Final Report

Low Emission Diesel (LED) Study: Biodiesel and Renewable Diesel Emissions in Legacy and New Technology Diesel Engines

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Abstract

For the purposes of this study, emissions and operation data using renewable diesel/biodiesel fuel blends and a petroleum-based reference California Air Resources Board (CARB) diesel will be gathered from a "legacy" (older) engine without a modern emissions control system, and two types of new technology diesel engines (NTDE), which are more current engines with emission control systems including selective catalytic reduction (SCR) and diesel particulate filters (DPF).

This study aims to:

1. Evaluate the NOx and PM emissions resulting from use of renewable diesel fuel and selected renewable diesel/biodiesel fuel blends in a legacy off-road engine.

2. Evaluate the NOx and PM emissions resulting from use of renewable diesel fuel and selected renewable diesel/biodiesel fuel blends in on-road and off-road NTDEs.

The three engines types were an off-road legacy engine, an on-road heavy-duty NTDE, and an off-road NTDE. The off-road legacy engine was a 2009 model year John Deere. The on-road NTDE was a 2019 Cummins engine, and the off-road NTDE was a 2018 Caterpillar engine. For this study, the emissions and performance effects of three renewable diesel/biodiesel blends – 100 percent renewable diesel (R100), 65 percent renewable diesel/35 percent biodiesel (R65/B35), and 50 percent renewable diesel/50 percent biodiesel (R50/B50) were tested in each engine against a petroleum-based CARB reference fuel (CARB reference fuel). The emissions test cycles for each test engine and fuel included an engine-appropriate transient cycle and an engine-appropriate steady state cycle.

Results and Conclusions:

NOx emissions in the legacy off-road engine for both cycles were reduced when using R100 fuel compared to the CARB reference fuel. There was no difference in NOx emissions for both cycles when compared to the CARB reference fuel for the R65/B35 blend (highest ratio of renewable diesel to biodiesel), while there were increased NOx emissions compared to the CARB reference fuel for the R50/B50 blends (lowest ratio of renewable diesel to biodiesel) for both transient and steady state cycles.

The results for this legacy engine are consistent with previously observed reductions in NOx emissions with R100 as the test fuel, and increased emissions of NOx from the use of biodiesel in fuel. They are also consistent with the observations that renewable diesel in a renewable diesel/biodiesel blend can reduce NOx emissions arising from the use of biodiesel, with the highest ratio of renewable diesel to biodiesel (R65/B35) in this study resulting in NOx emissions that were not significantly different from CARB reference fuel (also referred to as a NOx-neutral ratio), where the R50/B50 blend (the lowest ratio of renewable diesel to biodiesel) did result in higher NOx emissions than CARB reference fuel. Therefore, the renewable diesel in the R50/B50 blend did not sufficiently reduce NOx emissions from biodiesel such that emissions were NOx neutral, while the R65/B35 blend did result in NOx-neutral emissions.

PM emissions in the legacy off-road engine showed statistically significant reductions in comparison to the CARB reference fuel for all test biofuels and both cycles, with the greatest PM

reductions observed in the renewable diesel/biodiesel blends with the highest biodiesel concentrations, confirming previous observations that biodiesel does act to reduce PM emissions in legacy diesel engines.

NOx emissions from both NTDEs with R100 as the test fuel were not statistically different than the CARB reference fuel. NOx emissions in the renewable diesel/biodiesel blends were statistically higher than the CARB reference fuel for both NTDEs, with emissions increasing as the renewable diesel to biodiesel ratio decreased (i.e., biodiesel concentration increased and renewable diesel concentrations decreased), although the NOx emissions increases were not linear. These results indicate that in these particular NTDEs, equipped with state-of-the-art emissions control systems, NOx emissions resulting from the two renewable diesel/biodiesel blends tested (R65/B35 and R50/B50) were not completely controlled, i.e., were not NOx-neutral relative to CARB reference fuel, although the NOx emissions overall in the NTDE engines were orders of magnitude lower than those from the off-road legacy engine.

There were no statistical differences in PM emissions in the NTDEs observed in any test fuel or test cycle compared to the CARB reference fuel, indicating that PM emissions are effectively controlled by the exhaust aftertreatment systems, no matter the biofuel blend or test cycle.

Acronyms and Abbreviations

ADF .... Alternative Diesel Fuel
APC .... AVL particle counter
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
NRTC .... Nonroad Transient Cycle
NTDE .... new technology diesel engine
PEMS .... portable emissions measurement system
PM .... particulate matter
PN .... particle number
PSD .... particle size distribution
RMC .... Ramped Modal Cycle
QA .... quality assurance
QC .... quality control
THC .... total hydrocarbons
SCR .... selective catalytic reduction
SET .... Supplementary Emissions Test
SwRI .... Southwest Research Institute
UCR .... University of California Riverside
ULSD .... ultra-low sulfur diesel

Executive Summary

Background

The California Air Resources Board (CARB) must continue to reduce oxides of nitrogen (NOx) and particulate matter (PM) emissions from on-road and off-road diesel-powered vehicles and equipment, including on-road heavy-duty vehicles, off-road engines, stationary engines, portable engines, marine vessels and locomotives, as part of the California's State Implementation Plan.[1] Past studies have indicated that fuels such as renewable diesel, NOx-mitigated biodiesel, renewable diesel/biodiesel blends, cleaner refined diesel, gas to liquid diesel, and compressed natural gas can reduce NOx and/or PM emissions relative to conventional diesel.

Objectives and Methods

This study seeks to further characterize the emissions and performance effects of renewable diesel and renewable diesel/biodiesel blends in legacy engines (i.e., engines without selective catalytic reduction (SCR) exhaust treatment and diesel particulate filters (DPF) – also known as non-new technology diesel engines (non-NTDE)) – and in new technology diesel engines (NTDE). For the purposes of this study, NTDEs are defined as engines with SCR and DPF exhaust aftertreatment systems. Emissions are generally reported in grams/brake horsepower-hour (g/bhp-hr) unless otherwise noted. This study aims to:

1. Evaluate the NOx and PM emissions resulting from use of renewable diesel fuel and selected renewable diesel/biodiesel fuel blends in a legacy off-road engine.

2. Evaluate the NOx and PM emissions resulting from use of renewable diesel fuel and selected renewable diesel/biodiesel fuel blends in on-road and off-road NTDEs.

To achieve the objectives above, emissions testing was conducted using a renewable diesel fuel and renewable diesel/biodiesel blends using an engine dynamometer with an off-road legacy engine, a heavy-duty on-road NTDE, and an off-road NTDE. Performance testing was also conducted to measure changes in fuel economy.

Test Fuels

The test fuels included a CARB reference fuel (a petroleum-based, ultra-low sulfur diesel meeting ASTM 975 specifications and the properties in Table A.9 of the Alternative Diesel Fuel (ADF) regulation) as a baseline fuel, a neat (100 percent or 99 percent) renewable diesel fuel (R100/R99 – referred to as R100 in this study – meeting ASTM975 specifications and Table A.9 of the ADF regulation), a blend of 65 percent renewable diesel and 35 percent biodiesel (R65/B35) with neat biodiesel meeting ASTM6751 and Table A.8 of the ADF regulation, and a blend of 50 percent renewable diesel and 50 percent biodiesel (R50/B50).

[1] CARB. 2017. Revised Proposed 2016 State Strategy for the State Implementation Plan. March 7. Available at: https://www.arb.ca.gov/planning/sip/2016sip/rev2016statesip.pdf. Accessed: January, 2017.

