Final Report

CARB B5 Biodiesel Preliminary and Certification Testing

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Table of Contents

Table of Tables

Table of Figures

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 the 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. This remains an important issue with respect to implementing biodiesel within California, which has the most stringent emissions requirements for diesel fuel in the nation. 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 did not show clear trends at the B5 level.

The goal of this study is to evaluate different B5 blends as potential emissions equivalent biodiesel fuel formulations for California. For this work, a full emissions equivalent diesel fuel certification test was conducted on two low level biodiesel blends using CARB protocols. The two B5 blends included blends of one animal-based and one waste vegetable oil-based biodiesel with a CARB reference fuel. The certification test was successful for the animal-based B5 blend, with NO_x showing a 0.5% reduction relative to the CARB reference fuel, but was unsuccessful for the WVO-based B5 blend, which showed an increase of 1.0% in NO_x emissions. Preliminary testing done on a soy-based B5 blend also indicated that it likely would not pass the CARB certification test due to a NO_x increase. The results of this study provide the initial framework for the development of certified emissions equivalent biodiesel formulations that could be implemented into the California diesel fuel market.

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 Federal 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, but the trends in NO_x emissions for the B5 blends were less clear, with increases seen in some cases, but not others.

The present study expands upon the earlier CARB/UCR/UCD study to examine the viability of certifying B5-biodiesel blends 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, providing the ability to differentiate small differences in emissions. For this study, preliminary tests were performed on B5 blends made from three different feedstocks, soy-based, waste vegetable oil-based (WVO), and animal-based. Full certification tests were then performed on two of these fuels, the B5-animal and B5-WVO. 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 a 10% aromatic content diesel fuel meeting the CARB reference fuel specifications under title 13, California Code of Regulations (CFR), section 2282(g)(3). The B5 blends were made by blending neat biodiesels made from animal tallow, soy-bean oil, and waste vegetable oil feedstocks with the CARB reference fuel at a 5% 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 13 CCR 2282(g)(4)(C)1.b Alternative 1. This test sequence is presented in Table E-1. The preliminary testing was only a day of testing based on this sequence while certification testing was five days of 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 in 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. For the certification testing, measurements of the soluble organic fraction (SOF) of the PM were also made.

Results

The results of this study are summarized below. Results are generally statistically significant, except as noted. Results were considered to be statistically significant for p-values ≤ 0.05 and marginally statistically significant for $0.05 < \text{p-value} \leq 0.1$.

Preliminary Testing Results:

The NO_x emissions results showed statistically significant 1.2-1.3% increases with B5-WVO and B5-soy blends. The B5-animal did not show a statistically significant increase in NO_x emissions. The results showed consistent reductions of 4-6% for PM emissions with all the B5 blends. Consistent trends were not seen for THC and CO emissions for the B5 blends. Consistent trends of 0.8-1.0% increases in CO_2 emissions and 0.7-2.1% increases in brake specific fuel consumption calculated via a carbon balance method were observed for all the B5 fuel blends comparing to the CARB reference fuel. The differences in both the CO_2 and BSFC are higher than what would be expected based on differences in carbon content per unit of energy and overall energy content.

B5 Animal-based and B5 Waste Vegetable Oil Certification Testing Results:

- **B5- animal results**
  The results showed a statistically significant 0.5% reduction in NO_x emissions for the B5-animal. Statistically significant reductions for the B5-animal were found for PM (-4.2%), SOF (-13.7%), THC (-4.8%), and CO (-5.9%) emissions. A statistically significant 1.0%

increase in brake specific fuel consumption calculated via a carbon balance method was seen for the B5-animal. Slight increases in CO_2 emissions (i.e., 0.3%) were seen for the B5-animal, however, this difference was only marginally statistically significant. B5-animal passed the criteria of the certification test based on NO_x, PM, and SOF emissions. The B100-animal and the B5-animal both had cetane numbers that were on the order of 61, which was much higher than the cetane number for the reference fuel by itself and for the other B5 blends.

- **B5-WVO results**

  The results showed a statistically significant 1.0% increase in NO_x emissions for B5-WVO. The PM and CO emissions results showed statistically significant reductions for the B5-WVO, however, of 6.8% and 1.8%, respectively. No statistically significant fuel differences were found for THC or SOF emissions for the B5-WVO. A statistically significant 0.6% increase in brake specific fuel consumption calculated via a carbon balance method was seen for this blend. The differences in CO_2 emissions for the B5-WVO and CARB reference fuel were not statistically significant. B5-WVO did not pass the certification testing criteria based on NO_x emissions.

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 would 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 [1,2]. The results of this study showed that B20 and higher biodiesel blends would likely increase NO_x emissions in CARB diesel fuels. This study also showed that the magnitude of any NO_x increases would depend on the biodiesel feedstock, engine type, and driving cycle load. 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.

The present study expands upon the earlier CARB/UCR/UCD study to examine the viability of certifying B5-biodiesel blends 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, providing the ability to differentiate small differences in emissions. For this study, preliminary tests were performed on B5 blends made from three different biodiesel feedstocks: animal-based, waste vegetable oil-based (WVO), and soy-based. Full certification tests were then performed on two of these fuels, the B5-animal and B5-WVO.

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). The specifications and properties of this 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 D5291and heating value via ASTM D240.

Table 2-1. Properties of CARB Reference Fuel

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

Three different biodiesels were investigated in this study: an animal tallow biodiesel, a waste vegetable oil biodiesel, and a soy-based biodiesel. The animal-based biodiesel was selected as the primary option for the candidate fuel, since this biodiesel feedstock is more saturated and has been shown to have a lower tendency to increase NO_x [2,4,6,9,14–16]. In addition to the animal-based biodiesel, a waste vegetable oil biodiesel, and a soy-based biodiesel were included in the preliminary test matrix, in order to provide a broader range of biodiesel sources within the state.

The properties of all three neat biodiesel feedstocks are provided in Table 2-2. Select fuel properties for the B5-animal and B5-WVO are provided in Table 2-3. Some trends for cetane number are worth noting. Cetane number for the neat biodiesels showed a decreasing trend from the animal-based to the WVO-based to the soy-based biodiesels. Interestingly, the cetane number for the B5-animal blend was more similar to that of the B100-animal than the CARB reference fuel, while the cetane number for the B5-WVO blend was more similar to that of the CARB reference fuel than the B100-WVO.

The biodiesels were all blended at a B5 level for this test program. The B5 fuels were blended volumetrically. A single batch was used for each of the full certification tests. The B5 blends are denoted B5-soy, B5-animal, and B5-WVO throughout this report to differentiate between blends made from different feedstocks.

Table 2-2. Properties of Animal, Waste Vegetable Oil, and Soy Biodiesel

Property	ASTM Test Method	Units	Specification	Animal	WVO	Soy
Flash Point	ASTM D93	^{o}C	130 min.	144.0	>150*	159
Water and Sediment	ASTM D2709	% Vol.	0.05 max.	<0.005	0.000	0.000
Kinematic Viscosity, 40^{o}C	ASTM D445	mm^{2}/s	1.9 – 6.0	4.691	4.2*	4.220*
Sulfated Ash	ASTM D874	% mass	0.02	<0.005	<0.01*	<0.01*
Sulfur	ASTM D5453	Ppm	15 max.	6.5	11.1	1.1
Copper Strip Corrision	ASTM D130		No. 3 max.	1b	1a*	1a*
Cetane Number	ASTM D613		47 min.	61.1	54.6	49.2
Cloud Point	ASTM D2500	^{o}C	Report	15	4	0
Carbon Residue	ASTM D4530	% mass	0.05 max.	<0.05	<0.02*	<0.02*
Acid Number	ASTM D664	Mg KOH/g	0.5 max.	0.42	0.29	0.26
Free Glycerin	ASTM D6584	% mass	0.02 max.	<0.005	0.000	0.003
Total Glycerin	ASTM D6584	% mass	0.240 max.	0.109	0.197	0.106
Monoglycerides	ASTM D6584	% mass	Report	0.417	0.634	0.342
Diglycerides	ASTM D6584	% mass	Report	0.051	0.154	0.124
Triglycerides	ASTM D6584	% mass	0.050 max.	<0.05	0.093	0.000
Visual inspection	ASTM D4176	1-6	2 max.	1	1	1
Phosphorous content	ASTM D4951	% mass	0.001 max.	<0.0001	<.0001*	<0.0001*
Distillation at 90% Recovered	ASTM D1160	^{o}C	360 max.	352	325*	341*
Sodium/Potassium, combined	EN14538	ppm (µg/g)	5 max.	<1.0	<5.0*	<5.0*
Calcium/Magnesium, combined	EN14538	ppm (µg/g)	5 max.	<1.0	<2.0*	<2.0*
Oxidation Stability	EN15751	Hours	3 min.	13.0	6.1	4
Cold Soak Filtration	ASTM D7501	Seconds	360 max.	135	301	72
Moisture	ASTM D6304	%mass		0.024	370	190
Methanol Content	EN14110	%mass	0.2 max.		0.00	
Heating value	ASTM D240	BTU/lb		17133	17076	17140
API Gravity@60°F	ASTM D4052			30.20	28.40	28.43
Specific Gravity @60°F	ASTM D4052			0.8750	0.8851	0.8848
Carbon	ASTM D5291	wt%		76.19	76.67	77.10
Hydrogen	ASTM D5291	wt%		12.28	11.98	11.85
Carbon Unit per Energy		Lbs. Carbon/BTU		4.45x10^{-5}	4.49x10^{-5}	4.50x10^{-5}

* Are based on the most recent fuel specification testing

Table 2-3. Selected Properties for B5-Animal and B5-WVO

Property	ASTM Test Method	Units	B5-Animal	B5-WVO
Heating value	ASTM D240	BTU/lb	19661	19649
API Gravity@60°F	ASTM D4052		38.5	38.2
Specific Gravity @60°F	ASTM D4052		0.8326	0.8339
Carbon	ASTM D5291	wt%	85.78	85.85
Hydrogen	ASTM D5291	wt%	13.8	13.82
Carbon Unit per Energy		Carbon lbs. /BTU	4.36×10^{-5}	4.37×10^{-5}
Sulfur		ppm	4.5	5.3
Cetane number			61	52.2

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 all three B5 blends, i.e., B5-animal, B5-WVO, and B5-soy. Full certification testing was then performed on the B5-animal and B5-WVO, since these fuels were considered the most viable candidates based on the preliminary testing, as well as previous studies [1,2,17].

