARB/UCR/UCD study found that additives can provide additional benefits in CO emissions beyond what would otherwise be achieved by biodiesel alone, although this was only studied for a soy-based blend [1]. In other studies, adding additives to biodiesel blends has generally either shown modest additional benefits or no significant additional benefits with respect to CO [1,13,17–19].

Table 3-4. CO (g/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for the Preliminary Testing

	Fuel Type			
		Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
Preliminary Testing 1	CARB vs. B20- soy 0.01% KERN	0.78		
	B20-soy 0.01% KERN	0.73	-6.9%	**0.019**
	CARB vs. B20-soy 0.03% VISCON	0.79		
	B20-soy 0.03% VISCON	0.72	-8.9%	**0.009**
	CARB vs. B20-soy 0.25% OCTCET	0.81		
	B20-soy 0.25% OCTCET	0.72	-12.0%	**0.000**
	CARB vs. B20-soy 1% INNOSPEC 1	0.79		
	B20-soy 1% INNOSPEC 1	0.68	-14.5%	**0.000**
	CARB vs. B20-soy	0.78		
	B20-soy	0.76	-3.1%	0.278
Preliminary Testing 2	CARB vs. B20-soy 1.5% INNOSPEC 2	0.76		
	B20-soy 1.5% INNOSPEC 2	0.66	-14.2%	**0.002**
Certification Testing	CARB vs. B20-soy 1% INNOSPEC 1	0.80		
	B20-soy 1% INNOSPEC 1	0.67	-15.9%	**0.000**