Test Engines

There were three test engines used in the study: an off-road legacy engine, an on-road heavy-duty NTDE, and an off-road NTDE, as shown in Table ES-1. The selected off-road legacy engine was a John Deere 4045HF285 engine that has been used in previous biodiesel and renewable diesel engine testing conducted by University of California, Riverside (UCR) Bourns College of Engineering-Center for Environmental Research and Technology (CE-CERT) and CARB.[2] The on-road heavy-duty and off-road NTDEs were late-model engines to ensure that the engines were equipped with the most advanced emissions control technology currently available, including SCR and DPF. The on-road heavy-duty NTDE was a Cummins engine. Cummins engines are a staple of the California diesel engine market in Class 7 or Class 8 trucks. The off-road NTDE was a Caterpillar engine, which represents one of the most common engines in the off-road equipment category in California. The table below is a summary of the engines' characteristics:

Table ES-1. General Description of Test Engines

No.	Engine Type	SCR-Equipped?	DPF-Equipped?	HP	Model Year	Vocation	Manufacturer
1	Off-Road Legacy	No	No	115	2009	Construction	John Deere
2	On-Road Heavy-Duty NTDE	Yes	Yes	450	2019	T7 or T8 Truck	Cummins
3	Off-Road NTDE	Yes	Yes	225	2018	Industrial Off-road	Caterpillar

Test Procedures

The test cycles used for this program included the Federal Test Procedure (FTP), the Non-Road Transient Cycle (NRTC), and steady state Ramped Modal Cycles (RMC). The NRTC is the transient test used in the engine certification procedure for off-road diesel-fueled engines, and the FTP is the transient test used for engine certification for heavy-duty diesel fueled on-highway engines. The RMCs are steady state cycles used in engine certification for both on-highway and off-road engines, with different steady state cycles used for the different engines. For the John Deere off-road legacy engine, a five-mode D2 ISO 8718 steady state cycle was utilized (D2 cycle), which is the cycle typically used for certification of constant speed off-road engines.[3] For the Cummins on-road heavy-duty NTDE, a 13-mode, Supplementary Emissions Test (SET) RMC steady state cycle was used, as is used in the federal certification of this engine. For the Caterpillar off-road NTDE, an eight-mode C1 ISO 8718 steady state cycle was used (C1 cycle), which is the cycle typically used for certification of variable speed off-road engines.

The engine emissions testing was performed at the UCR's college of Engineering-Center for Environmental Research and Technology's (CE-CERT) heavy-duty engine dynamometer

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[2] Durbin et al. 2011. CARB Assessment of the Emissions from the Use of Biodiesel as a Motor Vehicle Fuel in California, "Biodiesel Characterization and NOx Mitigation Study," Final Report. October. Available at: https://www.arb.ca.gov/fuels/diesel/altdiesel/20111013_CARB%20Final%20Biodiesel%20Report.pdf.

[3] https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-data-vehicles-engines-and-equipment.

laboratory. This engine dynamometer test laboratory is equipped with a 600-hp General Electric DC electric engine dynamometer.

Emissions of NOx, PM, non-methane hydrocarbons (NMHC), total hydrocarbons (THC), carbon monoxide (CO), and carbon dioxide (CO_2) were measured during all tests, along with a determination of fuel consumption made via carbon balance. The emissions measurements were made using the standard analyzers in 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 ≤ 0.05 using a 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. Comparisons where $0.05 \leq p$ values < 0.1 were considered marginally statistically significant for this report, and are also noted in the text. Statistically significant results are bolded and the percent difference compared to CARB reference fuel is shown in red text in the tables. It should be noted that for the on-road heavy-duty NTDE, a subset of outlier tests were observed over the FTP that were not included in the data presented in the Executive Summary. These data are discussed in greater detail in Appendix A.

NOx Emissions

Average NOx emissions, and percentage differences and statistical comparisons between the test biofuels and CARB reference diesel for the off-road legacy engine are shown in Table ES-2. For the off-road legacy engine, NOx emissions were lower for the R100 fuel than those from the CARB reference fuel for both the NRTC and D2 cycles. The R100 fuel showed statistically significant NOx reductions of 5.4% for the NRTC and 4.9% for the D2 cycle. The R65/B35 blend showed no statistically significant difference compared to the CARB reference fuel for either the NRTC or D2 cycles. The R50/B50 showed statistically significant increases in NOx emissions of 1.8% for the NRTC and 4.2% for the D2 cycle in comparison to the CARB reference fuel.

Table ES-2. NOx Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine

Cycle	Fuel Type	Ave. NOx Emissions (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	2.09	-	-
	R100	**1.98**	**-5.4**	**0.00**
	R65/B35	2.07	-1.2	0.18
	R50/B50	**2.13**	**1.8**	**0.05**
D2	CARB reference fuel	2.01	-	-
	R100	**1.91**	**-4.9**	**0.00**
	R65/B35	2.01	0.0	0.97
	R50/B50	**2.09**	**4.2**	**0.02**

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

Average NOx emissions, and percentage differences and statistical comparisons between the test biofuels and CARB reference diesel for the on-road heavy-duty NTDE are shown in Table ES-3. For the on-road NTDE, no statistically significant NOx emissions differences were found between the CARB reference fuel and R100 for either the FTP or RMC cycles. The FTP cycle showed statistically significant increases of 46.6% for R65/B35 and 49.5% for R50/B50. The RMC cycle showed statistically significant increases of 14.2% for R65/B35 and 15.4% for R50/B50. Engine out NOx sensor data for the RMC cycle showed that there are increases in engine out NOx levels for the biodiesel blends, which is likely a key factor contributing to the higher tailpipe emissions for the renewable diesel/biodiesel blends. Comparison of the engine out and tailpipe out (after emissions control system) NOx data showed that the SCR provided a 95% to 96% reduction in NOx emissions for the different fuels.

Table ES-3. NOx Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the On-Road NTDE

Cycle	Fuel Type	NOx Emissions (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
FTP	CARB reference fuel	0.11	-	-
	R100	0.12	4.8	0.34
	R65/B35	**0.16**	**46.6**	**0.00**
	R50/B50	**0.17**	**49.5**	**0.00**
RMC	CARB reference fuel	0.13	-	-
	R100	0.14	2.3	0.19
	R65/B35	**0.15**	**14.2**	**0.00**
	R50/B50	**0.15**	**15.4**	**0.00**

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

Average NOx emissions, and percentage differences and statistical comparisons between the test biofuels and CARB reference diesel for the off-road NTDE are shown in Table ES-4. For the off-road NTDE testing, NOx emissions showed no statistically significant differences between R100 and the CARB reference fuel for either test cycle. For the NRTC cycle, statistically significant increases of 88.3% for the R65/B35 blend and 146.9% for the R50/B50 blend were observed. For the C1 cycle, statistically significant increases of 55.1% for the R65/B35 blend and 119.4% for the R50/B50 blend were observed.

The engine-out data for the off-road NTDE did not show any statistically significant differences between the R100 and the CARB reference fuel for either cycle. The engine out data show consistently higher and statistically significant increased NOx emissions for the R65/B35 blends and the R50/B50 fuels blends compared with the CARB reference fuel for both cycles. Comparison of the engine out and tailpipe NOx data showed that the SCR provided NOx reduction efficiencies of 93% for the CARB reference fuel, 91% for R100, 88% for R65/B35, and 85% for R50/B50. The SCR provided NOx reductions of 98% to 99% for all fuels for the C1 cycle.