All testing was conducted in accordance with the Federal Test Procedure (FTP) for heavy-duty engines [18]. 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 B5 blend. 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 are termed morning tests, while the last four tests in a day are 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) [19,20]. Also, information on the quality assurance/quality control (QA/QC) procedures used for the MEL is provided in Appendix B.

As a part of the certification testing procedure, soluble organic fraction (SOF) analysis was performed on PM filters collected during the B5-animal and B5-WVO certification testing. For the B5-animal testing, PM filters from each test were analyzed for SOF. For the B5-WVO testing, since this blend did not pass the NO_x certification criteria, only 3 SOF analyses were performed for both the CARB reference fuel and the B5-WVO. For these three analyses on each fuel, filters from 12 different tests were aggregated into 3 different groups.

SOF analyses were conducted by the Desert Research Institute (DRI). PM filters were sent to DRI in coolers packed with blue ice. The filters were weighed prior to extraction with a Mettler Toledo MT5 electro microbalance with ±0.001 mg sensitivity. Prior to weighing, the filters were equilibrated at a temperature of 21.5±1.5°C and a relative humidity of 35±5% for a minimum of 24 hours. The polyethylene ring was also carefully removed from the exposed Teflon-membrane filters (47 mm) prior to weighing. The filters were subsequently extracted with dichloromethane followed by hexane in an Accelerated Solvent Extractor (Dionex 3000), dried, reconditioned and re-weighted to determine the SOF. A combination of dichloromethane with hexane was used for the extraction, since it gives good recovery for aliphatic hydrocarbons, cycloalkanes, PAH, hopanes, and steranes, i.e., the classes of compounds that are prevalent in motor vehicle emissions.

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. 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 testing are presented in Figure 3-1 on a gram per brake horsepower hour (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. The NO_x emissions results for the preliminary testing showed 1.2-1.3% statistically significant increases with the B5-soy and B5-WVO biodiesel blends compared to the CARB reference fuel. The B5-animal emissions results did not show any statistical differences in NO_x compared to the CARB reference fuel. Therefore, this fuel blend was considered the most viable candidate fuel for the actual certification testing. 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 increase NO_x emissions when biodiesel is used, as discussed in greater detail in the literature [1,2,4,6,7,21–23]. The magnitude of NO_x emissions increases can also change with the biodiesel feedstock, with more saturated feedstocks, such as animal tallow, often showing smaller increases [2,6,8].

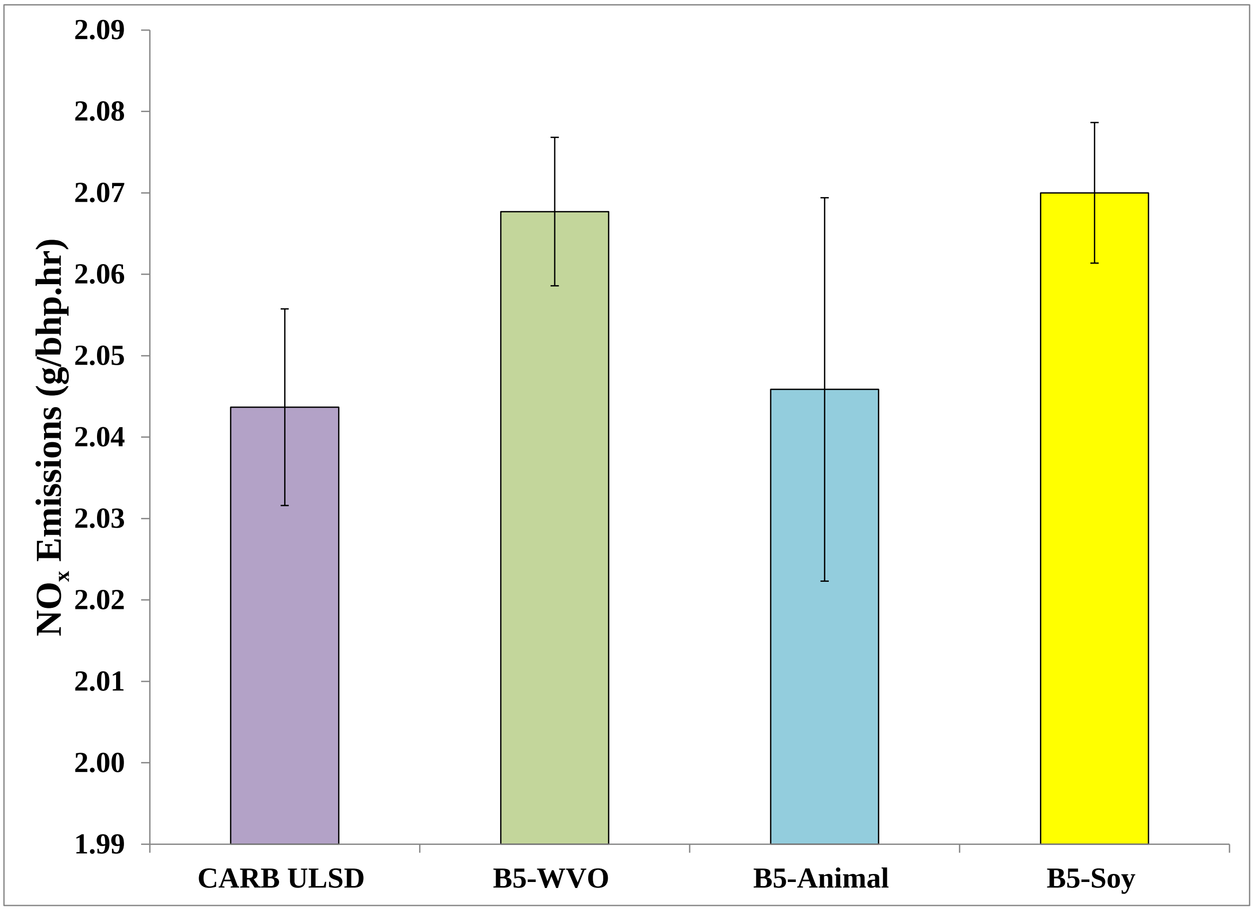

Figure 3-1.Average NO_x Emission Results for the Preliminary Testing

Table 3-1. NO_x (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**
CARB	2.044		
B5-Animal	2.046	0.1%	0.844
B5-WVO	2.068	1.2%	**0.020**
B5-Soy	2.070	1.3%	**0.001**

The NO_x certification testing results for the B5-animal and the B5-WVO are presented in Figure 3-2 on a gram per brake horsepower hour (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. The B5-animal emissions results showed a statistically significant 0.5% reduction in NO_x compared to the CARB reference fuel. The B5-WVO emissions results, on the other hand, showed a statistically significant 1.0% increase in NO_x compared to the CARB reference fuel. The CARB reference fuel results for the separate B5-animal and B5-WVO certification tests are shown with two different bars in the figures, denoted CARB vs. B5-Animal and CARB vs. B5-WVO. Based on the certification testing results, the B5-animal passed for NO_x emissions, while the B5-WVO failed the NO_x criteria. It is worth noting that while candidate fuels must pass for NO_x, PM, and SOF, for biodiesel blends NO_x emissions were considered the most important pollutant for this testing, since other pollutants generally tend to decrease for biodiesel blends.