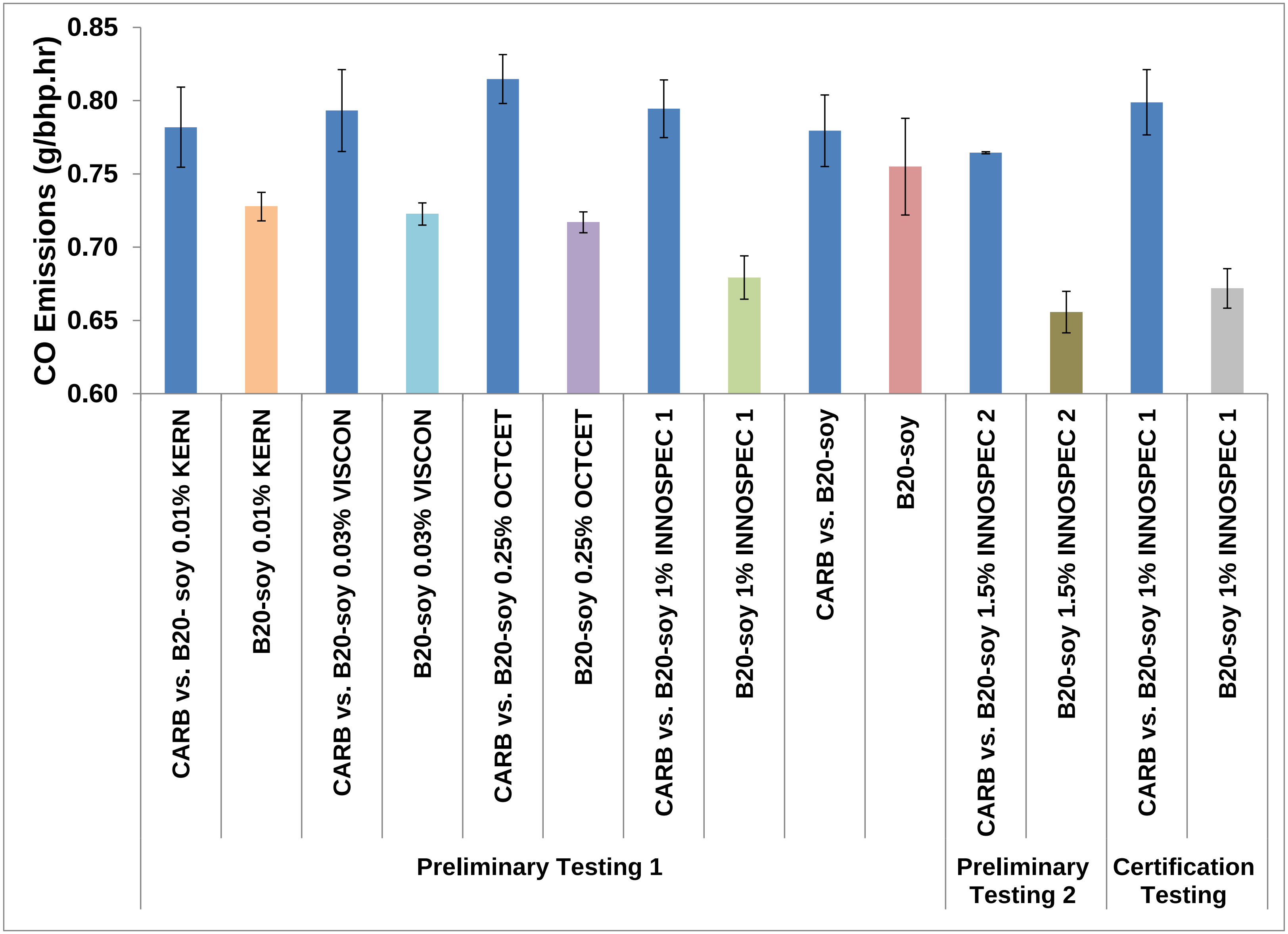

Figure 3-4. Average CO Emission Results for the Preliminary and Certification Testing

3.5 CO_2 Emissions

The CO_2 emission results for the preliminary and certification testing are presented in Figure 3-5 on a g/bhp-hr basis. Table 3-5 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. CO_2 emissions results showed increases for some of the B20 additive blends, but not for others. These increases were in the range of 0.2-1.2%. It should be noted that since the day to day variability in CO_2 emissions for the CARB reference fuel was approximately 1.5% over the course of the testing, these results should not be considered as a definitive comparison between the performance of specific additives. 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 [4,6,7,23–25]. For the present study, there was approximately a 0.46% difference in the carbon content per unit energy between the CARB reference fuel and the B20-soy, as shown in NA= Not Available

Table 2-2 and Table 2-3. This is comparable to the marginally statistically significant difference in CO_2 emissions seen for the certification test. It should be noted that CO_2 emissions are not part of the pass/fail criteria for the full certification test.

Table 3-5. CO_2 (g/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for the Preliminary and Certification Testing

	Fuel Type			
		Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
Preliminary Testing 1	CARB vs. B20- soy 0.01% KERN	621.96		
	B20-soy 0.01% KERN	624.63	0.4%	0.895
	CARB vs. B20-soy 0.03% VISCON	619.73		
	B20-soy 0.03% VISCON	621.44	0.3%	0.156
	CARB vs. B20-soy 0.25% OCTCET	629.17		
	B20-soy 0.25% OCTCET	630.63	0.2%	0.502
	CARB vs. B20-soy 1% INNOSPEC 1	629.79		
	B20-soy 1% INNOSPEC 1	633.51	0.6%	0.091
	CARB vs. B20-soy	620.14		
	B20-soy	623.95	0.6%	**0.008**
Preliminary Testing 2	CARB vs. B20-soy 1.5% INNOSPEC 2	623.41		
	B20-soy 1.5% INNOSPEC 2	630.69	1.2%	**0.047**
Certification Testing	CARB vs. B20-soy 1% INNOSPEC 1	624.62		
	B20-soy 1% INNOSPEC 1	626.46	0.3%	0.062