Table ES-4. NOx Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road NTDE

Cycle	Fuel Type	NOx Emissions (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	0.18	-	-
	R100	0.22	20.1	0.11
	R65/B35	**0.34**	**88.3**	**0.00**
	R50/B50	**0.45**	**146.9**	**0.00**
C1	CARB reference fuel	0.014	-	-
	R100	0.015	10.5	0.56
	R65/B35	**0.021**	**55.1**	**0.01**
	R50/B50	**0.030**	**119.4**	**0.01**

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

PM Emissions

Average PM emissions, and percentage differences and statistical comparisons between the test biofuels and CARB reference fuel for the off-road legacy engine are presented in Table ES-5. PM emissions decreases were observed for the renewable diesel and the renewable diesel/biodiesel blends for both the NRTC and the D2 cycles. The reductions for the NRTC when compared to the CARB reference fuel were 38% for R100, 53% for R65/B35, and 63% for R50/B50. The reductions for the D2 compared to the CARB reference fuel were 27% for R100, 51% for R65/B35, and 58% for R50/B50.

Table ES-5. Average PM emissions, and Percentage Differences and Statistical Comparisons Between the Test Biofuels and CARB Reference Fuel for the Off-Road Legacy Engine

Cycle	Fuel Type	PM Emissions (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference diesel	0.061	-	-
	R100	**0.038**	**-38**	**0.00**
	R65/B35	**0.028**	**-53**	**0.00**
	R50/B50	**0.023**	**-63**	**0.00**
D2	CARB reference diesel	0.052	-	-
	R100	**0.038**	**-27**	**0.00**
	R65/B35	**0.025**	**-51**	**0.00**
	R50/B50	**0.022**	**-58**	**0.00**

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

For the on-road NTDE, PM mass emissions in general were low and near background levels, and averaged less than 0.001 g/bhp-hr for all tests conditions and both cycles. As the PM standard for heavy-duty on-road engines is 0.01 g/bhp-hr, the PM emissions observed are for the most part at least 20-fold lower than the PM standard. The PM emissions for the different fuels generally did not show statistically significant differences, with the exception of the R50/B50, which had emissions that were lower than those for the CARB reference fuel at a marginally statistically significant level over the FTP cycle.

For the off-road NTDE, PM mass emissions were more than a factor of 30 below the 0.015 g/bhp-hr PM standard for Tier 4 off-road engines in this size category for all test conditions and both cycles. No statistically significant differences in PM mass emissions were seen between fuels for either test cycle.

Total Hydrocarbon (THC) Emissions

For the off-road legacy engine, THC emissions showed significant decreases for renewable diesel and the renewable diesel/biodiesel blends for both the NRTC and D2 cycles. The reductions for the NRTC compared to the CARB reference fuel were 45% for R100, 49% for R65/B35, and 66% for R50/B50. The reductions for the D2 cycle compared to the CARB reference fuel were 35% for R100, 58% for R65/B35, and 71% for R50/B50.

For the on-road NTDE, THC emissions were near or below background levels for all tests conditions and both cycles. For the FTP, only R50/B50 showed a statistically significant reduction relative to the CARB reference fuel, with R100 and R65/B35 showing no statistically significant differences in THC emissions relative to the CARB reference fuel. For the RMC cycle, THC emissions levels were below the background levels for all tests, and hence there were no measurable THC emissions.

For the off-road NTDE, THC emissions were below the background levels for both the NRTC and C1 cycles and for all fuels. Therefore, there were no statistically significant differences in THC emissions relative to the CARB reference fuel.

CO Emissions

For the off-road legacy engine, CO emissions showed statistically significant decreases for the renewable diesel and the renewable diesel/biodiesel blends for both the NRTC and D2 cycles. The reductions for the NRTC compared to the CARB reference fuel were 22% for R100, 26% for R65/B35, and 32% for R50/B50. The reductions for the D2 cycle compared to the CARB reference fuel were 14% for R100, 28% for R65/B35, and 32% for R50/B50.

For the on-road NTDE, the FTP showed no statistically significant changes in CO emissions for any of the test biofuels relative to the CARB reference fuel. The RMC showed a slight reduction of 5% with R100, with no statistical difference in CO emissions observed with the R65/B35 and R50/B50 blends.

For the off-road NTDE, for the NRTC, measurable, but low CO emissions were found for the CARB reference fuel and R100. The NRTC CO emissions for the R100 fuel were 44% lower than those for the CARB reference fuel. The NRTC CO emissions for the R65/B35 and R50/B50 fuels were much lower than those for the CARB reference fuel and R100 fuels, and were near or below the background levels for all tests. For the C1 cycle, CO emissions were near or below background levels for all tests.

CO_2 Emissions

For the off-road legacy engine, statistically significant reductions in CO_2 emissions from the NRTC of 4.1% for R100, 2.6% for R65/B35, and 1.7% for R50/B50 were observed in comparison to the CARB reference fuel. For the D2 cycle, the R100 showed a statistically significant reduction in CO_2 emissions of 4.6% compared to the CARB reference fuel, while the R65/B35 and R50/B50 fuels did not show statistically significant differences compared to the CARB reference fuel.

For the on-road NTDE, CO_2 emissions from the FTP showed statistically significant decreases of 3.2% for R100, 0.9% for R65/B35, and 0.8% for R50/B50 compared to the CARB reference fuel. The steady state cycle showed statistically significant decreases of 2.9% for R100 and 0.5% for R65/B35, and a marginally statistically significant increase of 0.3% for R50/B50 compared to the CARB reference fuel.

For the off-road NTDE, CO_2 emissions showed statistically significant reductions for the R100 of 3.8% for the FTP and of 3.0% for the D2 cycle compared to the CARB reference fuel. CO_2 emissions did not show statistically significant differences for the R65/B35 and R50/B50 fuels compared to the CARB reference fuel for either the NRTC or C1 cycles.

Brake Specific Fuel Consumption (BSFC)

For the off-road legacy engine, BSFC, measured in gallons/bhp-hr, showed statistically significant increases in the NRTC ranging from 3.5% for R100, 3.8% for R65/B35, and 4.4% for R50/B50 fuels compared to the CARB reference fuel. For the D2 cycle, there was no statistically significant change in BSFC for R100. For the D2 cycle, the R65/B35 showed a statistically significant BSFC increase of 4.5% and the R50/B50 showed a marginally statistically significant BSFC increase of 3.4% compared to the CARB reference fuel.

For the on-road NTDE, BSFC for the transient cycle showed statistically significant increases in fuel consumption per bhp-hr for all of the biofuels, ranging from 4.8% for R100, 6.0% for R65/B35, and 57% for R50/B50. The steady state cycle also showed statistically significant increases in fuel consumption for all of the biofuels, ranging from 5.1% for R100, 6.6% for R65/B35, and 7.0% for R50/B50 when compared to the CARB reference fuel.

For the off-road NTDE, BSFC showed statistically significant increases for the NRTC BSFC ranging from 4.1% for R100, 5.8% for R65/B35, and 6.1% for the R50/B50 fuels compared to the CARB reference fuel. For the C1 cycle, BSFC showed statistically significant increases ranging from 5.0% for R100, 5.1% for R65/B35, and 5.2% for the R50/B50 fuels when compared to the CARB reference fuel.