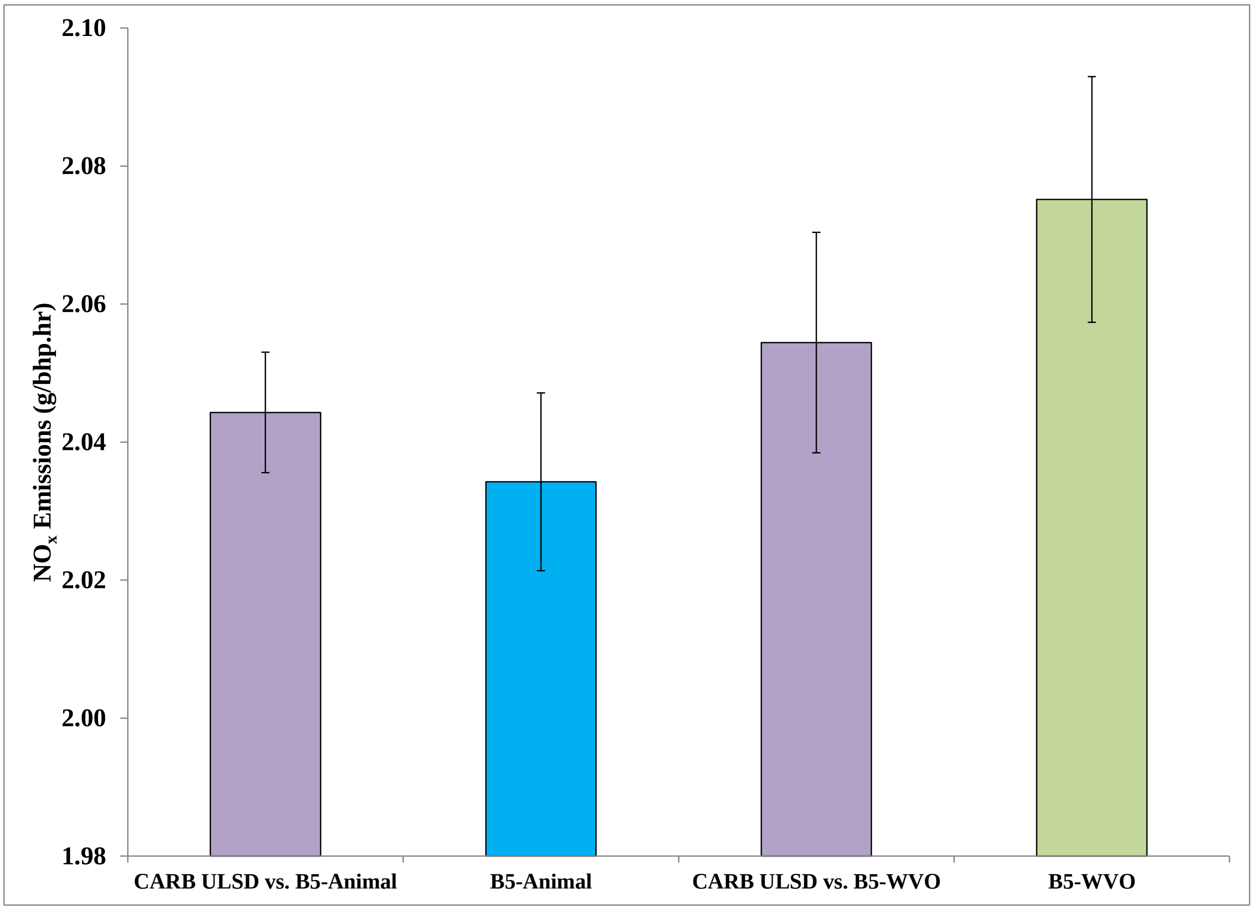

Figure 3-2. Average NO_x Emission Results for the Certification Testing

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

Fuel Type			
	Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
CARB	2.04		
B5-Animal	2.03	-0.5%	**0.006**
CARB	2.05		
B5-WVO	2.08	1.0%	**0.0001**

3.2 PM and Soluble Organic Fraction (SOF) Emissions

The PM emission results for the preliminary testing are presented in Figure 3-3 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 preliminary testing, the PM emissions results showed consistent, statistically significant reductions with the B5 biodiesel blends compared to CARB reference fuel. This is also in agreement with many previous studies reporting PM reductions with biodiesel [2,4–6,12]. The PM reductions were all in a similar 4-6% range for the different biodiesels. The major reason for PM emissions reductions with the biodiesel blends is the presence of oxygen in the biodiesel portion of the fuels, which reduces the formation of PM in rich zones during combustion [2,4–6,12].

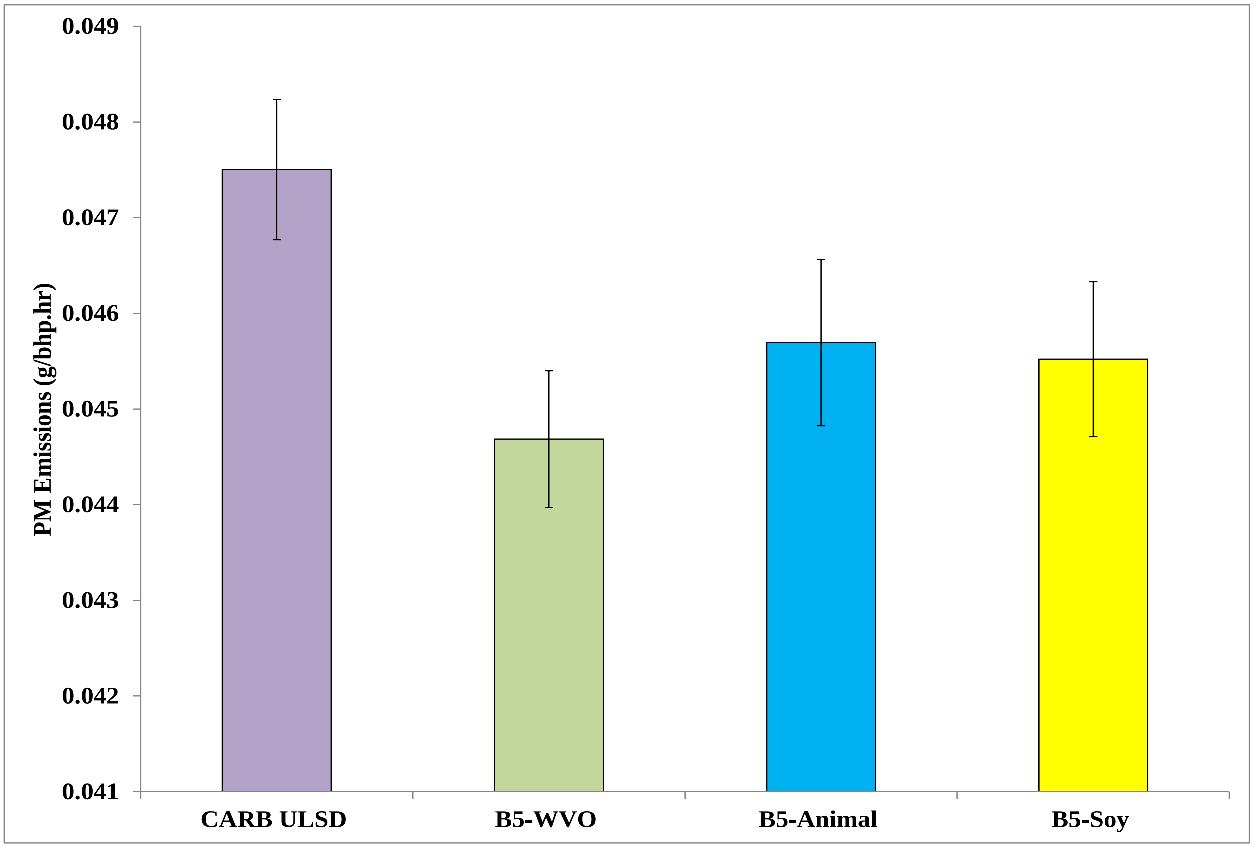

Figure 3-3. Average PM Emission Results for the Preliminary Testing

Table 3-3. PM (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**
CARB	0.048		
B5-Animal	0.046	-3.8%	**0.003**
B5-WVO	0.045	-5.9%	**0.001**
B5-Soy	0.046	-4.2%	**0.000**

The PM emission results for the 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 two fuels, along with the associated p-values for statistical comparisons using a t-test. Both biodiesel blends showed statistically significant reductions in PM emissions, which were in range of 4-7%. This was consistent with the preliminary testing. Both biodiesel blends passed for the PM criteria for these certifications tests.

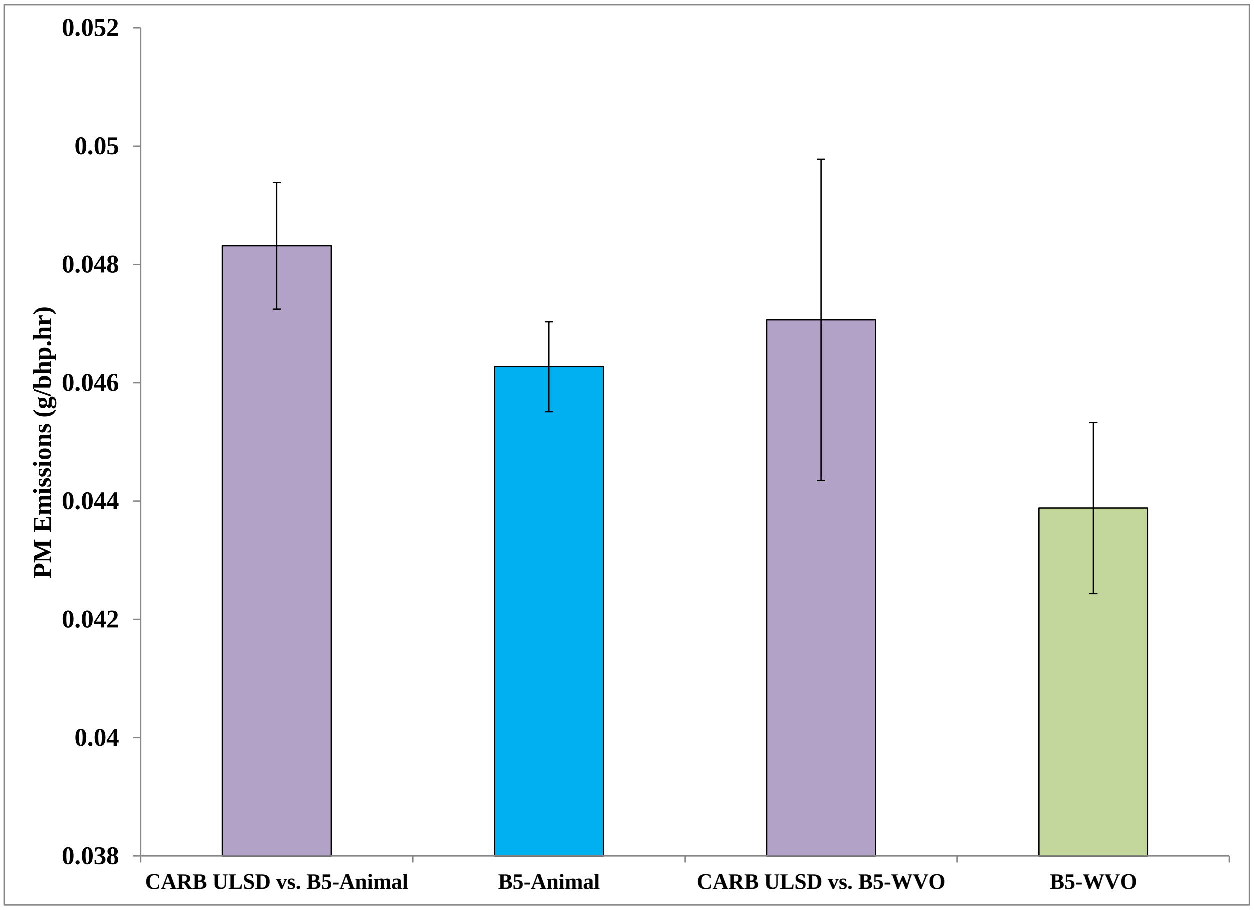

Figure 3-4. Average PM Emission Results for the Certification Testing

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

Fuel Type			
	Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
CARB	0.0483		
B5-Animal	0.0463	-4.2%	**0.000**
CARB	0.0471		
B5-WVO	0.0439	-6.8%	**0.000**

The SOF emissions results for the certification testing are presented in Figure 3-5 on a g/bhp-hr basis.

