Final Report

Renewable Diesel Agriculture Engine Emissions Testing

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Disclaimer

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Abstract

The purpose of this study is to quantify emissions and performance effects from renewable diesel and biodiesel blends relative to conventional diesel in an agricultural engine without selective catalytic reduction (SCR) exhaust treatment and without a diesel particulate filter (DPF) using an engine dynamometer. The University of California, Riverside (UCR), College of Engineering – Center for Environmental Research and Technology (CE-CERT) conducted emissions testing using a petroleum-derived California Air Resources Board Ultra-Low Sulfur (conventional CARB ULSD) reference diesel fuel, a pure renewable diesel (R100), and a blend of 80 percent renewable diesel with 20 percent biodiesel (R80/B20) on a 2006 model year Tier 2 off-road John Deere 4045TLV54 agricultural engine obtained from an operational 91 horsepower (HP) tractor. The C1 test cycle was used. This study aimed to:

- Evaluate the oxides of nitrogen (NOx) and particulate matter of 2.5 microns or less in diameter (PM2.5) emissions resulting from use of renewable diesel fuel and selected renewable diesel/biodiesel fuel blends in a legacy off-road engine.

- Evaluate the total hydrocarbon, carbon monoxide, carbon dioxide, soot, solid particulate number emissions and brake specific fuel consumption resulting from use of renewable diesel fuel and selected renewable diesel/biodiesel fuel blends in a legacy off-road engine.

Results and Conclusions:

NOx emissions showed decreases for both the R100 and the R80/B20 fuels compared to the conventional CARB ULSD reference fuel. The R100 fuel resulted in the lowest NOx emissions, with a statistically significant reduction of 13%. The R80/B20 showed a statistically significant reduction of 11% for NOx emissions.

PM2.5 emissions showed decreases for both the R100 and the R80/B20 fuels compared to the conventional CARB ULSD reference fuel. The R100 showed a statistically significant reduction of 22% for PM2.5. The R80/B20 showed a statistically significant reduction of 29%.

Acronyms and Abbreviations

ADF..Alternative Diesel Fuel
APC..AVL particle counter
BD..biodiesel
BSFC..brake specific fuel consumption
CAI...California Analytical Instruments
CARB...California Air Resources Board
CE-CERT...Bourns 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
COA..certificate of analysis
CPC..condensation particle counter
CVS..Constant Volume Sampling
DPF..diesel particle filter
ECM...engine control module
EEPS..Engine Exhaust Particle Sizer
EPA..U.S. Environmental Protection Agency
FTP...Federal Test Procedure
g/bhp-hr...grams per brake horsepower-hour
hp..horsepower
kw...kilowatt
LCFS..Low Carbon Fuel Standard
LED..low emission diesel
MEL...CE-CERT's Mobile Emissions Laboratory
NOx..nitrogen oxides
PM2.5...particulate matter of 2.5 microns in diameter or less
SPN..solid particle number
PSD..particle size distribution
RD..renewable diesel
RMC...Ramped Modal Cycle
QA..quality assurance
QC..quality control
THC..total hydrocarbons
SCR..selective catalytic reduction
SET..Supplementary Emissions Test
Soot..strongly absorbing particulates also known as black carbon
SwRI..Southwest Research Institute
UCR...University of California Riverside
ULSD...ultra-low sulfur diesel

Executive Summary

Background

The United States Environmental Protection Agency (U.S. EPA) and the California Air Resources Board (CARB) have set national and State ambient air quality standards for criteria air pollutants to protect public health and the environment. Large areas of California are currently designated as non-attainment for ozone and particulate matter less than 2.5 microns in diameter (PM2.5), including the San Joaquin Valley, which is designated as an "extreme" non-attainment area for ozone and a "severe" non-attainment area for PM2.5.

CARB and the California Air Districts have developed State Implementation Plans (SIP) outlining specific strategies to reduce PM2.5 emissions and emissions that result in formation of ozone and PM2.5, including development of more stringent regulations for stationary and mobile sources, as well as new and expanded incentive programs to replace older, higher-polluting engines with cleaner engines. U.S. EPA has provided substantial support to CARB and the California Air Districts for implementation of the SIPs, including initiation of programs to support the SIP goals (e.g., the Targeted Airshed Grant program, which is providing over three million dollars to the San Joaquin Valley Air Pollution Control District (SJVAPCD) to replace Tier 0 to Tier 2 off-road diesel agricultural tractors with new tractors that meet the Tier 4 final emissions standard).

Fuel switching from conventional, petroleum-based diesel to biomass-based diesels, including renewable diesel (RD) and/or biodiesel (BD), is an additional strategy that has the potential to reduce oxides of nitrogen (NOx, a primary ozone precursor and a secondary PM precursor) and PM2.5 emissions and therefore contribute to meeting California SIP goals. CARB and others have conducted emissions testing to evaluate RD and BD use relative to conventional diesel use in on-road engines. However, limited testing has been completed on off-road agricultural engines – typical of those used in the San Joaquin Valley.

Objectives

The purpose of this study is to quantify emissions and performance effects, using an engine dynamometer, with RD fuel and an RD/BD fuel blend relative to a petroleum-derived conventional ultra-low sulfur diesel (conventional CARB ULSD) reference fuel. This study was conducted using an agricultural engine without selective catalytic reduction (SCR) exhaust treatment and without a diesel particulate filter (DPF). The University of California, Riverside (UCR), College of Engineering – Center for Environmental Research and Technology (CE-CERT) conducted the emissions testing.

Test Fuels and Engine

The test fuels included a conventional CARB ULSD reference fuel as a baseline fuel, a neat (100 percent or 99 percent) RD fuel (R100) and a blend of 80 percent RD with 20 percent BD (R80/B20).

RD fuel is produced from animal fats and vegetable oils though a production process resulting in a hydrocarbon mixture meeting the ASTM D975 standard for diesel fuel for motor vehicles. BD is produced from the same feedstocks as RD, but the fats and oils are processed using a transesterification process, resulting in a fatty acid methyl ester that can be used as a diesel fuel additive in volumes of up to 20 percent under certain circumstances in California. The test engine was a 2006 model year John Deere 4045TLV54 engine obtained from an operational farm tractor.

Test Procedures

The test cycle utilized for this study is an international and Federal standard for exhaust emission measurement for a number of non-road engine applications – an eight-mode C1 ISO 8178 steady-state test cycle "C1 cycle." This test cycle is used for U.S. EPA and CARB certification of off-road engines. The test sequence was conducted by alternating between the baseline conventional CARB ULSD reference fuel and the two RD/BD fuels (i.e., R100 and R80/B20), with each fuel generally tested in triplicate for each test day. The full test sequence included six iterations for each of the test fuels.

The engine emissions testing was performed at 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.

Emissions of NOx, PM2.5, total hydrocarbons (THC), carbon monoxide (CO), soot and solid particle number (SPN) emissions, and carbon dioxide (CO_2) were measured during all tests, along with a determination of fuel consumption made via the carbon balance method. The emissions measurements were made using CE-CERT's heavy-duty Mobile Emissions Laboratory (MEL) trailer.

Results

Summary results for each of the pollutants are provided below. All statistical analyses are in comparison to the CARB reference fuel. For the discussion in this report, results are considered to be statistically significant for p values $\leq$0.05 using a 2-tailed, 2-sample, equal-variance t-test, meaning that the probability that the compared emissions differences would arise by chance is less than or equal to 5 percent. In the tables presented below, statistically significant results with p values $\leq$0.05 are bolded and the percent differences compared to CARB reference fuel are shown in red text in the tables.

NOx Emissions

Average NOx emissions, percentage differences and statistical comparisons between the test biofuels and CARB reference diesel are shown in Table ES-1. NOx emissions showed decreases for both the R100 and the R80/B20 fuels compared to the CARB reference fuel. The R100 fuel resulted in the lowest NOx emissions, with a statistically significant reduction of 13% compared to the CARB reference fuel. The R80/B20 showed a statistically significant reduction of 11% for NOx emissions compared to the CARB reference fuel.

Table ES-1. NOx Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Using the C1 Cycle

Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
CARB reference fuel	3.53	-	-
R100	**3.07**	**-13**	**0.000**
R80/B20	**3.15**	**-11**	**0.000**

PM2.5 Emissions

Average PM2.5 emissions, percentage differences and statistical comparisons between the test biofuels and CARB reference fuel are presented in Table ES-2. PM2.5 emissions showed decreases for both the R100 and the R80/B20 fuels compared to the CARB reference fuel. The R100 showed a statistically significant reduction of 22% for PM2.5 mass emissions compared to the CARB reference fuel. The R80/B20 showed a statistically significant reduction of 29% compared to the CARB reference fuel.