Total and Solid Particle Number Emissions

As diesel particulate emissions have been shown to result in adverse health impacts, some additional particle measurements were included in this study to characterize particulate emissions in regard to biofuels. The number of particles is especially important given the fact that a measurement of total mass gives no indication as to the relative count of fine particles compared to the larger particles. Clinical and toxicological studies have shown that ultrafine particles (less than 100 nm diameter) can act through mechanisms not shared with larger particle sizes.[4,5] Measurements of total particle number (TPN) (greater than 3 nm diameter) and solid particle number (SPN) emissions were made for the off-road legacy engine and the on-road NTDE. SPN represents the number of solid particles greater than 23 nm in diameter (equivalent to 0.023 microns, as compared to the common 2.5 micron (PM2.5) metric for fine particulate air pollution), as defined by the European Union solid particle number emissions regulations. For both engines, the biofuels showed reductions in both TPN and SPN emissions, with the exception of TPN for R100 for the legacy off-road engine D2 cycle, which also showed a relatively large measurement variability. TPN and SPN emissions for both engines were seen in lower concentrations for the higher biodiesel blends relative to R100 and CARB reference fuel. These trends are consistent with those seen for the PM mass for the off-road legacy engine, where the PM mass emissions are well above the background levels.

Particle Size Distributions

Diesel-generated combustion particles are typically divided in three modes, nucleation mode (5-50 nm diameter), accumulation mode (50-1,000 nm diameter), and coarse mode (1,000-10,000 nm diameter). The nucleation mode typically consists of organic volatile compounds and can contain

[4]Solid Particle Number Emission Factors of Euro VI Heavy-Duty Vehicles on the Road and in the Laboratory Int J Environ Res Public Health. 2018 Feb; 15(2): 304.
Published online 2018 Feb 9. doi: 10.3390/ijerph15020304, Barouch Giechaskiel
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5858373/.
[5] Review of evidence on health aspects of air pollution – REVIHAAP Project Technical Report, WHO 2013, https://apps.who.int/iris/bitstream/handle/10665/341712/WHO-EURO-2013-2663-42419-58845-eng.pdf?sequence=1.

ash and soot particles. Most soot particles agglomerate, however, and are usually found in the accumulation mode. Coarse mode particles are typically from larger soot particles breaking off of the exhaust walls.

For the off-road legacy engine, the R100, R65/R35, and R50/B50 fuels showed reductions in particle counts per bhp-hr over most of the particle size range compared to the CARB reference fuel for both cycles. These reductions were most significant for the larger particles in the accumulation mode, although reductions were also found in the nucleation mode size range, peaking around 30 nm for most of the biofuels relative to the CARB reference fuel. The R100 showed higher particle counts than the R65/B35 and R50/B50 fuels in the nucleation mode size range for both cycles and in the accumulation mode particle size range for the NRTC.

For the on-road NTDE, nucleation mode particles were about an order of magnitude lower than those measured for the off-road legacy engine. Surprisingly, the R65/B35 fuel showed the highest emissions for the FTP cycle, but also showed large measurement variability. Over the full test matrix, however, the use of biofuel blends generally resulted in lower particle counts in the different size ranges compared to the CARB reference fuel.

Conclusions

For NOx emissions, the results for this legacy engine are consistent with previously observed reductions in NOx emissions with R100 as the test fuel, and increased emissions of NOx from the use of biodiesel in fuel. They are also consistent with the observations that renewable diesel in a renewable diesel/biodiesel blend can reduce NOx emissions arising from the use of biodiesel, with the highest ratio of renewable diesel to biodiesel (R65/B35) in this study resulting in NOx emissions that were not significantly different from CARB reference fuel (also referred to as a NOx-neutral ratio), while the R50/B50 blend (the lowest ratio of renewable diesel to biodiesel) did result in higher NOx emissions than CARB reference fuel. Therefore, the renewable diesel in the R50/B50 blend did not sufficiently reduce NOx emissions from biodiesel such that emissions are NOx neutral, while the R65/B35 blend did result in NOx-neutral emissions.

NOx emissions from both NTDEs with R100 as the test fuel were not statistically different than the CARB reference fuel. NOx emissions in the renewable diesel/biodiesel blends were statistically higher than the CARB reference fuel for both NTDEs, with emissions increasing as the biodiesel to renewable diesel ratio increased (i.e., biodiesel concentration increased and renewable diesel concentrations decreased), although the NOx emissions increases were not linear. These results indicate that in these particular NTDEs, equipped with state-of-the-art emissions control systems, NOx emissions resulting from the two renewable diesel/biodiesel blends tested (R65/B35 and R50/B50) were not completely controlled, i.e., NOx-neutral relative to CARB reference fuel, although the NOx emissions overall in the NTDE engines were orders of magnitude lower than those from the legacy engine.

PM emissions in the legacy off-road engine showed statistically significant reductions in comparison to the CARB reference fuel for all test biofuels and both cycles, with the greatest PM reductions observed in the blends with the lowest renewable diesel/biodiesel ratios (highest biodiesel concentrations), confirming previous observations that biodiesel does act to reduce PM emissions in legacy diesel engines. There were no statistical differences in PM emissions in the

NTDEs observed in any test fuel or test cycle compared to the CARB reference fuel, indicating that PM emissions are effectively controlled by the exhaust aftertreatment systems, no matter the biofuel blend or test cycle.

1 Introduction

The California Air Resources Board (CARB) must continue to reduce oxides of nitrogen (NOx) and particulate matter (PM) emissions from on-road and off-road diesel-powered vehicles and equipment, including on-road heavy-duty vehicles, off-road engines, stationary engines, portable engines, marine vessels and locomotives, as part of the California's State Implementation Plan.[6] Past studies have indicated that fuels such as renewable diesel, NOx-mitigated biodiesel, renewable diesel/biodiesel blends, cleaner refined diesel, gas to liquid diesel, and compressed natural gas (CNG) can reduce NOx and/or PM emissions relative to diesel.

This study seeks to further characterize the emissions and performance effects of renewable diesel and renewable diesel/biodiesel blends in both legacy engines (i.e., engines without selective catalytic reduction (SCR) exhaust treatment and diesel particulate filters (DPF)) and in new technology diesel engines (NTDE). For the purposes of this study, NTDEs are defined as engines with SCR and DPF exhaust treatment.

CARB, in conjunction with researchers from the University of California at Riverside's (UCR) Bourns College of Engineering-Center for Environmental Research and Technology (CE-CERT), the University of California, Davis (UCD), and others, implemented a study ("joint study") to characterize the emissions impacts of biodiesel and renewable diesel, relative to CARB ULSD, in several on-road and off-road[7] engines under a variety of test conditions.[8] Based on the results of the joint study, CARB anticipates that use of certain renewable diesel/biodiesel blends would result in NOx and PM reductions in on-road and off-road legacy engines. However, the joint study did not specifically investigate the emissions impacts of renewable diesel or renewable diesel/biodiesel blends in legacy off-road engines.

Recent studies of on-road heavy-duty NTDEs have shown NOx emissions above engine certification standards as a result of decreased efficiency of SCR systems at low load/low speed engine conditions and malfunction of SCR systems due to engine maintenance issues.[9,10] Under these conditions, the emissions performance of an NTDE may be similar to a legacy engine. Although these studies did not consider the impact of renewable diesel or biodiesel in NTDEs under these conditions, the results of the joint study suggest that the use of renewable diesel/biodiesel blends may also result in NOx impacts in on-road and off-road NTDEs under these conditions (i.e., during low loads/low speed engine operation and when engines are experiencing maintenance issues).