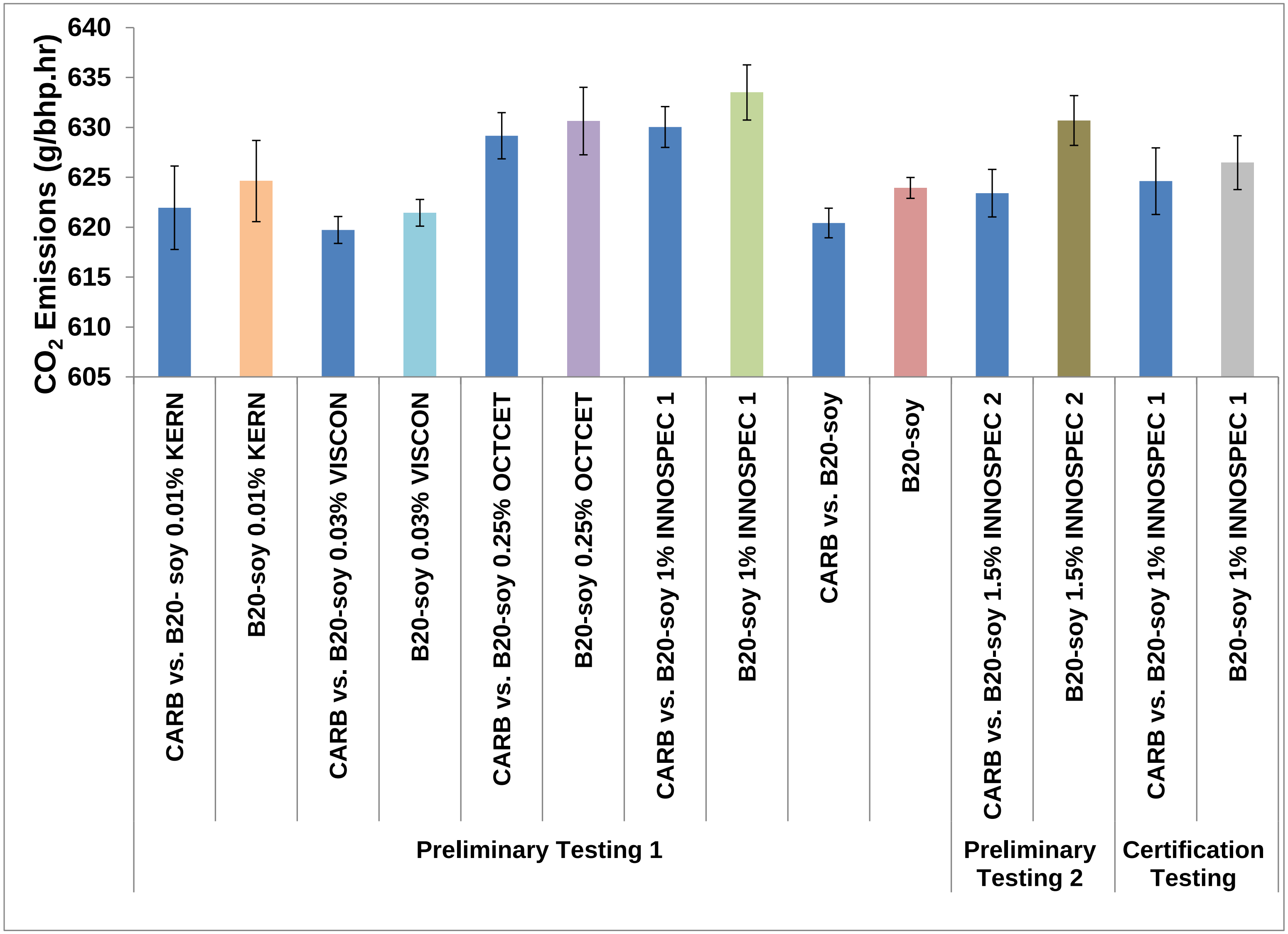

Figure 3-5. Average CO_2 Emission Results for the Preliminary and Certification Testing