Table **3-5** 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. Overall, the SOF represented only a small fraction of the total PM mass. The B5-animal emissions results showed a statistically significant reduction in SOF compared to the CARB reference fuel. Based on the certification testing results, the B5-animal passed the certification criteria for SOF. The B5-WVO emissions results showed no difference compared to the CARB reference fuel for SOF. The greater variability for the B5-WVO results is probably due to the limited number of SOF analyses conducted for the B5-WVO certification test, or the fact that the samples were aggregated from several individual tests. Since the B5-WVO results were not analyzed for all of the samples, these results were not analyzed in terms of pass/fail for the certification test.

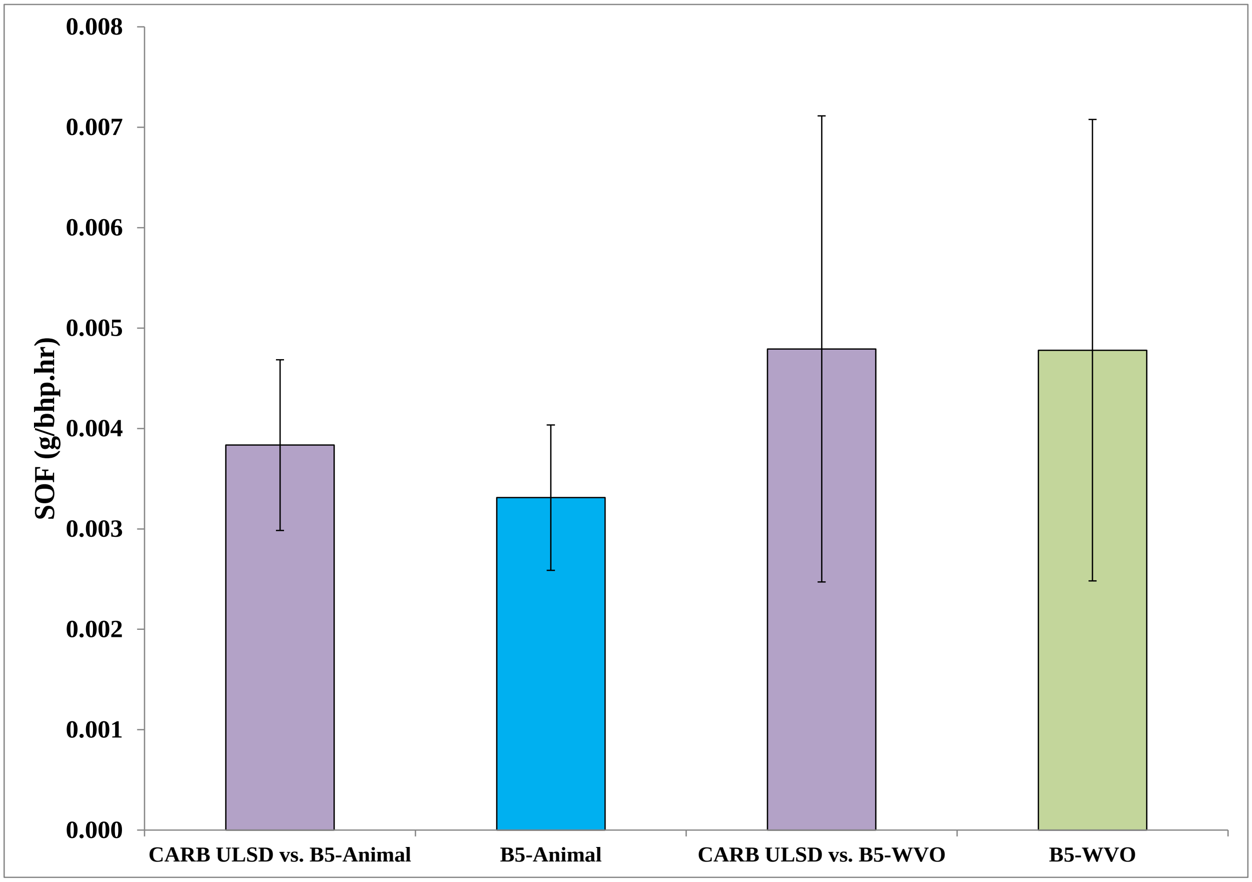

Figure 3-5. Average SOF Emissions Results for the Certification Testing

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

Fuel Type			
	Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
CARB	0.0038		
B5-Animal	0.0033	-13.7%	**0.043**

CARB	0.0048		
B5-WVO	0.0048	-0.3%	0.990

3.3 THC Emissions

The THC emission results for the preliminary testing are presented in Figure 3-6 for the FTP cycle on a g/bhp-hr basis. Table 3-6 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. No consistent trends for THC emissions were observed over the different B5 biodiesel blends during the preliminary testing. The B5-WVO emissions results showed a statistically significant 8.8% reduction in THC. Interestingly, the B5-soy emissions results showed a slight statistically significant increase in THC compared to the CARB reference fuel. This observation is opposite to that seen in other studies [1,4,6,14,15,24] and might be due to the low values of THC emissions over all the fuel blends or limited number of tests done in the preliminary testing.

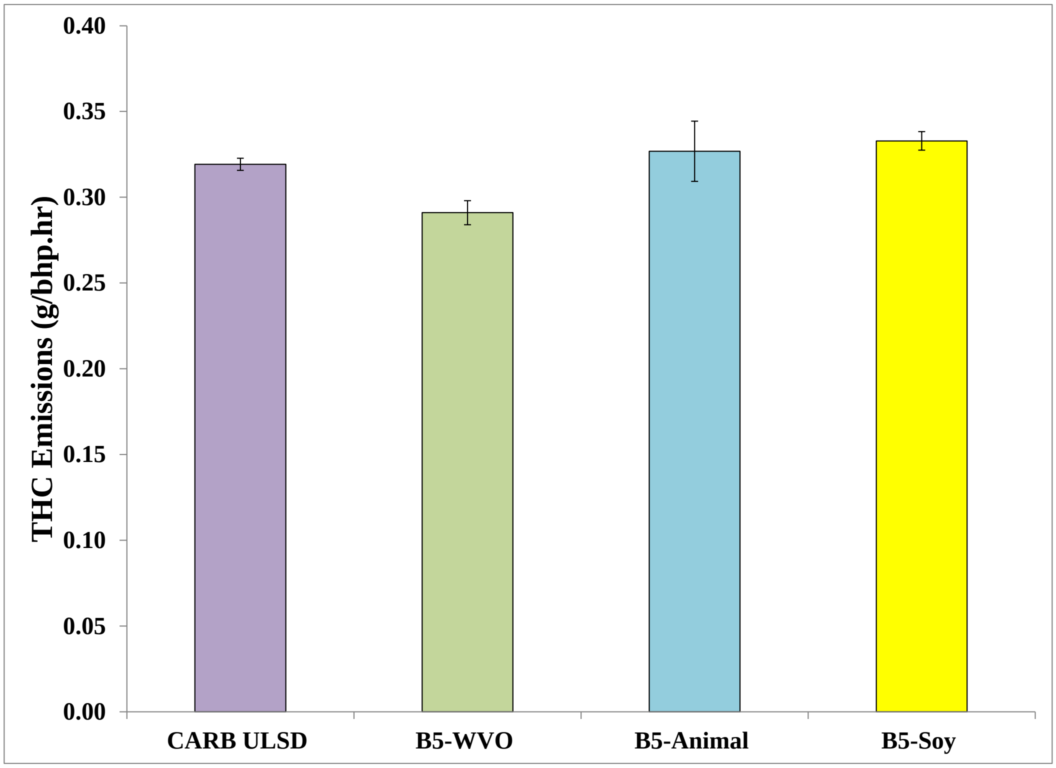

Figure 3-6. Average THC Emission Results the Preliminary Testing

Table 3-6. THC (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**
CARB	0.319		
B5-Animal	0.327	2.4%	0.367
B5- WVO	0.291	-8.8%	**0.000**

B5-Soy	0.333	4.3%	**0.001**

The THC emission results for the certification testing are presented in Figure 3-7 on a g/bhp-hr basis. Table 3-7 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. The emissions testing results for both blends showed reductions in THC compared to the CARB reference fuel for the certification testing. The reduction seen for B5-WVO was not statistically significant, however. The full certification results were generally consistent with previous studies that have shown reductions in THC with biodiesel. This 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]. The stronger THC trends for the certification tests compared to preliminary tests is probably due to the more robust test matrix and the greater number of test replicates..