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[6] CARB. 2017. Revised Proposed 2016 State Strategy for the State Implementation Plan. March 7. Available at: https://www.arb.ca.gov/planning/sip/2016sip/rev2016statesip.pdf. Accessed: January, 2017.
[7] Renewable diesel was not investigated in off-road engines in this study.
[8] Durbin et al. 2011. CARB Assessment of the Emissions from the Use of Biodiesel as a Motor Vehicle Fuel in California, "Biodiesel Characterization and NOx Mitigation Study," Final Report. October. Available at: https://www.arb.ca.gov/fuels/diesel/altdiesel/20111013_CARB%20Final%20Biodiesel%20Report.pdf. Accessed: August, 2017.
[9] Misra, Chandan, et al. In-Use NOx Emissions from Model Year 2010 and 2011 Heavy-Duty Diesel Engines Equipped with Aftertreatment Devices. Environ. Sci. Technol. 2013, 47, 7892-7898.
[10] Boriboomsomsin, Kanok, et al. 2017. Collection of Activity Data from On-Road Heavy-Duty Diesel Vehicles. Final Report for the California Air Resources Board. May.

A recent chassis dynamometer study has shown potential NOx increases for biodiesel and renewable diesel use relative to CARB ULSD in on-road NTDEs. However, the results depended on blend level (with petroleum diesel) and the driving cycle studied.[11] Additionally, a chassis dynamometer may not provide a true representation of fuel-to-fuel differences due to variability resulting from manual operation of the engine. The staff report for the 2015 ADF regulation also states that, for 2007 and later engines equipped with PM filters, there were no meaningful differences in PM emissions between conventional diesel and biodiesel.[12] However, the joint study indicates that PM emissions for these engines were essentially at the limit of detection, so differences in PM emissions due to fuels could not be discerned. Thus, further characterization of the NOx and PM emissions impacts from the use of renewable diesel and renewable diesel/biodiesel blends in on-road and off-road NTDEs is needed.

[11] Karavalakis, G., Jiang, Y., Yang, J., Durbin, T., et al., Emissions and Fuel Economy Evaluation from Two Current Technology Heavy-Duty Trucks Operated on HVO and FAME Blends, SAE Int. J. Fuels Lubr. 9(1):2016, doi:10.4271/2016-01-0876.

[12] CARB. 2015. Proposed Regulation on the Commercialization of Alternative Diesel Fuels – Staff Report: Initial Statement of Reasons. January 2. Available at: https://www.arb.ca.gov/regact/2015/adf2015/adf15isor.pdf.

2 Objectives

The purpose of this study is to further evaluate emissions and performance effects resulting from the use of renewable diesel and renewable diesel/biodiesel blends relative to CARB diesel in off-road legacy engines and in NTDEs. Specifically, this study aims to:

1. Evaluate the NOx and PM emissions resulting from renewable diesel fuel and selected renewable diesel/biodiesel fuel blends in a legacy off-road engine.

2. Evaluate the NOx and PM emissions from use of renewable diesel fuel and selected renewable diesel/biodiesel fuel blends in on-road and off-road NTDEs.

To achieve the objectives above, emissions testing was conducted using renewable diesel and renewable diesel/biodiesel blends in an off-road legacy engine, a heavy-duty on-road NTDE, and an off-road NTDE. Performance testing was also conducted to measure changes in fuel consumption.

3 Experimental Procedures

3.1 Test Fuels

Testing was conducted using a CARB reference fuel – a petroleum-based, ultra-low sulfur diesel meeting ASTM975 specifications and the properties of Table A.9 of the ADF regulation as a baseline fuel, a neat (100 percent or 99 percent) renewable diesel fuel (referred to as R100 in this study) meeting ASTM975 specifications and Table A.9 of the ADF regulation), a blend of 65 percent renewable diesel and 35 percent biodiesel (R65/B35) with neat biodiesel meeting ASTM6751 and Table A.8 of the ADF regulation, and a blend of 50 percent renewable diesel and 50 percent biodiesel (R50/B50).[13]

The CARB reference fuel was obtained from a single batch in a volume sufficient for the full test program to minimize variations in fuel properties over the course of the study. The certificate of analysis (COA) for this fuel is provided in Appendix B.

The neat biodiesel was also sourced from a single batch in volumes sufficient for the full test program, while the R100 renewable diesel was sourced in two batches, but from a well-controlled production process where the fuel properties change minimally over time. The neat biodiesel fuel was obtained from a BQ-9000 supplier[14] and was a low-saturation biodiesel. The biodiesel met the specifications in Table A.8 of the ADF regulation, with the exception of a higher cetane number.

The R100/R99 fuel was provided by a commercial supplier. Renewable diesel 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 renewable diesel and neat biodiesel described above were used as the blendstock for the R65/B35 and R50/B50 fuels. Blending of the renewable diesel/biodiesel blends was performed at the CE-CERT facilities in Riverside, California. The R65/B35 and R50/B50 blends were blended gravimetrically in fuel totes large enough to provide for single batches of R65/B35 and R50/B50 fuels that were sufficient for the full test program and were stored under nitrogen blankets to minimize variations in fuel properties over the course of the study.

Some additional blending of R65/B35 and R50/B50 fuels using the same batches of neat renewable diesel and biodiesel was also done in conjunction with the testing on the third engine, the off-road NTDE. Prior to conducting this second round of blending, some additional testing of the neat biodiesel was performed to evaluate its stability and quality, which included acid number, oxidation stability, water content, copper corrosion, and FAME content. These results showed that all of the properties were still within specifications, with the exception of oxidation stability, which had dropped to 1.2 hours. These results were discussed with representatives of the biodiesel industry, and it was determined that the fuel should still be acceptable for testing if an oxidation stability additive could be added to improve the oxidation stability of the biodiesel. The oxidation stability was improved by adding 1,000 ppmv of tert-Butylhydroquinone, which increased the

[13] CARB. 2020. Regulation on Commercialization of Alternative Diesel Fuels. Title 13, California Code of Regulations, Appendix 1 of Subarticle 2.[14] https://bq-9000.org.
[14] https://bq-9000.org.

oxidation stability to 4.3 hours. The additional supply of renewable diesel/biodiesel fuels were then blended using the same gravimetric methods as used in the previous round of blending.

Fuel analyses were conducted by Southwest Research Institute (SwRI) on the CARB reference fuel, the neat renewable diesel, the neat biodiesel, and the R65/B35 and R50/B50 blends. The CARB reference fuel and the neat renewable diesel were analyzed for ASTM D975 properties and the properties in Table A.9 of the ADF regulation. These properties, as well as the Certificate of Analysis (COA) results, the fuel analysis results, and the fuel specifications for the CARB reference fuel, are shown in Table 3-1. The neat biodiesel fuel was analyzed for ASTM D6751 properties and the properties in Table A.8 of the ADF regulation. These properties, as well as the results of the fuel analysis and the fuel specifications for the neat biodiesel, are shown in Table 3-2. The R65/B35 and R50/B50 blends were analyzed for biodiesel content, sulfur, nitrogen, density, and distillation temperature at 10 percent, 50 percent, and 90 percent of the sample, as shown in Table 3-3. The carbon/hydrogen/oxygen content was also measured via ASTM D5291 for the CARB reference fuel, the R100, and the B100, as the carbon weight fraction is used to determine the brake specific fuel consumption (BSFC). Full fuel analyses were conducted for one sample per fuel. Triplicate analyses were performed on cetane number and a single analysis was performed on all other fuel properties indicated in Tables 3-1 through 3-3. The fuel analysis results from SwRI for all test fuels are provided in Appendix C.