3.6 Brake Specific Fuel Consumption

The brake specific fuel consumption (BSFC) results for the preliminary and certification testing are presented in Figure 3-6 on a gallons/bhp-hr. The brake specific fuel consumption was calculated via the carbon balance method. Table 3-6 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 were 1.0-2.1% higher for the B20 soy and B20-soy with additive blends of both preliminary and certification testing compared to CARB reference fuel. For the certification test, the increase in BSFC emissions was 1.2% for the B20-soy 1.0% INNOSPEC 1 blend. It should be noted that BSFC is not part of the pass/fail criteria for the full certification test. This result is directionally consistent with the results of previous studies [4,6,7,23–25]. The increases in BSFC were slightly less than the 2.59% difference in the energy content between the CARB reference fuel and B20-soy used in this fuel, as shown in NA= Not Available

Table 2-2 and Table 2-3.

Table 3-6. BSFC (gal/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for the Preliminary Testing

	Fuel Type			
		Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
Preliminary Testing 1	CARB vs. B20- soy 0.01% KERN	0.063		
	B20-soy 0.01% KERN	0.063	1.0%	0.103
	CARB vs. B20-soy 0.03% VISCON	0.062		
	B20-soy 0.03% VISCON	0.063	1.2%	**0.001**
	CARB vs. B20-soy 0.25% OCTCET	0.063		
	B20-soy 0.25% OCTCET	0.064	1.1%	**0.013**
	CARB vs. B20-soy 1% INNOSPEC 1	0.063		
	B20-soy 1% INNOSPEC 1	0.064	1.5%	**0.002**
	CARB vs. B20-soy	0.062		
	B20-soy	0.063	1.5%	**0.000**
Preliminary Testing 2	CARB vs. B20-soy 1.5% INNOSPEC 2	0.063		
	B20-soy 1.5% INNOSPEC 2	0.064	2.1%	**0.011**
Certification Testing	CARB vs. B20-soy 1% INNOSPEC 1	0.063		
	B20-soy 1% INNOSPEC 1	0.064	1.2%	**0.000**