Table ES-2. PM2.5 Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Using the C1 Cycle

Fuel Type	Ave. (mg/bhp-hr)	% Diff vs. CARB	p-value (t-test)
CARB reference fuel	235	-	-
R100	**184**	**-22**	**0.000**
R80/B20	**167**	**-29**	**0.000**

THC Emissions

The R100 and R80/B20 fuels both showed THC reductions compared to the CARB reference fuel for the C1 cycle. The R100 showed a statistically significant reduction of 40% relative to the CARB reference fuel. The R80/B20 showed the lowest THC emissions, with a statistically significant reduction of 43% compared to the CARB reference fuel.

CO Emissions

R100 and R80/B20 fuels both showed CO reductions compared to the CARB reference fuel for the C1 cycle. The R100 showed a statistically significant reduction of 32% compared to the CARB reference fuel. The R80/B20 showed a statistically significant reduction of 23% compared to the CARB reference fuel.

CO_2 Emissions

CO_2 emissions showed statistically significant reductions of 2% for both the R100 and R80/B20 compared to the CARB reference fuel for the C1 cycle.

Brake Specific Fuel Consumption (BSFC)

R100 and R80/B20 fuels both showed statistically significant increases of 6% in BSFC compared to the CARB reference for the C1 cycle.

Soot

R100 and R80/B20 fuels both showed soot reductions compared to the CARB reference fuel for the C1 cycle. The R100 showed a statistically significant reduction of 22% compared to the CARB reference fuel. The R80/B20 showed a statistically significant reduction of 31% compared to the CARB reference fuel.

Solid Particle Number Emissions

Measurements of SPN emissions greater than 23 nm in diameter, as defined by the European Union solid particle number emissions regulations, were also made. R100 showed a statistically significant 3% increase in SPN emissions compared to the CARB reference fuel. The R80/B20 showed a statistically significant 3% decrease in SPN emissions compared to the CARB reference fuel.

Conclusions

For this off-road legacy agriculture tractor engine, the NOx emissions results from the C1 cycle are consistent with previously observed reductions in NOx emissions with R100 as the test fuel compared to the CARB reference fuel for legacy engines. When blended with BD, namely R80/B20 in this test, NOx emissions were lower than those for the CARB reference fuel, although higher than those for the R100.

For this off-road legacy agriculture tractor engine, PM2.5 and soot emissions both showed decreases for both the R100 and R80/B20 fuels for the C1 cycle compared to the CARB reference fuel, with the R80/B20 showing the lowest PM2.5 and soot emissions. The lower PM2.5 and soot emissions for R100 and R80/B20 fuels are consistent with previous findings that biofuels can provide PM2.5 emissions reductions in legacy diesel engines.

1 Introduction

The United States Environmental Protection Agency (U.S. EPA) and the California Air Resources Board (CARB) have set national and State ambient air quality standards for criteria air pollutants to protect public health and the environment. Large areas of California are currently designated as non-attainment for ozone and particulate matter less than 2.5 microns in diameter (PM2.5), including the San Joaquin Valley, which is designated as an “extreme” non-attainment area for ozone and a “severe” non-attainment area for PM2.5. CARB and the California Air Districts have developed State Implementation Plans (SIP) outlining specific strategies to reduce PM2.5 emissions and emissions that result in formation of ozone and PM2.5, including development of more stringent regulations for stationary and mobile sources, as well as new and expanded incentive programs to replace older, higher-polluting engines with cleaner engines. U.S. EPA has provided substantial support to CARB and the California Air Districts for implementation of the SIPs, including initiation of programs to support the SIP goals (e.g., the Targeted Airshed Grant program, which is providing over three million dollars to the San Joaquin Valley Air Pollution Control District (SJVAPCD) to replace Tier 0 to Tier 2 off-road diesel agricultural tractors with new tractors that meet the Tier 4 final emissions standard).

Fuel switching from conventional, petroleum-based diesel to biomass-based diesels, including renewable diesel (RD) and/or biodiesel (BD) blends, is an additional strategy that has the potential to reduce oxides of nitrogen (NOx, a primary ozone precursor and a secondary PM precursor) and particulate matter of 2.5 microns in diameter or less (PM2.5) emissions and contribute to meeting SIP goals in California. CARB and others have conducted emissions testing to evaluate RD and BD use relative to conventional diesel use in on-road engines. However, limited testing has been completed on off-road, agricultural engines – typical of those used in the San Joaquin Valley. Because off-road agricultural equipment comprises approximately 18 percent of total off-road NOx emissions and approximately 15 percent of total off-road PM2.5 emissions in California, U.S. EPA, CARB, and SJVAPCD are interested in quantifying the potential emissions impacts of fuel switching in older agricultural engines without selective catalytic reduction (SCR) control technology and without diesel particulate filters (DPF).

2 Objectives

The purpose of this study is to quantify emissions and performance effects from RD and RD/biodiesel (BD) blends relative to petroleum-derived conventional ultra-low sulfur diesel (conventional CARB ULSD) reference fuel in an agricultural engine without SCR exhaust treatment and without a DPF using an engine dynamometer. The University of California, Riverside (UCR), College of Engineering – Center for Environmental Research and Technology (CE-CERT) conducted emissions testing using a reference petroleum-derived diesel fuel, a pure RD (R100), and a blend of 80 percent RD and 20 percent BD (R80/B20) on a 2006 model year Tier 2 off-road agricultural tractor engine.

3 Experimental Procedures

3.1 Test Fuels

The test fuels included a reference CARB ULSD, used as a baseline fuel, a neat (100 percent or 99 percent) RD fuel (R100), and a blend of 80 percent RD with 20 percent BD (R80/B20).

The baseline fuel was a reference CARB ULSD meeting the reference fuel specifications in Table A.9 of the Alternative Diesel Fuel (ADF) regulation,[1] and did not contain any RD or BD. The reference CARB ULSD used for this study was the same fuel used in a recent Low Emissions Diesel (LED) study.[2] The certificate of analysis (COA) for this fuel is provided in Appendix A.

The neat RD and neat BD were sourced from local California-based retailer suppliers, and were representative of in-use California fuels. RD for commercial sale is typically blended as R99, but for simplicity in presenting the results below, this fuel will be denoted as R100 throughout the results and conclusion sections of this report. The neat RD and neat BD were used as the blendstock for the R80/B20 fuel. The RD/BD was blended gravimetrically at the CE-CERT facilities in Riverside, CA.

Fuel analyses were conducted by Southwest Research Institute (SwRI) on the neat RD, the neat BD, and the R80/B20 blend. Fuel analyses for the reference CARB diesel fuel were conducted for ASTM D975 properties and the properties in Table A.9 of the ADF regulation.[1,2] Fuel analyses for the neat RD were conducted for the properties in Table A.9 of the ADF regulation.[1] The results of the analyses for the reference CARB diesel fuel and the neat RD are presented in Table 3-1. The neat BD was analyzed for a subset of properties, as shown in Table 3-2. The R80/B20 blend was analyzed for BD content, cetane number, density, and distillation temperature at 10 percent, 50 percent, and 90 percent of the sample. The results of these analyses are presented in Table 3-3. Fuel analyses were also performed for the carbon/hydrogen/oxygen content via ASTM D5291 for the neat fuels. Fuel analyses were conducted for one sample per fuel, with the exception of cetane number, which was performed in triplicate analyses for each of the fuels. The fuel analysis results from SwRI for all test fuels are provided in Appendix B.

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[1] Regulation on Commercialization of Alternative Diesel Fuels, Title 13, California Code of Regulations, Appendix 1 of Subarticle 2, "Reference CARB Diesel Specifications"

[2] Durbin, T.D., Karavalakis, G., Johnson, K.C., McCaffery, C., Zhu, H., and Li, H., 2021, Low Emissions Diesel Study, Final report by the University of California at Riverside CE-CERT to CARB, November 2021.

Table 3-1. CARB Reference Fuel and Renewable Diesel (RD) Analysis Results and Specifications

Property	ASTM Test Method	ULSD Fuel Specifications	Units	Certificate of Analysis Results	CARB Reference Fuel Analysis Results (SwRI)	Renewable Diesel Fuel Analysis Results (SwRI)
Sulfur	D5453	15 max.	ppm	<1	<0.5	<0.5
Aromatics	D5186	10 max.	Vol. %	10.0	9.9	0.3
Polycyclic aromatic hydrocarbons	D5186	1.4 max.	Wt. %	1.2	1.2	<0.1
Nitrogen content	D4629	10 max.	ppm	5.8	4.9	<1.0
Unadditized Cetane Number	D613	48 min.	unitless	48.4	48.1 48.3 48.2	>74.8 >74.8 >74.8
API Gravity	D287	33-39	unitless	38.1*	38.0	49.1
Specific Gravity	D287	-	g/ml	-	0.8348	0.7835
Carbon weight fraction	D5291	-	wt%	-	86.30	84.73
Kinematic Viscosity, 40ºC	D 445	2.0 – 4.1	mm^2/s	2.6	2.544	2.980
Flash Point	D93	130 min.	ºF	191	189.0	162.0
Distillation Temperature, atmospheric, IBP	D86-IBP	340 – 420	ºF	396	395.5	373.1
Distillation Temperature, atmospheric, T10	D86-T10	400 – 490	ºF	436	435.7	508.6
Distillation Temperature, atmospheric, T50	D86-T50	470 – 560	ºF	486	486.5	548.1
Distillation Temperature, atmospheric, T90	D86-T90	550 – 610	ºF	559	559.3	567.3
Distillation Temperature, atmospheric, TEP	D86-EP	580 – 660	ºF	600	601.6	600.1

*API gravity for certificate of analysis used ASTM Method D4052.