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

Property	ASTM Test Method	Units	Certificate of Analysis Results	Fuel Analysis Results (SwRI)	ULSD Fuel Specifications	Renewable Diesel Fuel Analysis Results (SwRI)
Sulfur	D5453	ppm	<1	<0.5	15 max.	<0.5
Aromatics	D5186	Vol. %	10.0	9.9	10 max.	1.2
Polycyclic aromatic hydrocarbons	D5186	Wt. %	1.2	1.2	1.4 max.	0.2
Nitrogen content	D4629	ppm	5.8	4.9	10 max.	<1.0
Unadditized Cetane Number	D613	unitless	48.4	48.1 48.3 48.2	48 min.	79.6 80.1 79.8
API Gravity	D287	unitless	38.1*	38.0	33-39	49.1
Specific Gravity	D287	g/ml	-	0.8348	-	0.7835
Carbon weight fraction	D5291	wt%	-	86.30	-	84.96
Kinematic Viscosity, 40°C	D 445	mm^2/s	2.6	2.544	2.0 – 4.1	3.031
Flash Point	D93	°F	191	189.0	130 min.	146.0
Distillation Temperature, atmospheric, IBP	D86-IBP	°F	396	395.5	340 – 420	285.8
Distillation Temperature, atmospheric, T10	D86-T10	°F	436	435.7	400 – 490	487.7
Distillation Temperature, atmospheric, T50	D86-T50	°F	486	486.5	470 – 560	552.3
Distillation Temperature, atmospheric, T90	D86-T90	°F	559	559.3	550 – 610	566.9
Distillation Temperature, atmospheric, TEP	D86-EP	°F	600	601.6	580 – 660	586.9

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

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

Property	ASTM Test Method	Units	Fuel Analysis Results (SwRI)	ADF Specification
Distillation, 90% recovery	D1160	ºF	669.2	620 - 680
API Gravity (by Meter)	D287	ºAPI	28.6	27 - 33
Specific Gravity	D287	g/ml	0.8838	-
Kinematic Viscosity @ 40 ºC	D445-40	mm^2/s	4.399	1.9 – 6.0
Trace Nitrogen in Liquid Petroleum Hydrocarbons	D4629	ppm (wt/wt)	13.8	10 max
Sulfur by UVF	D5453	ppm (wt/wt)	3.03	15 max
Cetane Number	D613	unitless	56.7 55.8 56.6	47-50
Flash Point, Pensky Martens	D93	ºF	326.0	266 min
FAME content*	EN 14078	% Mass	97.3	Report
Carbon weight fraction	D5291	wt%	77.30	

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

Table 3-3. Fuel Property Analysis Results and Properties

Property	ASTM Test Method	Units	R65/R35	R50/B50
Sulfur Content	D5453	ppm	1.34	1.60
Nitrogen Content	D4629	ppm	4.8	6.8
Cetane Number Test #1	D613	unitless	68.4	67.6
Cetane Number Test #2	D613	unitless	67.6	67.7
Cetane Number Test #3	D613	unitless	67.1	67.7
Cetane Number - Average	D613	unitless	67.7	67.7
API Gravity	D287	degAPI	41.5	38.4
Viscosity at 40ºC, cSt	D445	cSt	-	-
Flash Point, ºF, minimum	D93	ºF	-	-
Distillation Temperature, atmospheric, IBP	D86-IBP	ºF	315.5	332.1
Distillation Temperature, atmospheric, T10	D86-T10	ºF	528.3	546.5
Distillation Temperature, atmospheric, T50	D86-T50	ºF	580.6	597.8
Distillation Temperature, atmospheric, T90	D86-T90	ºF	630.0	639.4
Distillation Temperature, atmospheric, TEP	D86-EP	ºF	654.0	659.6
FAME Content %	EN14078	% Mass	34.8	49.1

3.2 Test Engines

As discussed in Section 2, the goal of this test program is to further evaluate the emissions and performance effects of renewable diesel and renewable diesel/biodiesel blends in three engine types: an off-road legacy engine and on-road heavy-duty and off-road NTDEs. Table 3-4 provides a general description of the emissions technologies and engine characteristics of the engines used in this study.

Table 3-4. General Description of Test Engines

No.	Engine Type	SCR-Equipped?	DPF-Equipped?	HP	Model Year	Vocation	Manufacturer
1	Off-Road	No	No	115	2009	Construction	John Deere
2	On-Road Heavy-Duty	Yes	Yes	450	2019	T7 or T8 Truck	Cummins
3	Off-Road	Yes	Yes	225	2018	Construction	Caterpillar

The specifications of three test engines are provided in Table 3-5. The selected off-road legacy engine was a John Deere 4045HF285 engine that has been used in previous biodiesel and renewable diesel engine testing conducted by UCR CE-CERT and CARB.[15] The on-road heavy-duty and off-road NTDEs were late-model engines to ensure that the test engines were equipped with the most advanced DPF and SCR emissions control technology currently available. The emissions control technology in these late-model engines is becoming more representative of the in-use emissions control technology in the on-road and off-road fleets as the engine inventory turns over. The on-road heavy-duty engine was a Cummins engine. Cummins engines are a staple of the California diesel engine market in Class 7 or Class 8 trucks. Use of this engine also provides a basis to further evaluate the results of a recent chassis dynamometer study that found increases in NOx emissions for biodiesel and some blends of renewable diesel relative to CARB ULSD in two Cummins on-road heavy-duty NTDEs.[16] The off-road NTDE was a Caterpillar engine, which represents one of the most common off-road equipment engine manufacturers for California.

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[15] Durbin et al. 2011. CARB Assessment of the Emissions from the Use of Biodiesel as a Motor Vehicle Fuel in California, "Biodiesel Characterization and NOx Mitigation Study," Final Report. October. Available at: https://www.arb.ca.gov/fuels/diesel/altdiesel/20111013_CARB%20Final%20Biodiesel%20Report.pdf.[16] Karavalakis, G., Jiang, Y., Yang, J., Durbin, T. et al., "Emissions and Fuel Economy Evaluation from Two Current Technology Heavy-Duty Trucks Operated on HVO and FAME Blends," SAE Int. J. Fuels Lubr. 9(1):2016, doi:10.4271/2016-01-0876.

[16] Karavalakis, G., Jiang, Y., Yang, J., Durbin, T. et al., "Emissions and Fuel Economy Evaluation from Two Current Technology Heavy-Duty Trucks Operated on HVO and FAME Blends," SAE Int. J. Fuels Lubr. 9(1):2016, doi:10.4271/2016-01-0876.

Table 3-5. Specifications of the Test Engines

Category	Off-Road Legacy	On-Road NTDE	Off-Road NTDE
Engine Manufacturer	John Deere	Cummins	Caterpillar
Engine Model	4045HF285	C-15	C7.1 ACERT
Model Year	2009	2019	2018
Engine Family	9JDXL6.8105	KCEXH0912XAW	JPKXL07.0BN1
Engine Type	In-line 4-cylinder, 4-stroke (Tier 3)	In-line 6-cylinder, 4-stroke	In-line 6-cylinder, 4-stroke (Tier 4)
Displacement	4.5 liters	14.9 liters	7.01 liters
Power Rating	115 hp (86 kW)	450 hp (336 kW)	225 hp (168 kW)
Speed Rating	2400 rpm	1800 rpm	2200 rpm
Fuel Type	Diesel	Diesel	Diesel
Induction	Turbocharged	Turbocharged	Turbocharged
Emissions controls: 1. Exhaust Gas Recirculation (EGR) 2. SCR 3. DPF	1. No 2. No 3. No	1. Yes 2. Yes 3. Yes	1. Yes 2. Yes 3. Yes

The CARB reference fuel, neat renewable diesel (R100/R99), and the R65/B35 and R50/B50 blends were tested in all engines.