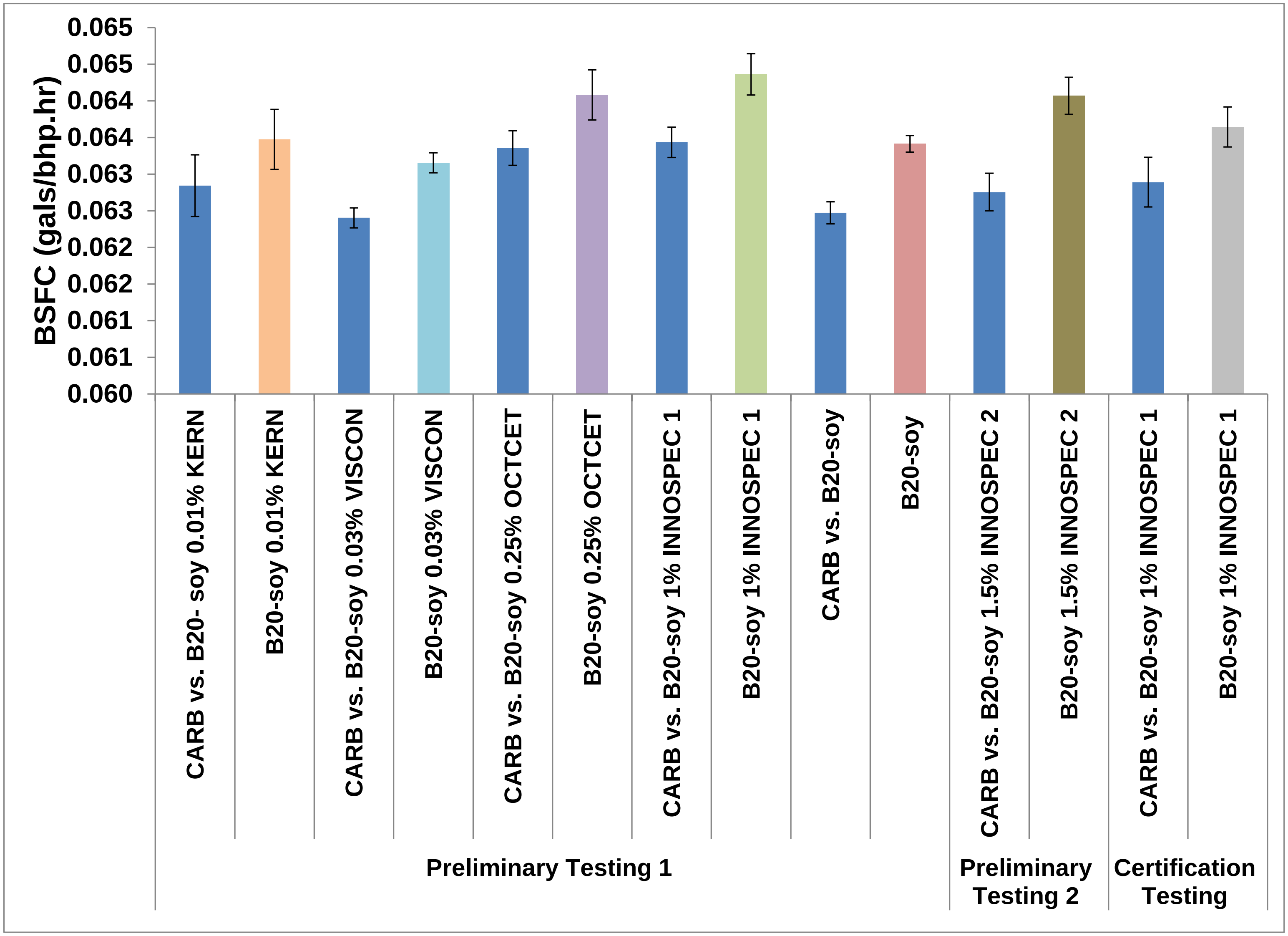

Figure 3-6. Average Brake Specific Fuel Consumption Results for the Preliminary Testing

4 Summary

This goal of this study was to investigate and to attempt to certify B20 biodiesel blends with additives for California based on the full CARB emissions equivalent certification testing protocol. For this study some preliminary testing was first performed on soy-based B20 blends with 5 different additive combinations. A full certification test was then performed on one of the B20-soy additive combinations to evaluate the viability of this strategy for implementation into the California fuel marketplace. This study was conducted in CE-CERT's heavy-duty engine dynamometer laboratory with a 2006 Cummins ISM engine.

A summary of the results is as follows:

Preliminary Testing Results:

- NO_x emissions results showed a statistically significant 1.2-5.1% increase with B20-soy with additive blends compared to the CARB reference fuel. The B20-soy 1% INNOSPEC 1 blend from the preliminary testing showed the lowest increase in NO_x emissions (1.2%). Therefore, this blend was selected for the certification testing.
- PM emissions results showed consistent, statistically significant reductions ranged from 15.7-24.7% with B20 with additive blends and B20-soy compared to CARB reference fuel.
- THC emissions results showed consistent 10.8-15.5% statistically significant reductions for the B20 and B20 additive blends. Only for the B20-soy 1.5% INNOSPEC 2 the THC differences were not statistically significant.
- CO emissions results showed reductions ranged from 6.9-14.5% compared to the CARB reference fuel for the B20-soy additive blends. The B20-soy blend CO emissions results did not show statistically significant differences compared to the CARB reference fuel, however.
- CO_2 emissions results showed increases for some of the B20 additive blends, but not for others. These increases were in the range of 0.2-1.2%. BSFC results showed increases of 1.0-2.1% with B20-soy and B20-soy with additives, which were statistically significant or marginally statistically significant for all cases. The magnitude of the increases in BSFC results for the B20-soy and B20-soy with additives are comparable to the differences seen in the energy contents of the different fuels tested.