Table 3-2. Biodiesel (B100) Fuel Analysis Results

Property	ASTM Test Method	Units	BD Fuel Analysis Results (SwRI)
Distillation, 90% recovery	D1160	°F	666
API Gravity (by Meter)	D287	°API	29.7
Specific Gravity	D287	g/ml	0.8778
Kinematic Viscosity @ 40 °C	D445-40	mm^2/s	4.043
Trace Nitrogen in Liquid Petroleum Hydrocarbons	D4629	ppm (wt/wt)	12.7
Sulfur by UVF	D5453	ppm (wt/wt)	4
Cetane Number	D613	unitless	53.1 53.2 53.0
Flash Point, Pensky Martens	D93	°F	299
Fatty Acid Methyl Ester (FAME) content*	EN 14078	% Mass	94.1
Carbon weight fraction	D5291	wt %	77.1
Oxidation Stability	EN 15751	hours	3.1

* EN 14078 was substituted for EN 14103 to determine FAME content

Table 3-3. R80/B20 Fuel Property Analysis Results and Properties

Property	ASTM Test Method	Units	R80/B20
Cetane Number Test #1	D613	unitless	71.1
Cetane Number Test #2	D613	unitless	71.2
Cetane Number Test #3	D613	unitless	71.3
Cetane Number – Average	D613	unitless	71.2
API Gravity	D287	degAPI	45.0
Distillation Temperature, atmospheric, IBP	D86-IBP	ºF	392.0
Distillation Temperature, atmospheric, T10	D86-T10	ºF	522.7
Distillation Temperature, atmospheric, T50	D86-T50	ºF	562.6
Distillation Temperature, atmospheric, T90	D86-T90	ºF	605.0
Distillation Temperature, atmospheric, TEP	D86-EP	ºF	651.0
FAME Content %	EN14078	% Mass	19.4

3.2 Test Engine

The specifications of the test engine are provided in Table 3-4. The selected legacy off-road agriculture tractor engine was a 4.5 liter John Deere 4045TLV54 engine obtained from a farm tractor that was operational, but was being turned in as part of an incentive program. The engine utilized direct diesel injection and had a turbocharger, but was not equipped with any exhaust aftertreatment.

Table 3-4. Specifications of the Test Engines

Engine Manufacturer	John Deere
Engine Model	4045TLV54
Model Year	2006
Engine Family	6JDXL04.5083
Engine Type	In-line 4-cylinder, 4-stroke (Tier 2)
Displacement	4.5 liters
Power Rating	91 hp (68 kW)
Speed Rating	2400 rpm
Fuel Type	Diesel
Induction	Turbocharged
Emissions controls: 1. Exhaust Gas Recirculation (EGR) 2. Selective Catalytic Reduction (SCR) 3. Diesel Particulate Filter (DPF)	 1. No 2. No 3. No

3.3 Emissions Testing

Testing was conducted in UCR CE-CERT's heavy-duty engine dynamometer test laboratory. This facility is equipped with a 600 horsepower (hp) General Electric DC electric engine dynamometer that was obtained from the U.S. EPA National Vehicle and Fuels Emission Laboratory in Ann Arbor, MI. The system is installed as a fully Code of Federal Regulations (CFR) compliant laboratory by Dyne Systems of Jackson, Wisconsin. This facility is described in greater detail in Appendix C.

The emissions measurements for this project were conducted with CE-CERT's heavy-duty Mobile Emissions Laboratory (MEL) trailer. The heavy-duty dynamometer laboratory is in a location that has ready and full access to the MEL. CE-CERT's MEL is a heavy-duty emissions measurement laboratory with a full dilution tunnel and CFR compliant analytical instrumentation that can be utilized for either stationary or on-road measurements. The MEL is equipped with a Horiba MEXA-ONE-DC emissions bench. NOx emissions were measured with a CLA-01SL chemiluminescence analyzer. CO and CO_2 emissions were measured with AIA-11 and AIA-22 nondispersive infrared (NDIR) analyzers, respectively. THC emissions were measured with a FIA-

01 flame ionization detector (FID). Brake specific fuel consumption was obtained via the carbon balance method based on the THC, CO, and CO_2 emissions. The MEL is described in greater detail in Appendix C, with associated laboratory quality assurance and quality control procedures described in Appendix D.

The mass concentrations of PM2.5 were determined by gravimetric analysis of particulates collected on 47 mm diameter 2 µm pore Teflon filters (Whatman brand). The filters were weighed to determine the net weight gains between pre- and post-testing using a UMX2 ultra precision microbalance with buoyancy correction following 40 CFR Part 1065 weighing procedure guidelines.

Additional measurements of different particle properties were also conducted. This included an AVL Micro Soot Sensor (MSS) for measuring particle soot, and an AVL particle counter (APC) with a 23 nm diameter cut point for measuring solid particle number (SPN). The APC is designed to meet the requirements for the measurements of solid particles above 23 nm in diameter, as defined by the European Union solid particle number emissions regulations.[3]

[3] Solid particle number is defined as the total number of particulates of a diameter greater than 23 nm present in the diluted exhaust gas after it has been conditioned to remove volatile material, as described in Appendix 5 to Annex 4a to the European Union Regulation. 2015. Available at: https://unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/R083r5e.pdf.

3.4 Test Matrix and Test Sequence

The test cycle utilized for this study was an eight-mode C1 ISO 8178 steady-state test cycle. This is one of the cycles used for the certification of this engine. This cycle is described in greater detail in Appendix E. The test cycle was run manually through the modes using the same profile and cycle timings as used for the ramped modal cycle. The test cycle load points were developed based on an engine map conducted on the CARB reference fuel before the first emissions test on the engine.

The test sequence was conducted by alternating among the baseline fuel (i.e., reference CARB ULSD), the RD fuel and the RD/BD fuel (i.e., R100 and R80/B20), with each fuel tested in triplicate for most test days. In the test sequence described below, "C" represents the reference CARB ULSD fuel, "B1" represents the neat renewable diesel fuel (R100), and "B2" represents the R80/B20 blend. The test sequence is described in Table 3-5. The test sequence included six iterations for each of the test fuels.

The C1 cycles were run as hot running tests. The engine temperature was stabilized by bringing the engine to the first operating testing point load for about 5 minutes of operation followed by a 60 second soak period. For any given fuel, the engine was run over one iteration of the C1 cycle on the fuel prior to running the first emissions test on that fuel sequence. To prevent excessive heat buildup in the engine, the engine was also soaked for approximately 10 minutes between emissions tests.

Table 3-5. Test Sequence Used for the Off-Road Legacy Agriculture Tractor Engine

Day	Fuel Test Sequence
1	CCC
2	B1B1B1 B2B2
3	CCC
4	B1B1B1
5	B2B2B2B2

C = reference CARB ULSD
B1 = R100
B2 = R80/B20

4 Engine Testing Results

The results presented in the figures represent the average of all test runs performed on that fuel sequence. The error bars represent one standard deviation from the mean. The tables show the average emission values for all fuels, the percentage differences for the R100 and the R80/B20 compared to the CARB reference fuel for each engine and test cycle, and the associated p-values for statistical comparisons between the CARB reference fuel and the R100 and R80/B20 fuels emissions using a 2-tailed, 2-sample, equal-variance t-test. 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 differences would occur by chance is less than or equal to 5 percent. Statistically significant results are bolded and the percent differences compared to CARB reference fuel are shown in red text in the tables. More detailed test results are provided in Appendix F.

4.1 NOx Emissions

The NOx emission results for the off-road legacy engine are presented in Figure 4-1 on a gram per brake horsepower hour (g/bhp-hr) basis. Table 4-1 shows the average emissions for each test fuel, and percentage differences and the associated p-values for statistical comparisons between the CARB reference fuel and the biofuels.

The R100 and R80/B20 fuels both showed statistically significant reductions for NOx compared to the CARB reference fuel. The R100 fuel resulted in the lowest NOx emissions, with a statistically significant reduction of 13% compared to the CARB reference fuel. The R80/B20 showed a statistically significant reduction of 11% for NOx emissions compared to the CARB reference fuel.