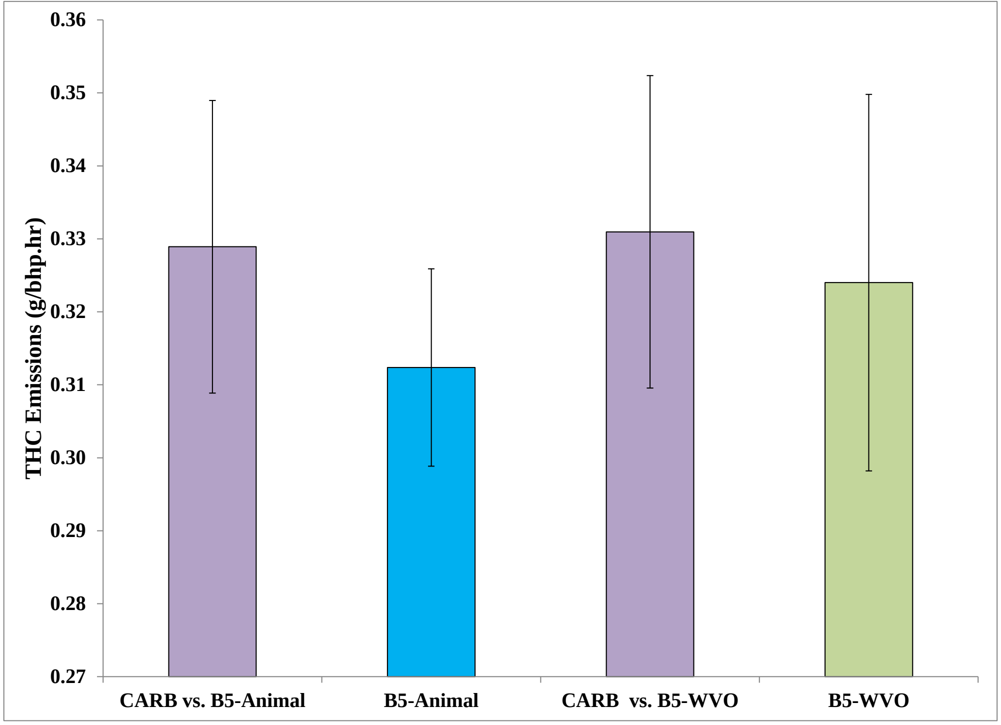

Figure 3-7. Average THC Emission Results for the Certification Testing

Table 3-7. THC (g/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for the Certification Testing

Fuel Type			
	Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
CARB	0.33		
B5-Animal	0.31	-4.8%	**0.001**
CARB	0.33		
B5-WVO	0.32	-2.1%	0.330

3.4 CO Emissions

The CO emission results for the preliminary testing are presented in Figure 3-8 on a g/bhp-hr basis. Table 3-8 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. The results of testing did not show consistent trends for CO emissions over all the biodiesel fuel blends. Interestingly, emissions testing results showed a statistically significant increase of 3.8% in CO emissions for B5-WVO compared to the CARB reference fuel in the preliminary testing. This is contrary to most studies in the literature, which generally show CO reductions with biodiesel [4,6,7,26]. The B5-WVO results showed a reduction in CO emissions for more robust certification testing, however, indicating that this may have been an anomaly for this particular day of the preliminary testing.

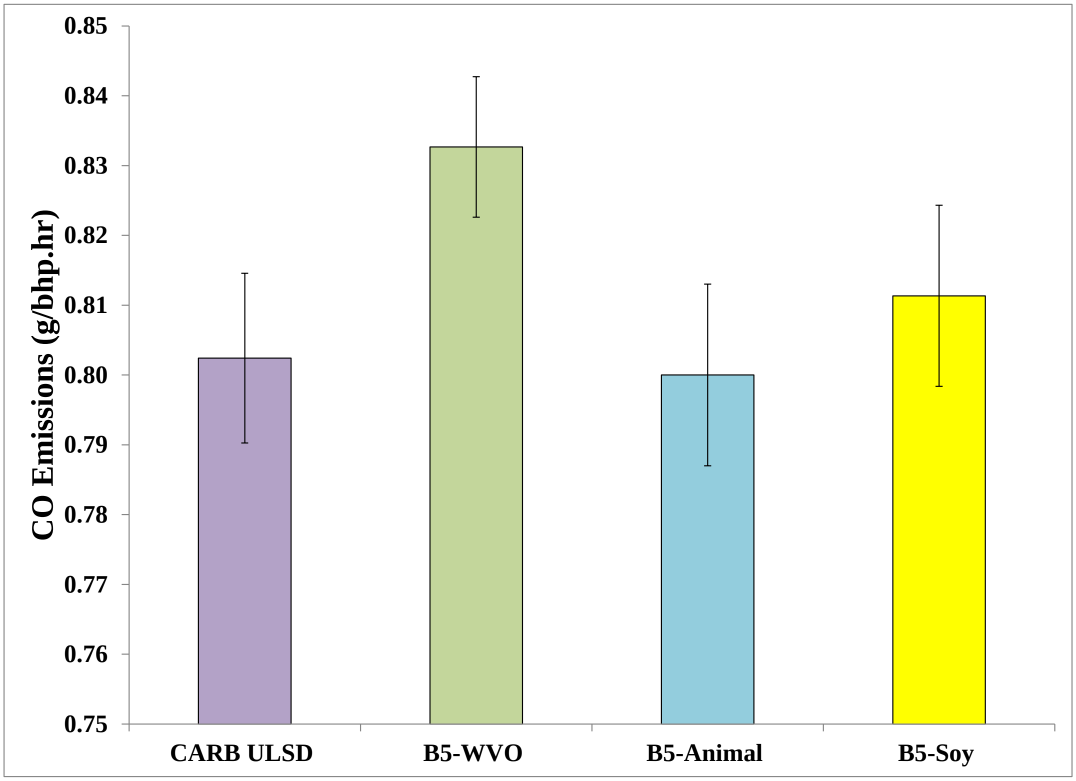

Figure 3-8. Average CO Emission Results for the Preliminary Testing

Table 3-8. 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**
CARB	0.802		
B5-Animal	0.800	-0.3%	0.761
B5- WVO	0.833	3.8%	**0.011**

B5-Soy	0.811	1.1%	0.272

The CO emission results for the certification testing are presented in Figure 3-9 on a g/bhp-hr basis. Table 3-9 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. The results for both B5 blends showed statistically significant reductions in CO emissions compared to the CARB reference fuel in the range of 2-6%. This is consistent with previous studies that have shown CO reductions for biodiesel due to the oxygen content in the biodiesel that promotes more complete combustion.

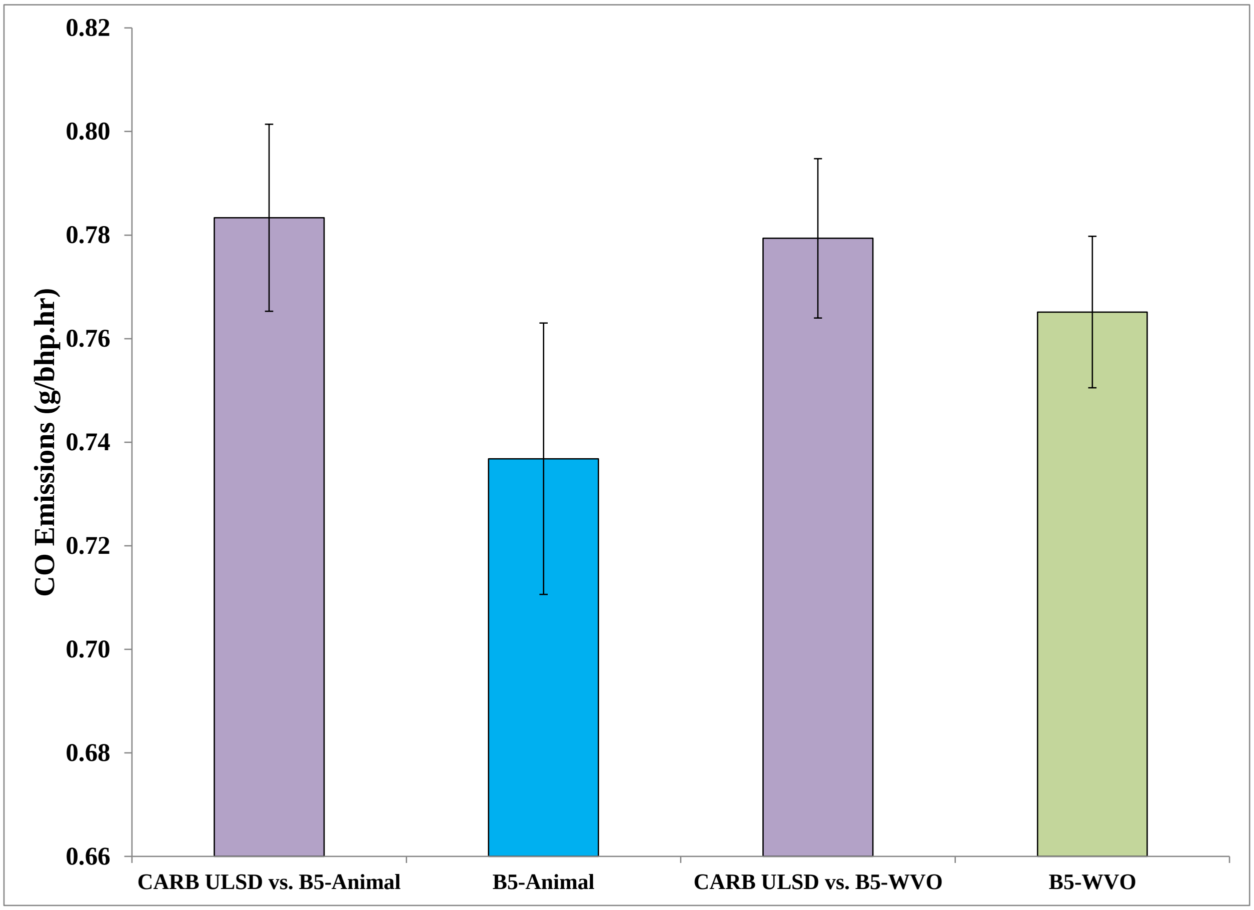

Figure 3-9. Average CO Emission Results for the Certification Testing

Table 3-9. CO (g/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for the Certification Testing

Fuel Type			
	Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
CARB	0.78		
B5-Animal	0.74	-5.9%	**0.000**
CARB	0.78		
B5-WVO	0.77	-1.8%	**0.002**

3.5 CO_2 Emissions

The CO_2 emission results for the preliminary testing are presented in Figure 3-10 on a g/bhp-hr basis.