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 hp General Electric DC electric engine dynamometer that was obtained from the United States Environmental Protection Agency'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 D.

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. NOx emissions were measured with a 600 HPLC chemiluminescence analyzer from California Analytical Instruments (CAI). CO and CO_2 emissions were measured with a 602P nondispersive infrared (NDIR) analyzer from CAI. THC emissions were measured with 600HFID flame ionization detector (FID) from CAI. 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 D, with associated laboratory quality assurance and quality control procedures described in Appendix E.

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 and engine out emissions were collected for different engines, as summarized in Table 3-6. For the off-road legacy engine and the on-road NTDE, additional measurements included particle number (PN) and particle size distributions (PSD). An Engine Exhaust Particle Sizer (EEPS) (TSI 3090, MCU firmware version 3.05) was used to obtain real-time second-by-second PSDs between 5.6 and 560 nm in diameter. PN measurements were made using a TSI 3022 Condensation Particle Counter (CPC). Solid PN measurements were made using an AVL particle counter (APC) with a 23 nm diameter cut point. 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.[17]

For the off-road NTDE, engine-out emissions were measured with a gas-phase SEMTECH-DS gas-phase analyzer portable emissions measurement system (PEMS) with an associated exhaust flow meter. The PEMS was set up to collect second-by-second engine out emissions, which provided information on the impacts of the R100, R65/B35, and R50/B50 test fuels on the combustion emissions prior to the emission control system, as well as the conversion efficiency for the SCR system.

In conjunction with the emissions measurements, information on the engine parameters were also collected from the engine control module (ECM). For the legacy off-road engine and the off-road NTDE, engine parameters were collected with a HEM data logger. For the on-road NTDE, engine parameters were collected with a Cummins INSITE Engine Diagnostics software package.

[17] 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.

Table 3-6. Measurements Type and Instrumentation Used for Data Other Than Emissions

Engine	Particle Size Distribution (PSD)	Particle Number (PN)	Solid PN Measurements	Engine-Out Emissions	Engine Control Module (ECM) Parameters
Off-Road Legacy	Engine Exhaust Particle Sizer (EEPS) 5.6-560 nm diameter	TSI 3022 Condensation Particle Counter (CPC)	AVL Particle Counter (APC) with greater than 23 nm diameter.[18]		HEM data logger
On-Road NTDE	Engine Exhaust Particle Sizer (EEPS) 5.6-560 nm diameter	TSI 3022 Condensation Particle Counter (CPC)	AVL Particle Counter (APC) with greater than 23 nm diameter.		Cummins INSITE Engine Diagnostics
Off-Road NTDE				Gas-Phase SEMTECH-DS PEMS with Exhaust Flow Meter	HEM data logger

3.4 Test Matrix and Test Sequence

Three test cycles were used for this program: the NRTC, the FTP, and steady state ramped modal cycles. The NRTC is the transient test used in the engine certification procedure for off-road engines, and the FTP is the transient certification test used for engine certification for on-highway engines. The ramped modal cycles are steady state cycles used in in engine certification for both on-highway and off-road engines, with different cycles run for the different engines. For the John Deere constant speed off-road legacy engine, a 5-mode D2 ISO 8718 cycle was utilized, as per U.S. EPA's certification.[19] For the Cummins on-road NTDE, a 13-mode, supplementary emissions test cycle was used, as was used in the certification of this engine. For the Caterpillar off-road NTDE, an 8-mode C1 ISO 8718 cycle was used, which is the cycle typically utilized for certification of variable speed off-road engines. All of the steady state cycles were run as ramped modal cycles (RMCs), as opposed to having each mode tested as a discrete mode. These cycles are described in greater detail in Appendix F. A summary of the test cycles used for each engine is provided in Table 3-7.

[18] https://www.avl.com/documents/10138/885965/AVL+Particle+Counter.pdf

[19] https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-data-vehicles-engines-and-equipment

Table 3-7. Test Cycles to Be Used for Each Engine

Engine Characteristics				Test Cycles		
Engine No.	Engine Type	SCR-Equipped?	DPF-Equipped?	NRTC[1]	FTP[2]	RMC[3]
1	Off-Road Legacy	No	No	✓		✓
2	On-Road Heavy-Duty NTDE	Yes	Yes		✓	✓
3	Off-Road NTDE	Yes	Yes	✓		✓

Note: "✓" denotes cycles that were tested for each engine. Blank cells denotes cycle/engine combinations that were not be tested.
[1] NRTC is the transient test used in the engine certification procedure for off-road engines.
[2] FTP is the transient certification test used for engine certification for on-highway engines
[3] The RMCs are steady state cycles used in in engine certification for both on-highway and off-road engines.

Engine mapping for each test cycle was based on the CARB reference fuel. The test cycles were developed based on an engine map conducted on the CARB reference fuel before the first test on a particular engine. An engine map was run daily on the first fuel to be tested for that day to warm up the engine.

The test sequence for each of the cycles was conducted by alternating among the baseline fuel (i.e., the CARB reference fuel) and the three biofuel blends (i.e., R100/R99, R65/B35, and R50/B50), with the specific sequence of cycles developed for each engine based on manufacturers' recommendations. The test sequences for each of the individual engines are described below. In the test sequences described below, "C" represents the CARB reference fuel, "B1" represents the neat renewable diesel fuel (R100/R99), "B2" represents the R65/B35 blend, and "B3" represents the R50/B50 blend. The full test matrix showing all engines, test cycles, and fuel test sequences is shown below in Table 3-12.

3.4.1 Off-Road Legacy Engine

The off-road legacy engine was tested over the D2 and NRTC test cycles. The test sequence for the off-road legacy engine is presented in Table 3-8. The D-2 tests were run as hot stabilized tests warmed up prior to the start of the emissions test. The engine temperature was stabilized by bringing the engine to the first operating testing point load for about 250 seconds. The NRTC tests were run as hot start tests with a 20 minute soak in between tests. A preconditioning test was run prior to any tests on a new fuel, or to the extent that the engine had cooled and was outside of the ordinary 20 minute soak. For this engine, a modified version of the NRTC was utilized, as it was not designed to typically operate over such a duty cycle. For this modified NRTC, the rpm was held steady at the maximum rated speed, and then the engine was ramped through the torque profile for the NRTC.

Table 3-8. Test Sequence to Be Used for Each Test Cycle for the Off-Road Legacy Engine

Day	Fuel Test Sequence
1	CCC B1B1B1 B2B2B2
2	B3B3B3 CCC B1B1B1
3	B2B2B2 B3B3B3 CCC
4	B1B1B1 CCC B3B3B3
5	CCC B2B2B2 CCC

C = CARB reference fuel, B1 = R100, B2 = R65/B35
B3 = R50/B50

3.4.2 On-Road NTDE

The on-road NTDE was tested over the FTP and the 13-mode SET test cycles. The test sequence for the on-road NTDE is presented in Table 3-9. The FTP tests were run as hot start tests with a 20 minute soak in between tests. The engine was preconditioned over two hot start FTPs at the beginning of each test day, following a fuel switch, or if the engine has cooled and is outside of the ordinary 20 minute soak. For the on-road SET RMC cycle, the tests were run as hot running tests. For any given fuel, the engine was over a half SET RMC cycle for preconditioning, followed immediately by an official emissions test.