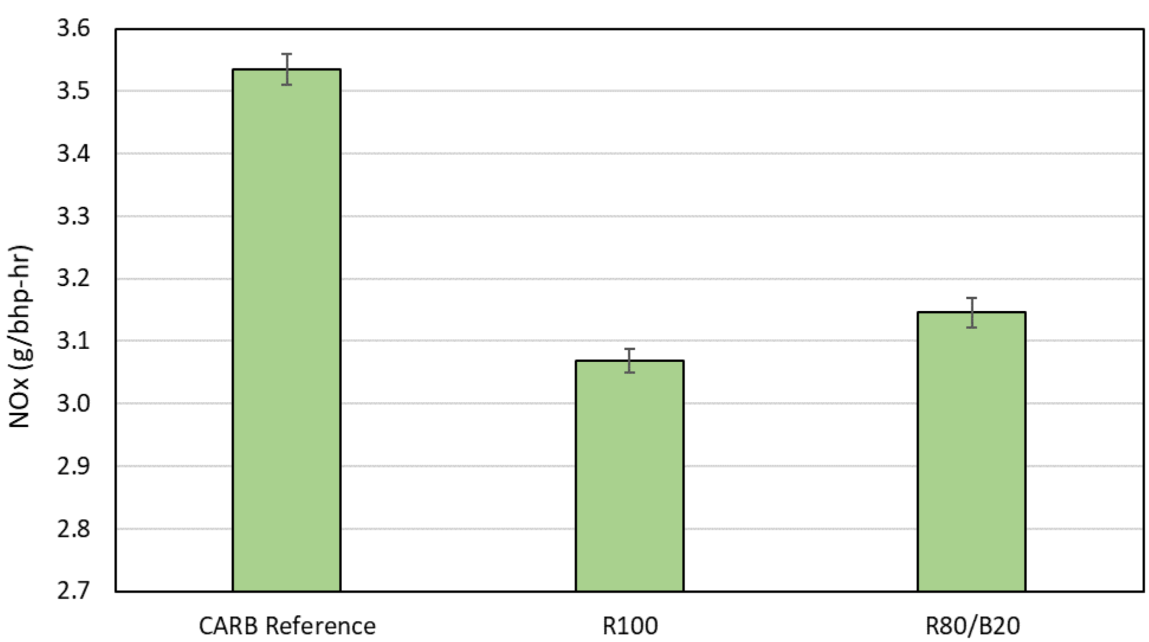

Figure 4-1. Average NOx Emission Results for the Off-Road Legacy Engine Testing Using the C1 Cycle

Table 4-1. NOx Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Using the C1 Cycle

Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
CARB reference fuel	3.53	-	-
R100	**3.07**	**-13**	**0.000**
R80/B20	**3.15**	**-11**	**0.000**

Statistically significant results are bolded and their percent differences are shown in red text.

4.2 PM2.5 Emissions

The PM2.5 emission results for the testing on the off-road legacy engine are presented in Figure 4-2 on a mg/bhp-hr basis. Table 4-2 shows the average emissions for each test fuel and test cycle, and percentage differences and the associated p-values for statistical comparisons between the CARB reference fuel and the biofuels.

The R100 and R80/B20 fuels both showed statistically significant PM2.5 reductions compared to the CARB reference fuel. The R100 showed a statistically significant reduction of 22% for PM2.5 mass emissions compared to the CARB reference fuel. The R80/B20 showed a statistically significant reduction of 29% compared to the CARB reference fuel.

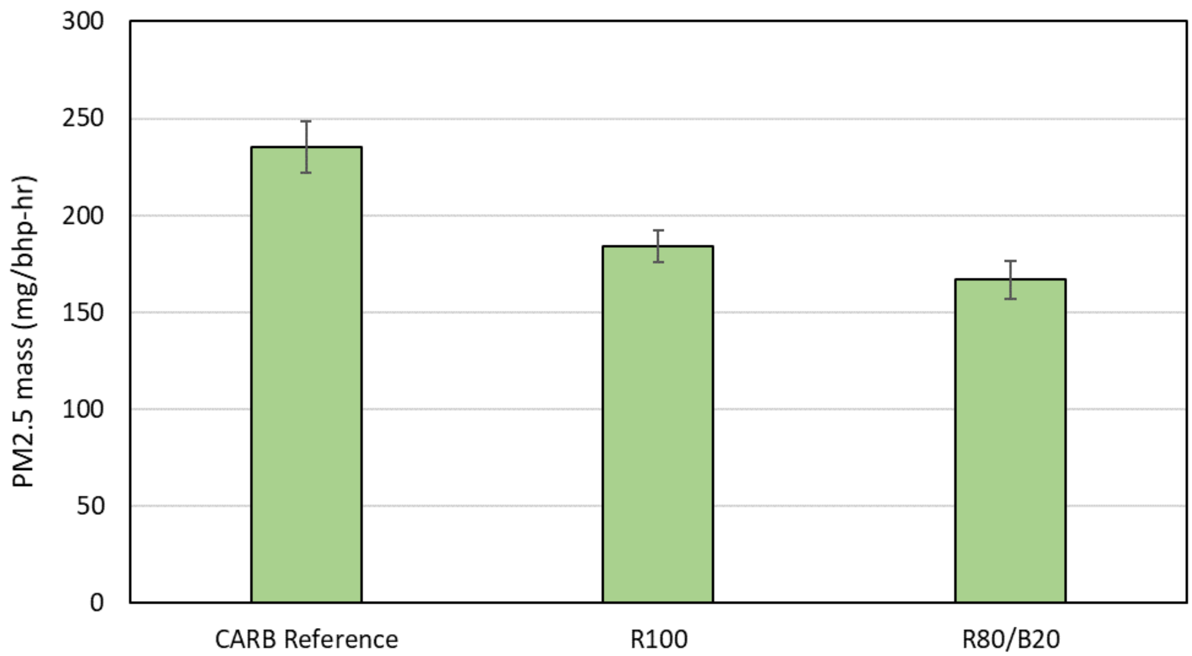

Figure 4-2. Average PM2.5 Emission Results for the Off-Road Legacy Engine Testing Using the C1 Cycle

Table 4-2. PM2.5 Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Using the C1 Cycle

Fuel Type	Ave. (mg/bhp-hr)	% Diff vs. CARB	p-value (t-test)
CARB reference fuel	235	-	-
R100	**184**	**-22**	**0.000**
R80/B20	**167**	**-29**	**0.000**

Statistically significant results are bolded and their percent differences are shown in red.

4.3 THC Emissions

The THC emission results for the testing on the off-road legacy engine are presented in Figure 4-3 on a g/bhp-hr basis. Table 4-3 shows the average emissions for each test fuel, and percentage differences and the associated p-values for statistical comparisons between the CARB reference fuel and the biofuels.

The R100 and R80/B20 fuels both showed THC reductions compared to the CARB reference fuel. The R100 showed a statistically significant reduction of 40% relative to the CARB reference fuel. The R80/B20 showed the lowest THC emissions, with a statistically significant reduction of 43%, compared to the CARB reference fuel.

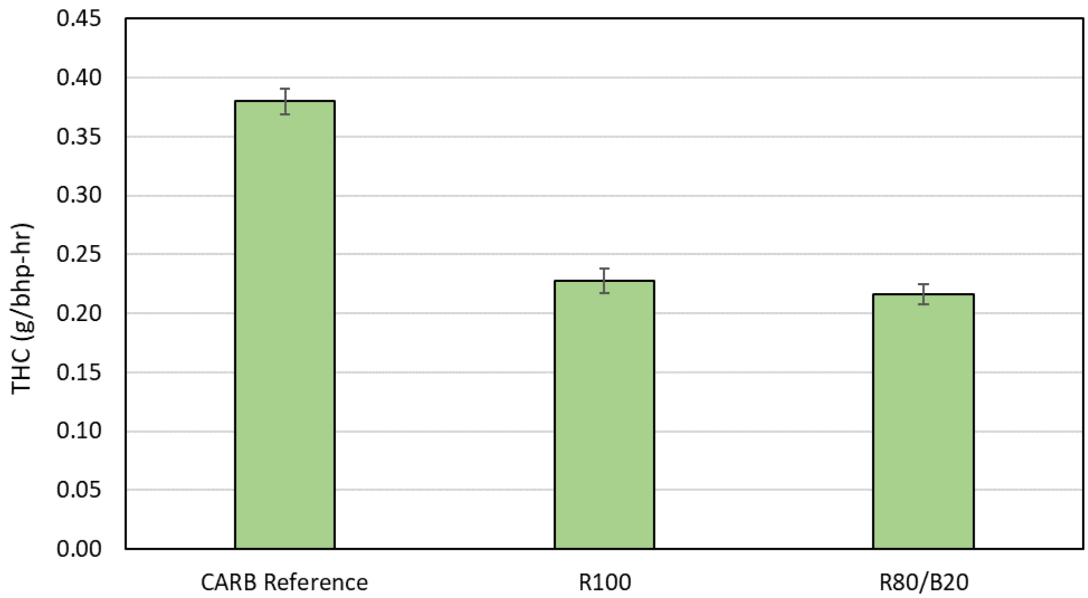

Figure 4-3. Average THC Emission Results for the Off-Road Legacy Engine Testing Using the C1 Cycle

Table 4-3. THC Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Using the C1 Cycle

Fuel Type	Ave. (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
CARB reference fuel	0.38	-	-
R100	**0.23**	**-40**	**0.000**
R80/B20	**0.22**	**-43**	**0.000**

Statistically significant results are bolded and their percent differences are shown in red text.