Certification Testing Results:

- Certification testing was performed on B20-soy 1.0% INNOSPEC 1 for the 2006 Cummins ISM engine over the FTP cycle.
- B20-soy 1.0% INNOSPEC 1 blend results for NO_x emissions showed a 2.5% statistically significant increase. Therefore, this blend did not pass the NO_x emissions criteria of the certification testing.
- PM emission results showed a statistically significant reduction of 20.6% with the B20-soy 1.0% INNOSPEC 1. The B20-soy 1% INNOSPEC 1 blend passed the PM emissions criteria of the certification testing.

- THC emissions results showed a statistically significant 16.8% reduction with the B20-soy 1.0% INNOSPEC 1.
- CO emissions results showed a statistically significant 15.9 reduction with the B20-soy 1.0% INNOSPEC 1
- CO_2 emissions and BSFC results showed slight increases of 0.3% and 1.2%, respectively, with the B20-soy 1.0% INNOSPEC 1. The increase in BSFC was statistically significant, while the CO_2 emissions increase was marginally statistically significant.
- The B20-soy 1.0% INNOSPEC 1 blend failed the full certification test procedure based on NO_x emissions.

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Appendix A : 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 A-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.

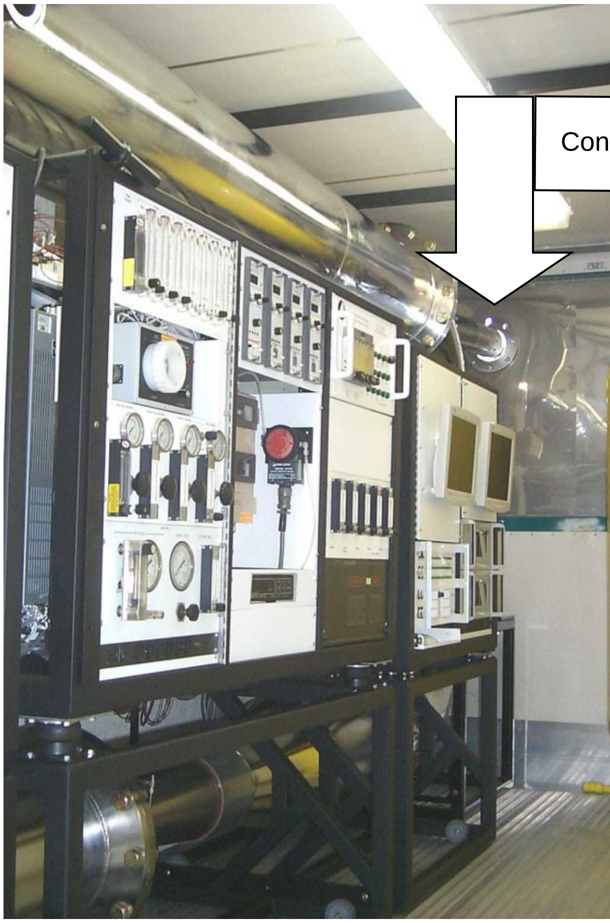

Figure A-1.

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 A-2. Picture of CE-CERT’s Heavy-Duty Engine Dynamometer Facility

Appendix B: QA/QC Procedures

Internal calibration and verification procedures are performed in MEL regularly in accordance with the CFR. A partial summary of routine calibrations performed by the MEL staff as part of the data quality assurance/quality control program is listed in Table B-1.