Table 3-10 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. The results for all the biodiesel blends showed statistically significant 0.8-1.0% increases of CO_2 emissions compared to the CARB reference fuel. Although other studies have shown increases in exhaust CO_2 emissions with biodiesel, this has generally been seen for higher biodiesel blend levels [4,6,7,26–28]. This could be related to the generally higher carbon content per unit of energy for biodiesel compared to typical diesel fuel. Although the neat biodiesel fuels for the present study had higher carbon contents per unit of energy than the CARB reference fuel, there is essentially no differences in the carbon contents for the B5 blends compared to the reference fuel, as seen in Table 2-1 through Table 2-3. The differences in the CO_2 increases for the more robust certification testing were also smaller and less statistically significant. It should be emphasized that an increase in exhaust CO_2 emissions for biodiesel, does not imply that the use of biodiesel has a negative impact on greenhouse gas emissions. The actual contribution of different fuels towards total greenhouse gas emissions would need to be assessed through a full lifecycle analysis, which would account for the emissions attributed to harvesting, extracting, producing, associated land use changes for the various fuels [29].

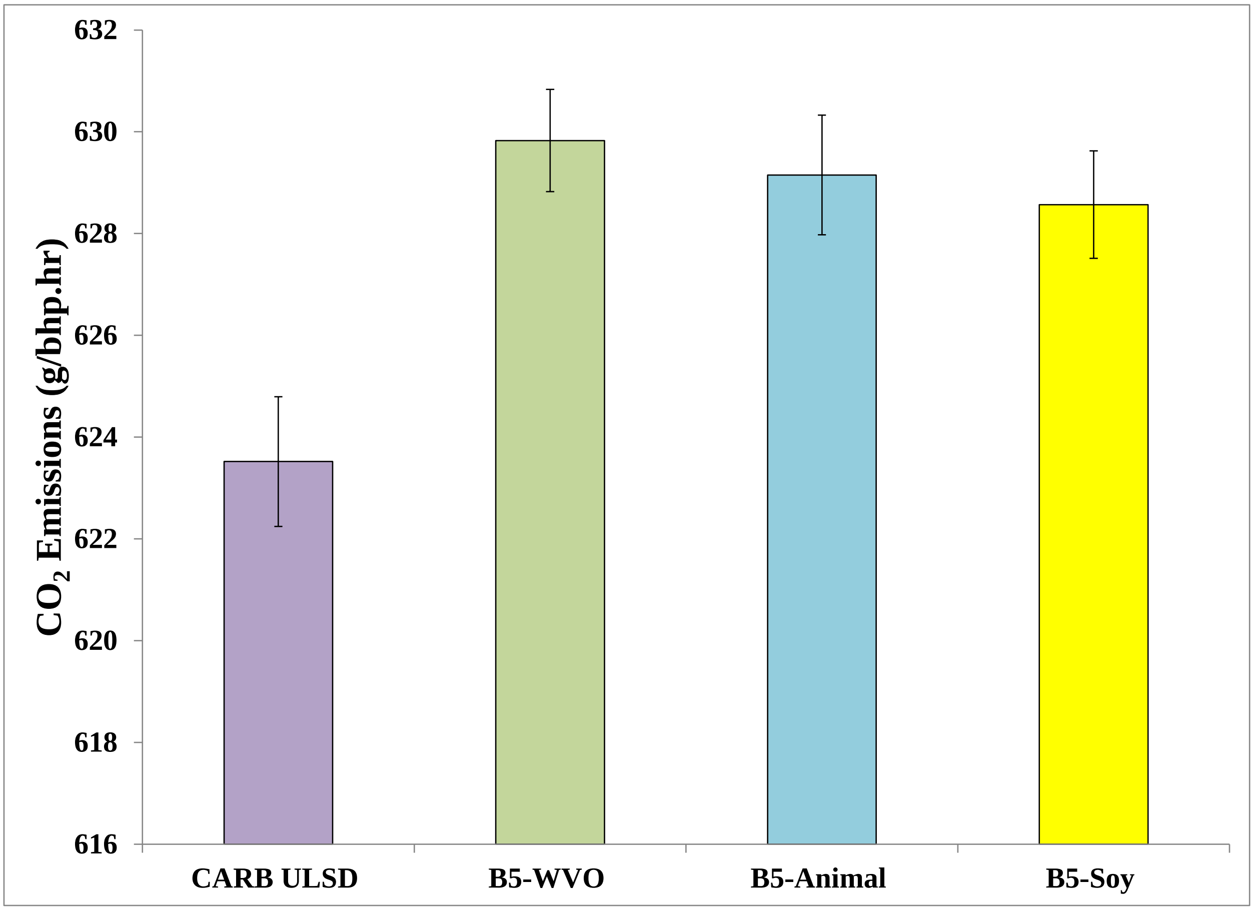

Figure 3-10. Average CO_2 Emission Results for the Preliminary Testing

Table 3-10. CO_2 (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**
CARB	623.518		
B5-Animal	629.151	0.9%	**0.000**
B5- WVO	629.826	1.0%	**0.000**
B5-Soy	628.569	0.8%	**0.000**

Table 3-11 shows results of CO_2 emissions for the certification testing. For the certification testing, CO_2 emissions were not different at a statistically significant level. Note that CO_2 emissions are not part of the emissions considered in the pass/fail criteria for the certification test.

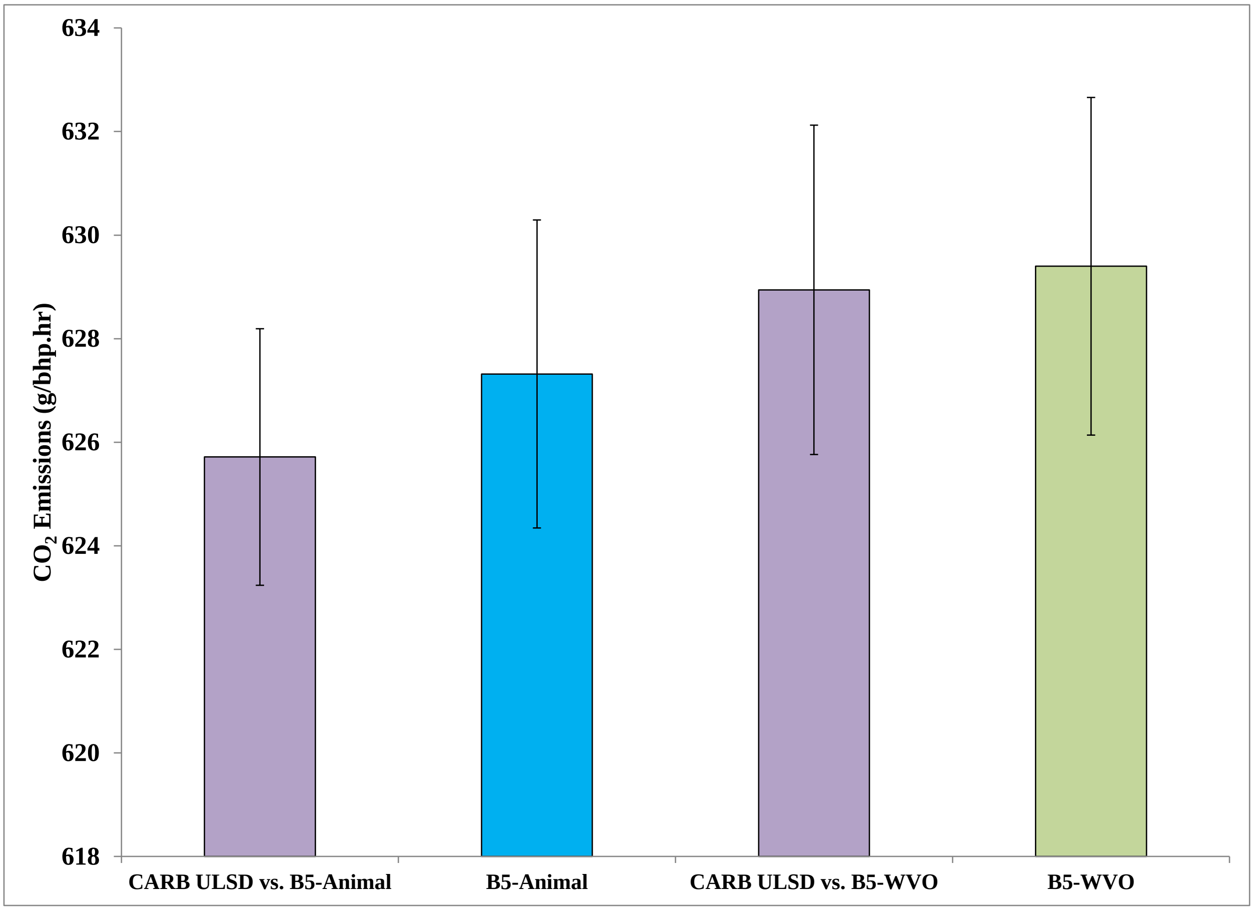

Figure 3-11. Average CO_2 Emission Results for the Certification Testing

Table 3-11. CO_2 (g/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for the Certification Testing

Fuel Type			
	Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
CARB	625.72		
B5-Animal	627.32	0.3%	0.072
CARB	628.94		
B5-WVO	629.40	0.1%	0.627

3.6 Brake Specific Fuel Consumption

The brake specific fuel consumption (BSFC) results for the preliminary testing are presented in Figure 3-12 on a gallons/bhp-hr. Table 3-12 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 was 0.7-2.1% higher for the B5 blends compared to CARB reference fuel. This result is directionally consistent with the results of previous studies, although BSFC impacts are usually more readily apparent at higher blend levels [4,6,7,26–28]. In the present study, although there are differences in the energy contents of the pure biodiesel compared to the CARB reference fuel, as shown in Table 2-1 and Three different biodiesels were investigated in this study: an animal tallow biodiesel, a waste vegetable oil biodiesel, and a soy-based biodiesel. The animal-based biodiesel was selected as the primary option for the candidate fuel, since this biodiesel feedstock is more saturated and has been shown to have a lower tendency to increase NOx [2,4,6,9,14–16]. In addition to the animal-based biodiesel, a waste vegetable oil biodiesel, and a soy-based biodiesel were included in the preliminary test matrix, in order to provide a broader range of biodiesel sources within the state.