4.4 CO Emissions

The CO emission results for the testing on the off-road legacy engine are presented in Figure 4-4 on a g/bhp-hr basis. Table 4-4 shows the average emissions for each test fuel, and percentage differences and the associated p-values for statistical comparisons between the CARB reference fuel and the biofuels.

The R100 and R80/B20 fuels both showed CO reductions compared to the CARB reference fuel. The R100 showed the lowest CO emissions with a statistically significant reduction of 32% compared to the CARB reference fuel, whereas the R80/B20 showed a statistically significant reduction of 23% compared to the CARB reference fuel.

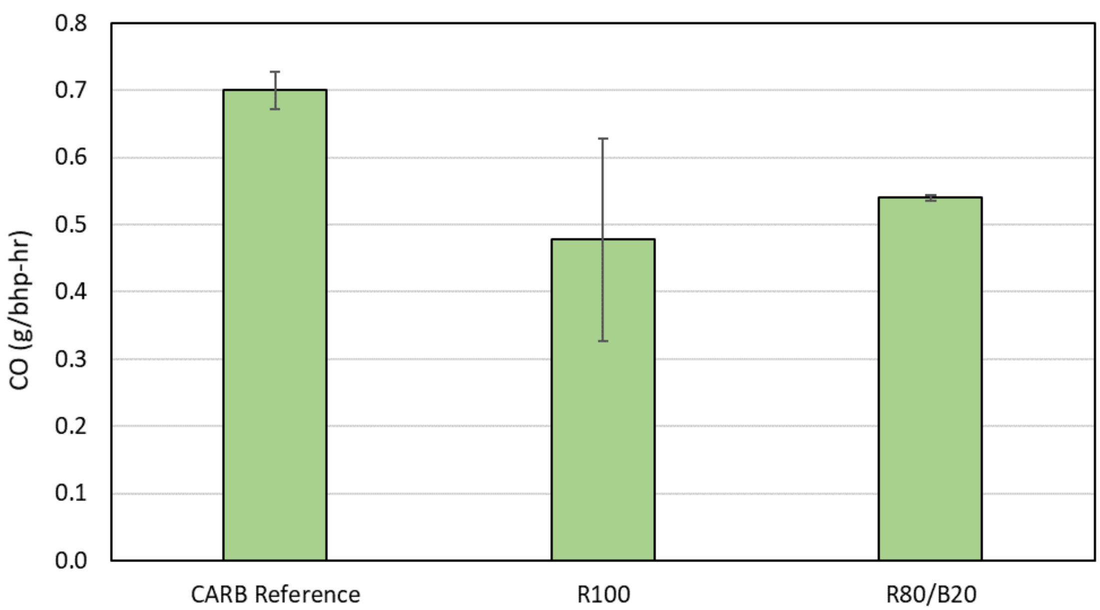

Figure 4-4. Average CO Emission Results for the Off-Road Legacy Engine Testing Using the C1 Cycle

Table 4-4. CO Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Using the C1 Cycle

Fuel Type	Ave. (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
CARB reference fuel	0.70	-	-
R100	**0.48**	**-32**	**0.005**
R80/B20	**0.54**	**-23**	**0.000**

Statistically significant results are bolded and their percent differences are shown in red text.

4.5 CO_2 Emissions

The CO_2 emission results for the testing on the off-road legacy engine are presented in Figure 4-5 on a g/bhp-hr basis. Table 4-5 shows the average emissions for each test fuel, and percentage differences and the associated p-values for statistical comparisons between the CARB reference fuel and the biofuels.

The R100 and R80/B20 fuels both showed statistically significant reductions of 2% in CO_2 compared to the CARB reference fuel.

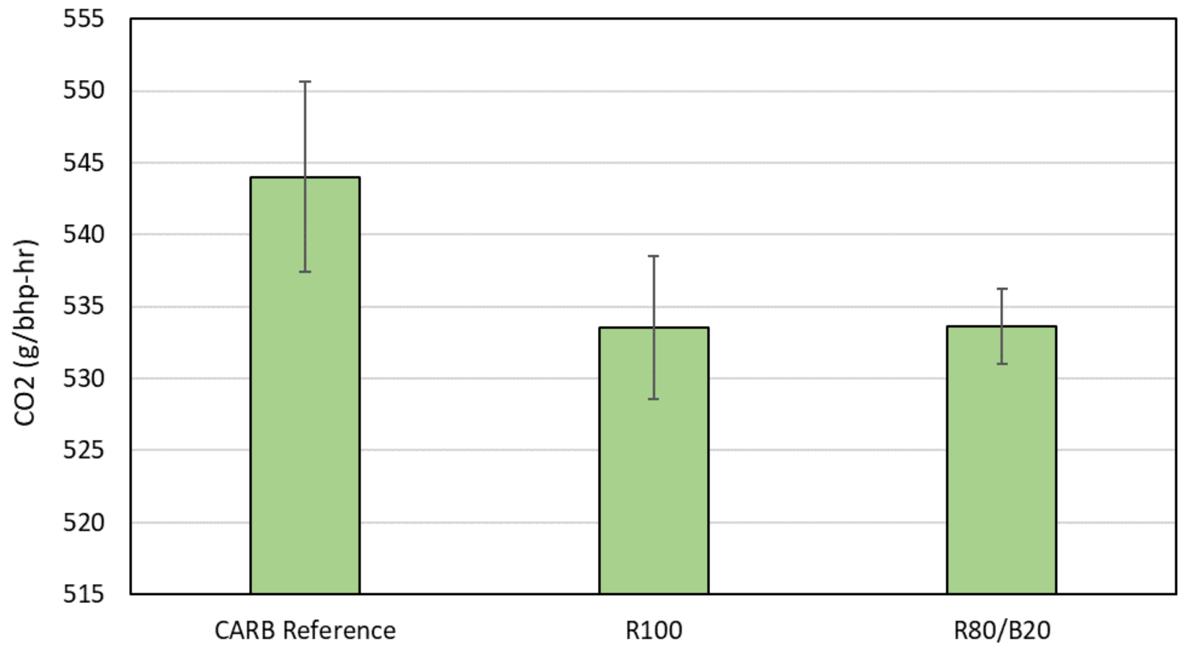

Figure 4-5. Average CO_2 Emission Results for the Off-Road Legacy Engine Testing Using the C1 Cycle

Table 4-5. CO_2 Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Using the C1 Cycle

Fuel Type	Ave. (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
CARB reference fuel	544	-	-
R100	**534**	**-2**	**0.012**
R80/B20	**534**	**-2**	**0.005**

Statistically significant results are bolded and their percent differences are shown in red text.

4.6 Brake Specific Fuel Consumption (BSFC)

The BSFC results for the off-road legacy engine are presented in Figure 4-6 on a gallons/bhp-hr basis. BSFC was calculated via the carbon balance method. Table 4-6 shows the average BSFC values for each test fuel, and percentage differences and the associated p-values for statistical comparisons between the CARB reference fuel and the biofuels.

The R100 and R80/B20 fuels both showed statistically significant increases of 6% in BSFC compared to the CARB reference.