The soluble organic fraction (SOF) of the PM was also determined for each test. The extraction for the SOF test was performed on the sample Teflon filter used for the PM mass measurements. These filters were stored in a freezer subsequent to the final gravimetric mass measurements and prior to shipment for analysis. The SOF analyses was performed by the Desert Research Institute (DRI) of Reno, NV using standard procedures. A total of 45 SOF samples was collected for the analysis, including 40 samples from emissions tests and 5 background/blank samples over the course of the testing.

Table B-1. Sample of Verification and Calibration Quality Control Activities

EQUIPMENT	FREQUENCY	VERIFICATION PERFORMED	CALIBRATION PERFORMED
CVS	Daily	Differential Pressure	Electronic Cal
	Daily	Absolute Pressure	Electronic Cal
	Weekly	Propane Injection	
	Monthly	CO_2 Injection	
	Per Set-up	CVS Leak Check	
	Second by second	Back pressure tolerance ±5 inH_20	
Cal system MFCs	Annual	Primary Standard	MFCs: Drycal Bios Meter
	Monthly	Audit bottle check	
Analyzers	Pre/Post Test		Zero Span
	Daily	Zero span drifts	
	Monthly	Linearity Check	
Secondary System Integrity and MFCs	Semi-Annual	Propane Injection: 6 point primary vs secondary check	
	Semi-Annual		MFCs: Drycal Bios Meter & TSI Mass Meter
Data Validation	Variable	Integrated Modal Mass vs Bag Mass	
	Per test	Visual review	
PM Sample Media	Weekly	Tunnel Banks	
	Monthly	Static and Dynamic Blanks	

Temperature	Daily	Psychrometer	Performed if verification fails
Barometric Pressure	Daily	Aneroid barometer ATIS	Performed if verification fails
Dewpoint Sensors	Daily	Psychrometer Chilled mirror	Performed if verification fails

Appendix C: Statistical Calculations for Certification Testing

The certification pass/fail criteria is determined as per 13 CCR 2282(g)(5). The criteria is evaluated for NO_x and PM emissions. The statistical criteria includes a tolerance of 1% and 2%, respectively, for NO_x and PM emissions. The tolerance is reduced by pooled variance term that increases with the variability in the data.

B20-soy 1% INNOSPEC 1 blend, NO_x									
	R	C	C	R	R	C	C	R	
Day 1	2.054	2.107	2.129	2.056	2.073	2.138	2.127	2.064	Day 1
Day 2	2.053	2.107	2.118	2.066	2.059	2.109	2.121	2.081	Day 2
Day 3	2.065	2.125	2.124	2.094	2.087	2.123	2.13	2.083	Day 3
Day 4	2.069	2.093	2.115	2.069	2.075	2.119	2.117	2.029	Day 4
Day 5	2.058	2.129	2.133	2.076	2.074	2.118	2.127	2.074	Day 5
n	t	x_R	x_c	$(x_c-x_R)/x_R$	S_R	S_c	S_p	$S_p(2/n)^{0.5}t/x_R$	
20	1.050772	2.068	2.120	2.5387%	0.0144	0.0106	0.0126	0.2031%	2.7418%
									CANDIDATE FUEL FAILS

B20-soy 1% INNOSPEC 1 blend, PM									
	R	C	C	R	R	C	C	R	
Day 1	0.066	0.052	0.053	0.066	0.068	0.054	0.054	0.067	
Day 2	0.064	0.051	0.051	0.064	0.074	0.052	0.052	0.066	
Day 3	0.062	0.051	0.051	0.064	0.066	0.054	0.053	0.067	
Day 4	0.064	0.051	0.052	0.066	0.065	0.052	0.053	0.066	
Day 5	0.063	0.052	0.051	0.064	0.063	0.052	0.051	0.066	
n	t	x_R	x_c	$(x_c-x_R)/x_R$	S_R	S_c	S_p	$S_p(2/n)^{0.5}t/x_R$	
20	1.0507721	0.066	0.052	-20.6020%	0.0025	0.0012	0.0020	0.9969%	-19.6051%
									CANDIDATE FUEL PASSES