The properties of all three neat biodiesel feedstocks are provided in **Table 2-2. Select fuel properties for the** B5-animal and B5-WVO are provided in Table 2-3. Some trends for cetane number are worth noting. Cetane number for the neat biodiesels showed a decreasing trend from the animal-based to the WVO-based to the soy-based biodiesels. Interestingly, the cetane number for the B5-animal blend was more similar to that of the B100-animal than the CARB reference fuel, while the cetane number for the B5-WVO blend was more similar to that of the CARB reference fuel than the B100-WVO.

The biodiesels were all blended at a B5 level for this test program. The B5 fuels were blended volumetrically. A single batch was used for each of the full certification tests. The B5 blends are denoted B5-soy, B5-animal, and B5-WVO throughout this report to differentiate between blends made from different feedstocks.

Table 2-2, the differences in the energy contents of the B5 blends, as shown in Table 2-3, and the CARB reference fuel are very minor. Note that specific gravity and carbon weight fraction analyses were performed for the B5-animal and B5-WVO fuels, but not for the B5-soy fuel. Therefore, the B5-soy fuel economy calculation was based on a weighted average of the CARB reference fuel and B100-soy specific gravity and carbon weight fraction values.

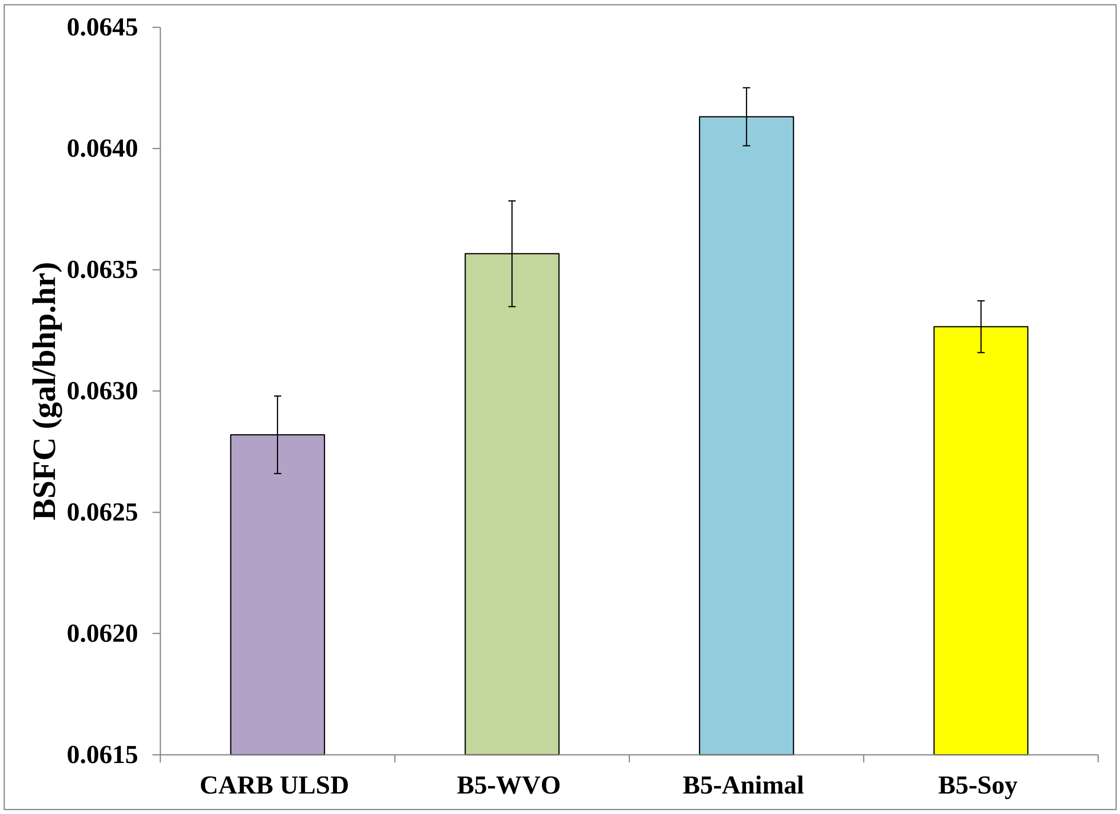

Figure 3-12. Average Brake Specific Fuel Consumption Results for the Preliminary Testing

Table 3-12. 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**
CARB	0.063		
B5-Animal	0.064	2.1%	**0.000**
B5- WVO	0.064	1.2%	**0.000**
B5-Soy	0.063	0.7%	**0.000**

Table 3-13 shows the results of BSFC for both biodiesel blends used in the certification testing. As can be seen, the BSFC results for both biodiesel blends showed 0.6-1.0% increases in fuel consumption compared to CARB reference fuel that were statistically significant. Note that BSFC is not a pass/fail criteria consideration for the certification test.

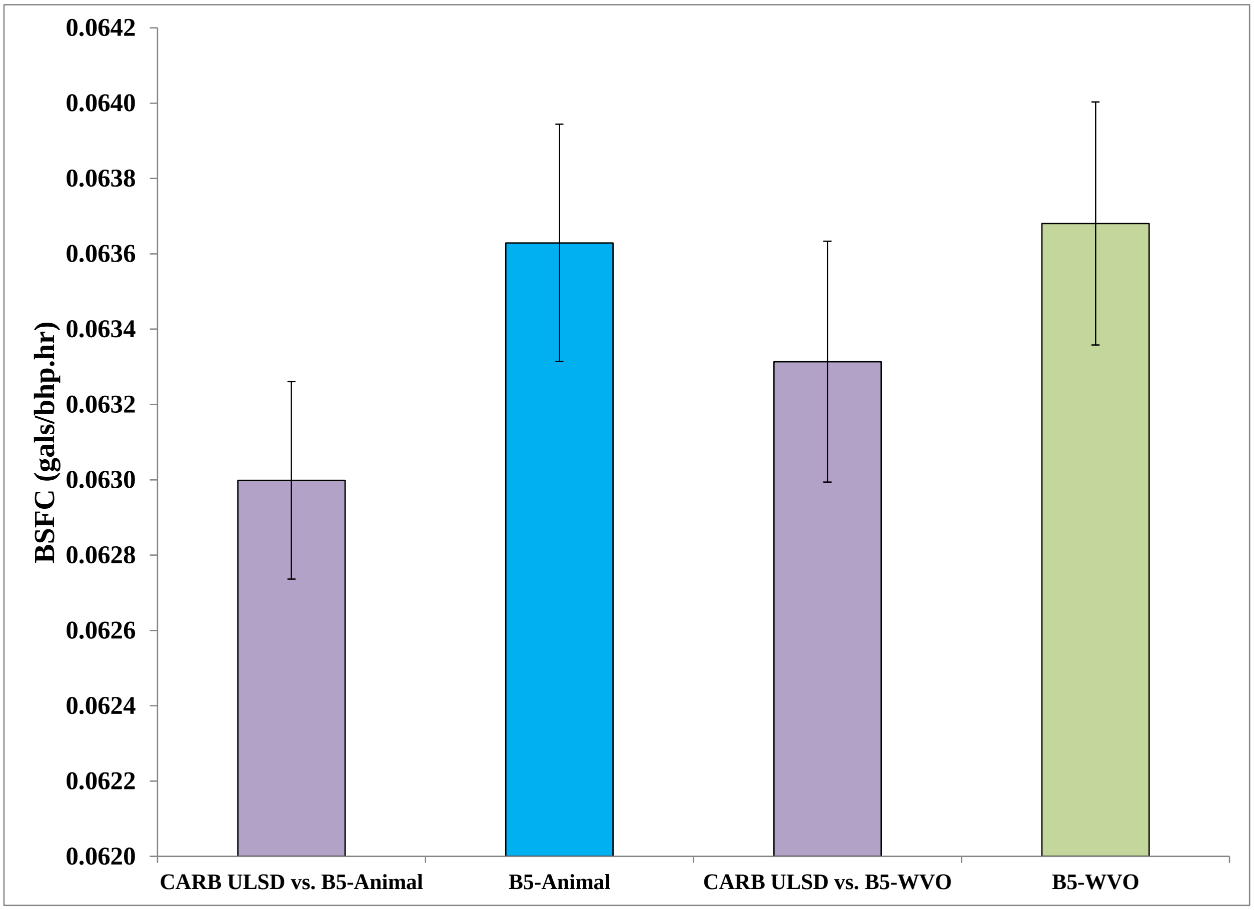

Figure 3-13. Average Brake Specific Fuel Consumption Results for the Certification Testing