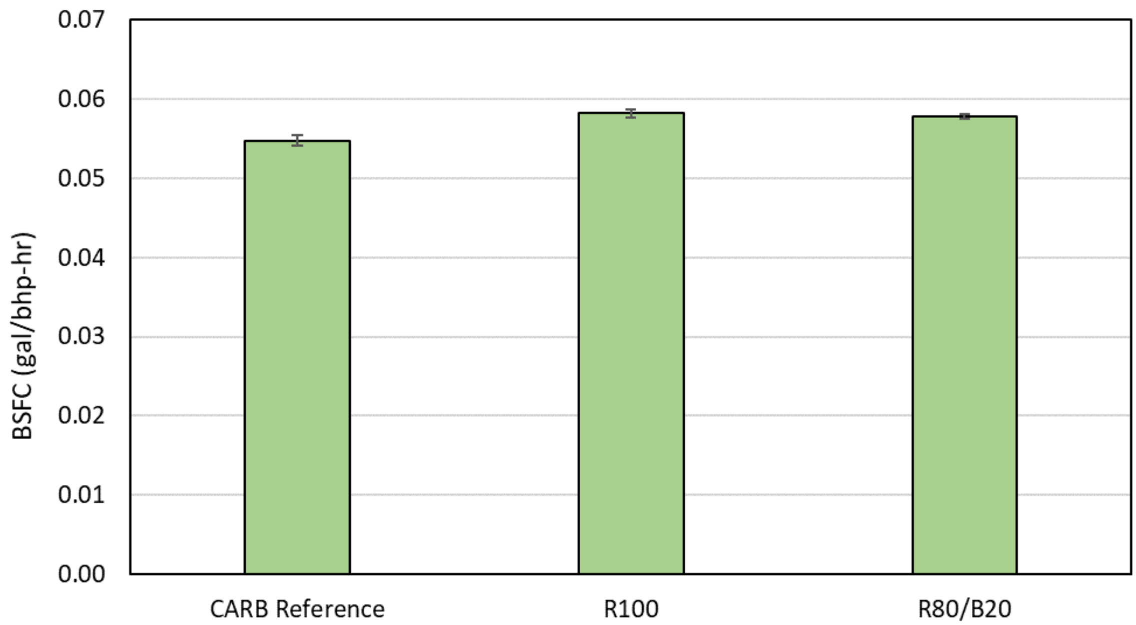

Figure 4-6. Average Brake Specific Fuel Consumption Results for the Off-Road Legacy Engine Testing Using the C1 Cycle

Table 4-6. BSFC (gal/bhp-hr), and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Using the C1 Cycle

Fuel Type	Ave. (gal/bhp-hr)	% Diff vs. CARB	p-value (t-test)
CARB reference fuel	0.055	-	-
R100	**0.058**	**6**	**0.000**
R80/B20	**0.058**	**6**	**0.000**

Statistically significant results are bolded and their percent differences are shown in red text.

4.7 Soot emissions

The soot emission results for the testing on the off-road legacy engine are presented in Figure 4-7 on a mg/bhp-hr basis. Table 4-7 shows the average emissions for each test fuel, and percentage differences and the associated p-values for statistical comparisons between the CARB reference fuel and the biofuels.

The R100 and R80/B20 fuels both showed soot reductions compared to the CARB reference fuel. The R100 showed a statistically significant reduction of 22% compared to the CARB reference fuel The R80/B20 showed the lowest soot emissions with a statistically significant reduction of 31% compared to the CARB reference fuel..

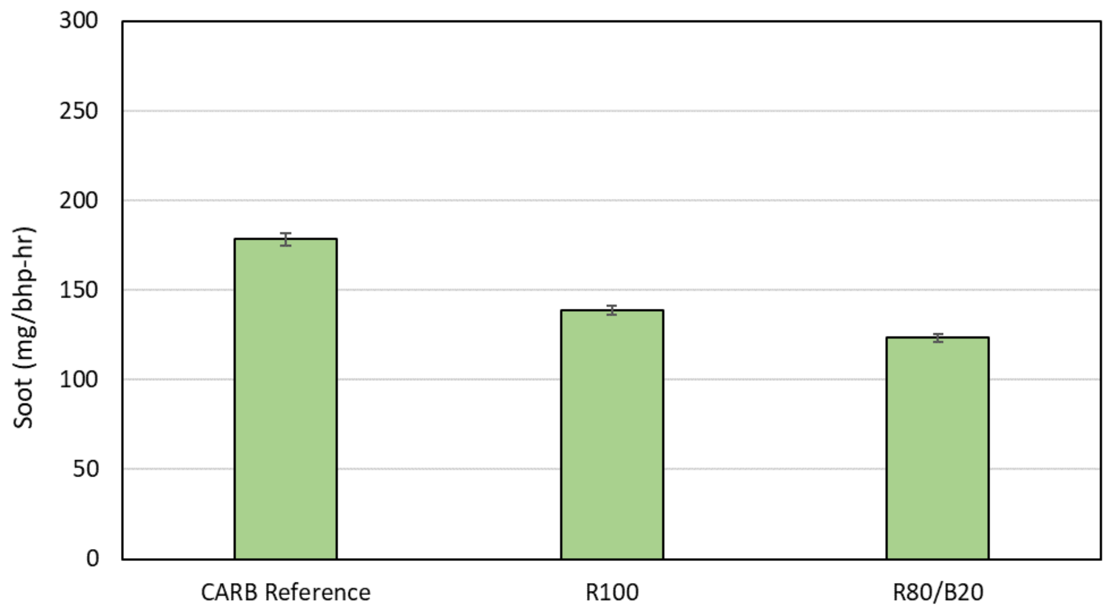

Figure 4-7. Average Soot Emissions for the Off-Road Legacy Engine Using the C1 Cycle

Table 4-7 Soot and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Testing Using the C1 Cycle

Fuel Type	Ave. (mg/bhp-hr)	% Diff vs. CARB	p-value (t-test)
CARB reference fuel	178	-	-
R100	**139**	**-22**	**0.000**
R80/B20	**123**	**-31**	**0.000**

Statistically significant results are bolded and their percent differences are shown in red text.

4.8 Solid Particle Number Emissions

Measurements of solid particle number (SPN) emissions were made for the off-road legacy engine. SPNs represent measurements of solid particles above 23 nm in diameter, as defined by the European Union solid particle number emissions regulations. SPN emissions in #/bhp-hr for each engine, fuel, and cycle are shown in Figure 4-8. Table 4-8 shows the average emissions for each test fuel, and percentage differences and the associated p-values for statistical comparisons between the CARB reference fuel and the biofuels.

The R100 showed a statistically significant 3% increase in SPN emissions compared to the CARB reference fuel. The R80/B20 showed a statistically significant 3% decrease in SPN emissions compared to the CARB reference fuel.

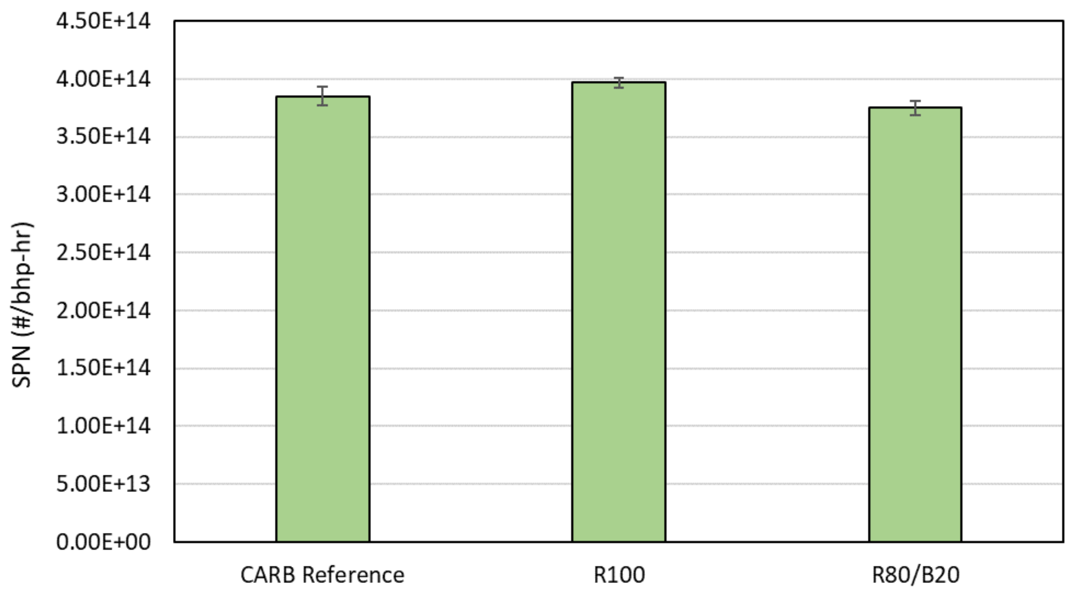

Figure 4-8. Average Solid Particle Number Emissions for the Off-Road Legacy Engine Using the C1 Cycle

Table 4-8. SPN Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Testing Using the C1 Cycle

Fuel Type	Ave. (#/bhp-hr)	% Diff vs. CARB	p-value (t-test)
CARB reference fuel	3.85E+14	-	-
R100	**3.97E+14**	**3**	**0.036**
R80/B20	**3.75E+14**	**-3**	**0.040**

Statistically significant results are bolded and their percent differences are shown in red text.

5 Summary and Conclusions

In an effort to improve the air quality in the San Joaquin Valley, CARB and U.S. EPA have implemented more stringent emissions regulations and have put in place incentive programs to replace older, higher-polluting engines with cleaner engines. Fuel switching from conventional, petroleum-based diesel to biomass-based diesels, including RD/BD blends, is an additional strategy that has the potential to NOx and PM2.5 emissions and contribute to meeting SIP goals in California. The purpose of this study is to quantify emissions and performance effects from RD and BD blends relative to conventional CARB ULSD reference fuel in an agricultural engine without SCR exhaust treatment and without a DPF using an engine dynamometer. For this study, a Tier 2 2006 model year legacy agriculture tractor engine was tested on a CARB reference diesel fuel, a pure RD (R100), and a blend of 80 percent RD with 20 percent BD (R80/B20). A summary of the results is provided below for each of the pollutants measured.

NOx Emissions

For the off-road legacy agriculture tractor engine, NOx emissions showed decreases for both the R100 and the R80/B20 fuels compared to the CARB reference fuel for the C1 cycle. The R100 fuel resulted in the lowest NOx emissions, with a statistically significant reduction of 13%, compared to the CARB reference fuel. The R80/B20 showed a statistically significant reduction of 11% for NOx emissions compared to the CARB reference fuel.

PM2.5 Emissions

For the off-road legacy agriculture tractor engine, PM2.5 emissions showed decreases for both the R100 and the R80/B20 fuels compared to the CARB reference fuel for the C1 cycle. The R100 showed a statistically significant reduction of 22% for PM2.5 mass emissions compared to the CARB reference fuel. The R80/B20 showed a statistically significant reduction of 29% compared to the CARB reference fuel.

THC Emissions

For the off-road legacy agriculture tractor engine, the R100 and R80/B20 fuels both showed THC reductions compared to the CARB reference fuel for the C1 cycle. The R100 showed a statistically significant reduction of 40% relative to the CARB reference fuel. The R80/B20 showed the lowest THC emissions, with a statistically significant reduction of 43% compared to the CARB reference fuel.

CO Emissions

For the off-road legacy agriculture tractor engine, the R100 and R80/B20 fuels both showed CO reductions compared to the CARB reference fuel for the C1 cycle. The R100 showed the lowest CO emissions with a statistically significant reduction of 32% compared to the CARB reference fuel, whereas the R80/B20 showed a statistically significant reduction of 23% compared to the CARB reference fuel.

CO_2 Emissions

For the off-road legacy agriculture tractor engine, for the C1 cycle, CO_2 emissions showed statistically significant reductions of 2% for both the R100 and R80/B20 compared to the CARB reference fuel.

Brake Specific Fuel Consumption (BSFC)

For the off-road legacy agriculture tractor engine, the R100 and R80/B20 fuels both showed statistically significant increases of 6% in BSFC compared to the CARB reference for the C1 cycle.

Soot

For the off-road legacy agriculture tractor engine, the R100 and R80/B20 fuels both showed soot reductions compared to the CARB reference fuel for the C1 cycle. The R100 showed a statistically significant reduction of 22% compared to the CARB reference fuel. The R80/B20 showed the lowest soot emissions with a statistically significant reduction of 31% compared to the CARB reference fuel.

Solid Particle Number Emissions

Measurements of SPN emissions greater than 23 nm in diameter, as defined by the European Union solid particle number emissions regulations, were also made. For this off-road legacy agriculture tractor engine, the R100 showed a statistically significant 3% increase in SPN emissions compared to the CARB reference fuel. The R80/B20 showed a statistically significant 3% decrease in SPN emissions compared to the CARB reference fuel.

Conclusions

For this off-road legacy agriculture tractor engine, the NOx emissions results from the C1 cycle are consistent with previously observed reductions in NOx emissions with R100 as the test fuel compared to the CARB reference fuel for legacy engines. When blended with biodiesel, namely R80/B20 in this test, NOx emissions were still solidly lower than those for the CARB reference fuel, although the emissions were slightly higher than those for the R100.

For this off-road legacy agriculture tractor engine, PM2.5 and soot emissions both showed decreases for both the R100 and R80/B20 fuels for the C1 cycle compared to the CARB reference fuel, with the R80/B20 showing the lowest PM2.5 and soot emissions. The lower PM2.5 and soot emissions for R100 and R80/B20 fuels are consistent with previous findings that biofuels can provide PM2.5 emissions reductions in legacy diesel engines.

Appendix A: CARB Reference Fuel Certificate of Analysis

haltermannsolutions

Certificate of Analysis

Telephone: (800) 969-2542 **FAX: (281) 457-1469**

PRODUCT: **CARB 48/10 ADF Reference Emissions Diesel Fuel, NBB-CARB Project**

Batch No.: HJ2521GP05

PRODUCT CODE: **HF2151**

Tank No.: TK96

Analysis Date: 11/20/2019

TEST	METHOD	UNITS	SPECIFICATIONS			RESULTS
			MIN	TARGET	MAX	
Distillation - IBP	ASTM D86	°F	340		420	396
5%		°F				429
10%		°F	400		490	436
20%		°F				449
30%		°F				462
40%		°F				473
50%		°F	470		560	486
60%		°F				499
70%		°F				512
80%		°F				531
90%		°F	550		610	559
95%		°F				580
Distillation - EP		°F	580		660	600
Gravity	ASTM D4052	°API	33		39	38.1
Flash Point	ASTM D93	°F	130			191
Viscosity, 40°C	ASTM D445	cSt	2.0		4.1	2.6
Sulfur	ASTM D5453	ppm wt			15	<1
Nitrogen	ASTM D4629[2]	ppm			10	5.8
Aromatic Hydrocarbon Content	ASTM D5186[2]	vol %			10	10.0
Polycyclic Aromatic Content	ASTM D5186[2]	wt %			1.4	1.2
Unadditized Cetane Number	ASTM D613[2]		48			48.4

Quality Assurance Technician

ANAB ACCREDITED ISO/IEC 17025 TESTING LABORATORY

[1] Haltermann Solutions is accredited to ISO/IEC 17025 by ANAB for the tests referred to with this footnote.

[2] Tested by ISO/IEC 17025 accredited subcontractor.

Appendix B: Southwest Research Institute Fuel Analysis Results

Table B-1. Fuel Analysis Results for R100

	Project Name		ODDB
	Lab Number		60206
	Sample Code		FS22002
Method			Renewable 100%
D1160	IBP	Deg C	
	05% AET	Deg C	
	10% AET	Deg C	
	20% AET	Deg C	
	30% AET	Deg C	
	40% AET	Deg C	
	50% AET	Deg C	
	60% AET	Deg C	
	70% AET	Deg C	
	80% AET	Deg C	
	90% AET	Deg C	
	95% AET	Deg C	
	FBP	Deg C	
	Pressure	mm Hg	
D287	API_60F	degAPI	49.1
	Specific Gravity	.	0.7835
	Density	g/ml	0.7831
D445 40c	Viscosity	cSt	2.980
D4629	Nitrogen	ppm	<1.0
D5186	Total Aromatics	Mass%	0.3
	MonoAromatics	Mass%	0.3
	PolyAromatics	Mass%	<0.1
D5291	Carbon	wt%	84.73
	Hydrogen	wt%	14.88
D5453	Sulfur	ppm	<0.5
D613	Cetane Number		>74.8
	Cetane Number		>74.8
	Cetane Number		>74.8
D86	PCorrIBP	degF	373.1
	PCorrD05	degF	481.1
	PCorrD10	degF	508.6
	PCorrD15	degF	521.7
	PCorrD20	degF	528.7
	PCorrD30	degF	538.3
	PCorrD40	degF	544.1
	PCorrD50	degF	548.1
	PCorrD60	degF	552.2
	PCorrD70	degF	556.2
	PCorrD80	degF	560.6
	PCorrD90	degF	567.3
	PCorrD95	degF	575.5
	PCorrFBP	degF	600.1
	Recoverd	mL	98.0
	Residue	mL	1.3
	Loss	mL	0.7
D93	Flash Point	degF	162.0
		degC	72.0
EN15751	Oxidation Stability		
	Run 1	hours	
	Run 2	hours	
	Average	hours	
EN14331	Ester Content	wt%	
	Methyl Linolenate	wt%	

Table B-2. Fuel Analysis Results for B100

	Project Name		ODDB
	Lab Number		60624
	Sample Code		FS22003
Method			Biodiesel 100%
D1160	IBP	Deg C	270
	05% AET	Deg C	336
	10% AET	Deg C	341
	20% AET	Deg C	345
	30% AET	Deg C	346
	40% AET	Deg C	348
	50% AET	Deg C	349
	60% AET	Deg C	349
	70% AET	Deg C	350
	80% AET	Deg C	351
	90% AET	Deg C	352
	95% AET	Deg C	354
	FBP	Deg C	357
	Pressure	mm Hg	10.0
D287	API_60F	degAPI	29.7
	Specific Gravity	.	0.8778
	Density	g/ml	0.8772
D445 40c	Viscosity	cSt	4.043
D4629	Nitrogen	ppm	12.7
D5291	Carbon	wt%	77.09
	Hydrogen	wt%	11.98
D5453	Sulfur	ppm	3.53
D613	Cetane Number		53.1
	Cetane Number		53.2
	Cetane Number		53.0
D93	Flash Point	degF	299.0
		degC	148.5
EN15751	Oxidation Stability		
	Run 1	hours	3.2
	Run 2	hours	3.1
	Average	hours	3.1
EN14331	Ester Content	wt%	94.1
	Methyl Linolenate	wt%	1.4