Table 3-13. BSFC (gal/bhp-hr) Percentage Differences Between the Biodiesel blends and the CARB Reference Fuel for the Certification Testing

Fuel Type			
	Ave. (g/bhp.hr)	**% Diff vs. CARB**	**P-values**
CARB	0.063		
B5-Animal	0.064	1.0%	**0.000**
CARB	0.063		
B5-WVO	0.064	0.6%	**0.001**

4 Summary

This goal of this study was to investigate and test low blend level biodiesel blends for California based on the CARB certification testing protocol. For this study some preliminary testing was first performed on three different 5% biodiesel blends with different feedstocks blended with CARB reference fuel to identify potential low blend level biodiesel blends candidate fuels for certification testing. This included testing on B5-animal, B5-WVO, and B5-soy blends. Full CARB certification testing was subsequently performed for the B5-animal and B5-WVO. 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:

- The NO_x emissions results showed statistically significant 1.2-1.3% increases with B5-WVO and B5-soy blends. The B5-animal did not show a statistically significant increase in NO_x emissions.
- The PM emissions results showed consistent reductions of 4-6% with all the B5 blends.
- Consistent trends were not seen for THC and CO emissions for the B5 blends.
- Consistent trends of 0.8-1.0% increases in CO_2 emissions and 0.7-2.1% increases in brake specific fuel consumption calculated via a carbon balance method were observed for all the B5 fuel blends comparing to the CARB reference fuel. The differences in both the CO_2 and BSFC are higher than what would be expected based on differences in carbon content per unit of energy and overall energy content.

B5 Animal-based and B5 Waste Vegetable Oil Certification Testing Results:

- **B5- animal results**
  1. The NO_x emissions results showed a statistically significant 0.5% reduction for the B5-animal.
  2. Statistically significant reductions for the B5-animal were found for PM (-4.2%) and SOF (-13.7%).
  3. The emissions results showed a statistically significant 4.8% reduction for THC and 5.9% reduction for CO emissions for the B5-animal.
  4. A statistically significant 1.0% increase in brake specific fuel consumption calculated via a carbon balance method was seen for the B5-animal. Slight increases in CO_2 emissions (i.e., 0.3%) were seen for the B5-animal, however, this difference was only marginally statistically significant.
  5. B5-animal passed the criteria for NO_x, PM, and SOF for the certification test.
  6. It is worth noting that the B100-animal and the B5-animal both had cetane numbers that were on the order of 61, which was much higher than the cetane number for the reference fuel by itself and for the other B5 blends.

- **B5-WVO results**
    1. The NO_x emissions results showed a statistically significant 1.0% increase for B5-WVO.
    2. Statistically significant reductions for the B5-WVO were found for PM (-6.8%). The results did not show a statistically significant difference for SOF emissions for the B5-WVO.
    3. The results for CO emissions showed a statistically significant reduction of 1.8%. No statistically significant fuel differences were found for THC emissions for the B5-WVO.
    4. A statistically significant 0.6% increase in brake specific fuel consumption calculated via a carbon balance method was seen for this blend. The differences in CO_2 emissions for the B5-WVO and CARB reference fuel were not statistically significant.
    5. B5-WVO did not pass the certification testing criteria based on NO_x emissions.

See Appendix C for a summary of test results and certification statistical evaluations for NO_x, PM, and SOF emissions from the B5-animal certification test program and NO_x and PM emissions from the B5-WVO certification test program.

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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.

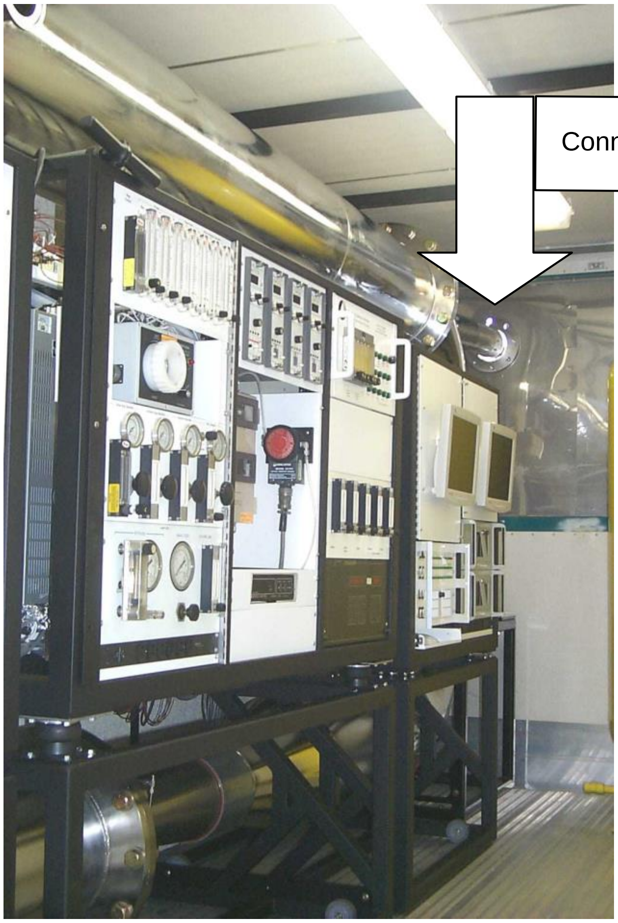

Figure A-1.

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.

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$_2$0	
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, PM, and SOF emissions. The statistical criteria includes a tolerance of 1%, 2%, and 6%, respectively, for NO_x, PM, and SOF emissions. The tolerance is reduced by pooled variance term that increases with the variability in the data.

B5 Animal-based, NO_x									
	R	C	C	R	R	C	C	R	
Day 1					2.044	2.054	2.059	2.040	
Day 2	2.044	2.035	2.024	2.036	2.033	2.023	2.022	2.046	
Day 3	2.051	2.028	2.019	2.049					
Day 4	2.046	2.030	2.047	2.044	2.043	2.036	2.032	2.043	
Day 5	2.031	2.014	2.049	2.056	2.051	2.035	2.022	2.044	
Day 6	2.037	2.039	2.031	2.033	2.046	2.030	2.056	2.069	
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	2.044	2.034	-0.4916%	0.0087	0.0129	0.0110	0.1787%	-0.3129%
									CANDIDATE FUEL PASSES

B5 Animal-based, PM									
	R	C	C	R	R	C	C	R	
Day 1					0.049	0.046	0.047	0.050	
Day 2	0.049	0.045	0.048	0.048	0.049	0.047	0.047	0.049	0.049
Day 3	0.047	0.047	0.046	0.049					0.047
Day 4	0.046	0.046	0.046	0.048	0.048	0.047	0.047	0.050	0.046
Day 5	0.048	0.046	0.047	0.048	0.049	0.046	0.046	0.049	0.048
Day 6	0.047	0.045	0.046	0.047	0.047	0.045	0.046	0.048	0.047
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	0.048	0.046	-4.2319%	0.0011	0.0008	0.0009	0.6383%	-3.5936%
									CANDIDATE FUEL PASSES

B5 Animal-based, SOF									
	R	C	C	R	R	C	C	R	
Day 1					0.0042	0.0048	0.0033	0.0047	
Day 2	0.0035	0.0034	0.0031	0.0038	0.0049	0.0041	0.0033	0.0052	
Day 3	0.0038	0.0028	0.0033	0.0029					
Day 4	0.0058	0.0033	0.0029	0.0042	0.0028	0.0041	0.0048	0.0030	
Day 5	0.0027	0.0034	0.0032	0.0037	0.0030	0.0025	0.0022	0.0036	
Day 6	0.0037	0.0037	0.0032	0.0030	0.0042	0.0027	0.0021	0.0040	
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	0.004	0.003	-13.6549%	0.0009	0.0007	0.0008	6.8430%	-6.8119%
									CANDIDATE FUEL PASSES

B5 WVO, NO_x									
	R	C	C	R	R	C	C	R	
Day 1	2.056	2.070	2.071	2.062	2.058	2.065	2.070	2.018	
Day 2	2.053	2.062	2.067	2.053	2.043	2.084	2.093	2.074	
Day 3	2.036	2.046	2.065	2.056	2.052	2.081	2.108	2.079	
Day 4	2.063	2.045	2.111	2.036	2.029	2.068	2.061	2.049	
Day 5	2.044	2.065	2.048	2.047	2.049	2.085	2.079	2.073	
Day 6	2.064	2.096	2.091	2.083	2.053	2.093	2.080	2.076	
n	t	x_R	x_c	$(x_c-x_R)/x_R$	S_R	S_c	S_p	$S_p(2/n)^{0.5}t/x_R$	
24	1.04825	2.054	2.075	1.0100%	0.0160	0.0178	0.0169	0.2493%	1.2593%
									CANDIDATE FUEL FAILS

B5 WVO, PM									
	R	C	C	R	R	C	C	R	
Day 1	0.046	0.045	0.045	0.048	0.047	0.045	0.046	0.049	
Day 2	0.046	0.044	0.045	0.048	0.048	0.046	0.046	0.048	
Day 3	0.046	0.044	0.044	0.046	0.048	0.045	0.047	0.048	
Day 4	0.058	0.043	0.042	0.046	0.047	0.043	0.044	0.047	
Day 5	0.045	0.043	0.042	0.046	0.046	0.043	0.043	0.046	
Day 6	0.044	0.043	0.042	0.046	0.046	0.043	0.043	0.043	
n	t	x_R	x_c	$(x_c-x_R)/x_R$	S_R	S_c	S_p	$S_p(2/n)^{0.5}t/x_R$	
24	1.04825	0.047	0.044	-6.7613%	0.0027	0.0014	0.0022	1.3990%	-5.3623%
									CANDIDATE FUEL PASSES