Table B-3. Fuel Analysis Results for R80/B20 Blend

	Project Name		ODDB
	Lab Number		60934
Method	Sample Code		FS22004
D287	API_60F	degAPI	45.0
	Specific Gravity	.	0.8017
	Density	g/ml	0.8012
D613	Cetane Number		71.1
	Cetane Number		71.2
	Cetane Number		71.3
D86	PCorrIBP	degF	392.0
	PCorrD05	degF	500.4
	PCorrD10	degF	522.7
	PCorrD15	degF	534.1
	PCorrD20	degF	541.9
	PCorrD30	degF	550.7
	PCorrD40	degF	556.9
	PCorrD50	degF	562.6
	PCorrD60	degF	568.5
	PCorrD70	degF	575.9
	PCorrD80	degF	586.5
	PCorrD90	degF	605.0
	PCorrD95	degF	628.3
	PCorrFBP	degF	651.0
	Recoverd	mL	98.1
	Residue	mL	1.4
	Loss	mL	0.5
EN14078	FAME Content	vol%	19.4

Appendix C: Laboratory Resources

CE-CERT Mobile Emissions Laboratory

Controlling emissions from heavy-duty diesel engines is a major priority for the regulatory community and industry. CE-CERT has worked with regulatory agencies, engine manufacturers, exhaust aftertreatment companies, fuel companies, and vehicle end users over the past two decades 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 in conjunction with engine or chassis dynamometer laboratories or under actual operating conditions (Figure C-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 be pulled by a class 8 tractor for over the road testing (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 C-1. Mobile Emissions Laboratory

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 U.S. EPA's National Vehicle and Fuels Emission Laboratory in Ann Arbor, MI. 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 C-2. CE-CERT's Heavy-Duty Engine Dynamometer Facility

Appendix D: QA/QC Procedures

Internal calibration and verification procedures are performed in MEL regularly in accordance with the 40 CFR Part 1065. 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 D-1.

Table D-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 E: Test Cycles

(2) The following duty cycle applies for ramped-modal testing:

RMC mode	Time in mode (seconds)	Engine speed [1,3]	Torque (percent) [2,3]
1a Steady-state	126	Warm Idle	0.
1b Transition	20	Linear Transition	Linear Transition.
2a Steady-state	159	Intermediate Speed	100.
2b Transition	20	Intermediate Speed	Linear Transition.
3a Steady-state	160	Intermediate Speed	50.
3b Transition	20	Intermediate Speed	Linear Transition.
4a Steady-state	162	Intermediate Speed	75.
4b Transition	20	Linear Transition	Linear Transition.
5a Steady-state	246	Maximum Test Speed	100.
5b Transition	20	Maximum Test Speed	Linear Transition.
6a Steady-state	164	Maximum Test Speed	10.
6b Transition	20	Maximum Test Speed	Linear Transition.
7a Steady-state	248	Maximum Test Speed	75.
7b Transition	20	Maximum Test Speed	Linear Transition.
8a Steady-state	247	Maximum Test Speed	50.
8b Transition	20	Linear Transition	Linear Transition.
9 Steady-state	128	Warm Idle	0.

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

Figure E-1. Test Points and Sequences for C1 for Off-Road Agricultural Engine

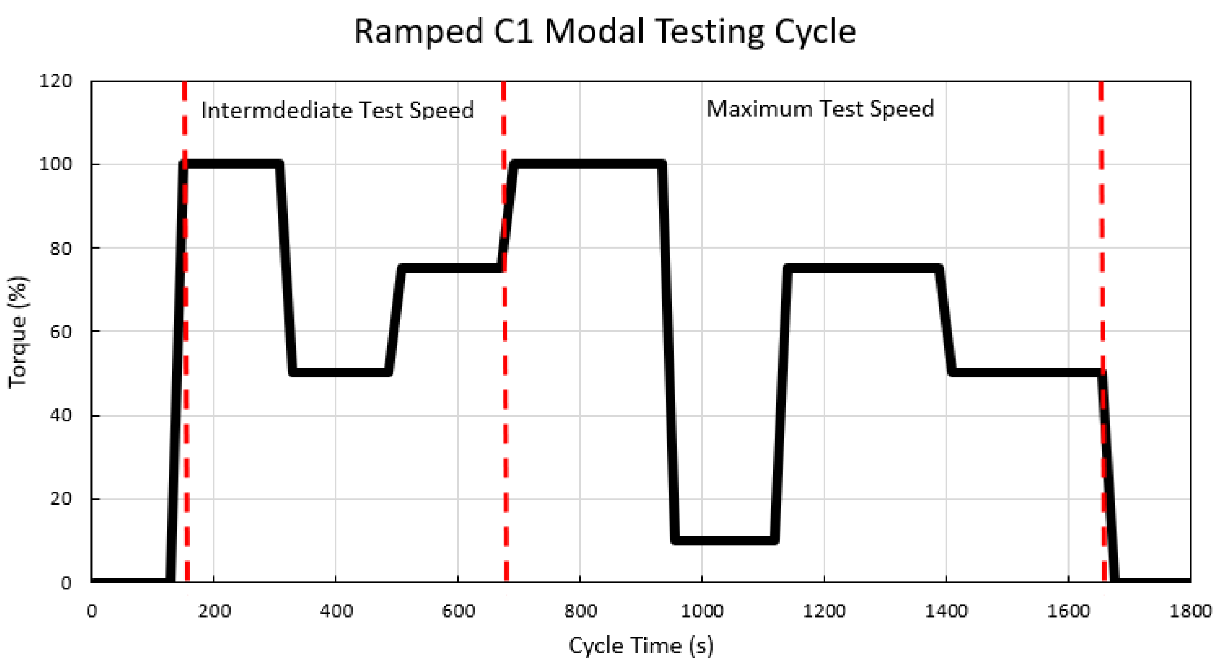

Figure E-2. Graphical Presentation of the C1 RMC for Off-Road Agricultural Engine

Appendix F: Detailed Emissions Test Results

Appendix F-1: Detailed Emissions Test Results for Legacy Off-Road Agriculture Tractor Engine - (Eight mode C1 Cycle)

File ID	Fuel	Work (bhp-hr)	CO (g/bhp-hr)	CO2 (g/bhp-hr)	THC (g/bhp-hr0	NOx (g/bhp-hr)	Soot (mg/bhp-hr)	F.C. (gal/bhp-hr)	PM2.5 (mg/bhp-hr)
202207270821	CARB Ref	23.8	0.72	549.7	0.38	3.56	183.19	0.055	242.56
202207270909	CARB Ref	23.6	0.73	554.0	0.39	3.53	178.42	0.056	222.04
202207271014	CARB Ref	23.8	0.72	543.4	0.39	3.49	174.99	0.055	216.09
202207291448	CARB Ref	23.7	0.67	539.7	0.38	3.53	176.07	0.054	250.09
202207291540	CARB Ref	23.6	0.68	540.9	0.37	3.54	181.57	0.054	244.54
202207291625	CARB Ref	23.7	0.68	536.4	0.36	3.55	175.81	0.054	236.67
202207280741	R100	23.2	0.60	533.5	0.21	3.04	135.12	0.058	174.72
202207280835	R100	23.0	0.63	541.4	0.23	3.06	139.54	0.059	178.79
202207280922	R100	23.0	0.61	537.4	0.23	3.05	135.49	0.059	176.44
202207301040	R100	23.1	0.34	529.9	0.24	3.08	141.42	0.058	190.23
202207301126	R100	22.9	0.33	530.8	0.24	3.09	141.01	0.058	192.15
202207301212	R100	22.8	0.34	528.4	0.22	3.08	139.68	0.058	192.35
202207281319	R80/B20	22.8	0.54	534.1	0.20	3.11	120.30	0.058	155.80
202207281411	R80/B20	22.8	0.54	531.0	0.21	3.12	120.78	0.058	159.47
202208010758	R80/B20	23.1	0.53	530.2	0.22	3.15	123.02	0.057	184.95
202208010853	R80/B20	22.9	0.54	536.5	0.23	3.16	123.98	0.058	165.96
202208010939	R80/B20	22.9	0.54	536.4	0.22	3.17	126.81	0.058	166.17
202208011034	R80/B20	22.8	0.55	533.3	0.22	3.16	124.62	0.058	168.15