Table 3-9. Test Sequence for the FTP and RMC/SET Cycles on the On-Road NTDE

Day	Fuel Test Sequence
1	CCC B1B1B1
2	B2B2B2 CCC
3	B1B1B1 B3B3B3
4	CCC B2B2B2
5	B3B3B3 CCC
6	B2B2B2 B1B1B1
7	CCC B3B3B3

C = CARB reference fuel, B1 = R100/R99, B2 = R65/B35
B3 = R50/B50

3.4.3 Off-Road NTDE

The off-road NTDE was run over the NRTC and the C1 steady state RMC. The test sequences used for the NRTC and C1 cycles are provided in Table 3-10 and Table 3-11, respectively.

Table 3-10. Test Sequence for the NRTC Cycle on the Off-Road NTDE

Day	Fuel Test Sequence
1	CCC CCC
2	B1B1B1 B1B1B1
3	B2B2B2 B2B2B2
4	B3B3B3 B3B3B3
5	B1B1B1 B1B1B1
6	B3B3B3 B3B3B3
7	B2B2B2 B2B2B2
8	CCC CCC

Table 3-11. Test Sequence for the Ramped Modal C1 Cycle on the Off-Road NTDE

Day	Fuel Test Sequence
1	CCC B1B1B1
2	B2B2B2 CCC
3	B1B1B1 B3B3B3
4	CCC B2B2B2
5	CCC
6	B1B1B1
7	B2B2B2 B3B3B3

The NRTC tests were run as hot start tests with a 20 minute soak in between tests. Four preconditioning NRTC cycles with 20 minutes soaks in between were run prior to any tests on a new fuel, as per recommendations from the manufacturer. For the C1 cycle, two C1 cycles were run prior to any tests on a new fuel. The C1 tests were run as hot stabilized tests, with the engine warmed up prior to the start of the emissions test. The engine temperature was stabilized by bringing the engine to the first operating testing load point and running the engine for 200 seconds.

Since the off-road NTDE was purchased new, the engine was operated for 50 hours to break it in prior to conducting any emissions testing. The engine break-in was conducted over a series of steady state test points based on recommendations from the engine manufacturer. The engine break-in was performed with a standard market CARB ULSD obtained from a local retail outlet.

Table 3-12. Full Test Matrix for All Engines and Cycles

Engine No.	Engine Type	Duty Cycle	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
1	On-Road NTDE	FTP	CCC B1B1B1	B2B2B2 CCC	B1B1B1 B3B3B3	CCC B2B2B2	B3B3B3 CCC	B2B2B2 B1B1B1	CCC B3B3B3	-
		SET	CCC B1B1B1	B2B2B2 CCC	B1B1B1 B3B3B3	CCC B2B2B2	B3B3B3 CCC	B2B2B2 B1B1B1	CCC B3B3B3	-
2	Off-Road Legacy	NRTC	CCC B1B1B1 B2B2B2	B3B3B3 CCC B1B1B1	B2B2B2 B3B3B3 CCC	B1B1B1 CCC B3B3B3	CCC B2B2B2 CCC	-	-	-
		ISO 8178 D2	CCC B1B1B1 B2B2B2	B3B3B3 CCC B1B1B1	B2B2B2 B3B3B3 CCC	B1B1B1 CCC B3B3B3	CCC B2B2B2 CCC	-	-	-
3	Off-Road NTDE	NRTC	CCC CCC	B1B1B1 B1B1B1	B2B2B2 B2B2B2	B3B3B3 B3B3B3	B1B1B1 B1B1B1	B3B3B3 B3B3B3	B2B2B2 B2B2B2	CCC CCC
		ISO 8178 C1	CCC B1B1B1	B2B2B2 CCC	B1B1B1 B3B3B3	CCC B2B2B2	CCC	B1B1B1	B2B2B2 B3B3B3	-

C = CARB reference fuel
B1 = R100/R99
B2 = R65/B35
B3 = R50/B5

4 Engine Testing Results

The results for each of the confirmatory test comparisons are summarized in this section. 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 on the average value. The tables show the average emission values for all fuels, the percentage differences for the R100 and the R65/B35 and R50/B50 fuels 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, R65/B35 and R50/B50 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. Comparisons where $0.05 \leq p$ values < 0.1 were considered marginally statistically significant for this report, and are also noted in the text. 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 G.

4.1 NOx Emissions

4.1.1 Off-Road Legacy Engine 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 test cycle, and percentage differences and the associated p-values for statistical comparisons between the CARB reference fuel and the biofuels for each of the test cycles.

R100 fuel resulted in the lowest NOx emissions from biofuel use for both the NRTC and the D2 cycle, with statistically significant reductions of 5.4%, for the NRTC cycle and 4.9% for the D2 cycle compared to the CARB reference fuel. The R65/B35 showed no statistically significant differences compared to the CARB reference fuel for either the NRTC or D2 cycles. The R50/B50 showed statistically significant increases of 1.8% for the NRTC and 4.2% for the D2 cycle compared to the CARB reference fuel.

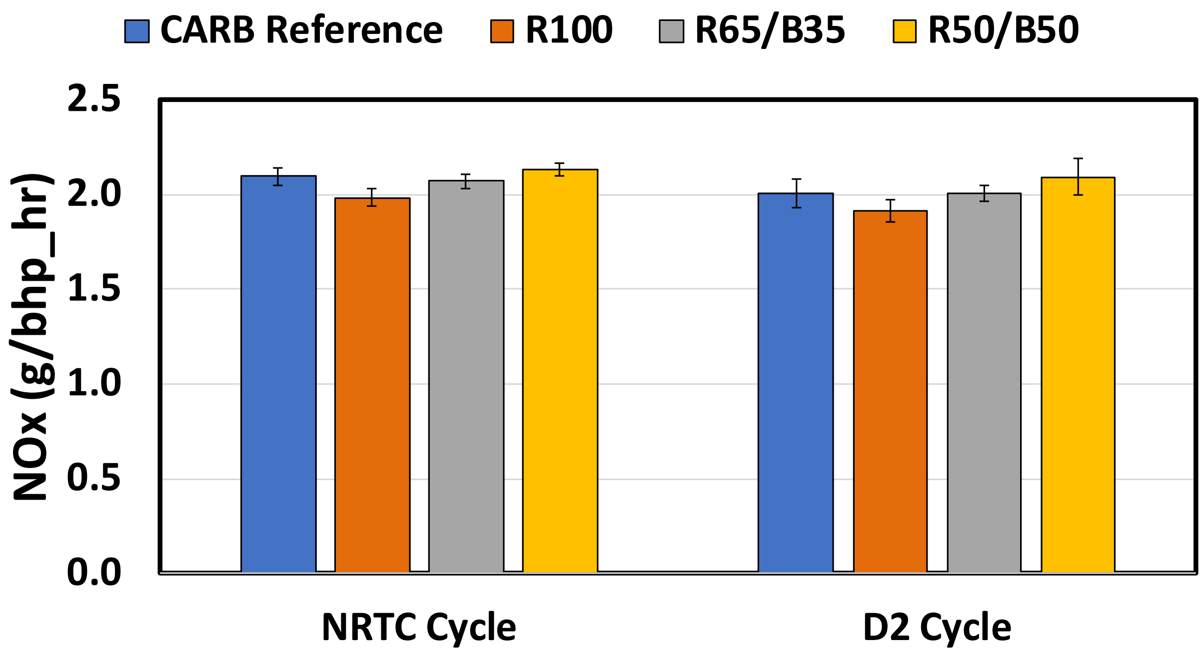

Figure 4-1. Average NOx Emission Results for the Off-Road Legacy Engine Testing

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

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	2.09	-	-
	R100	**1.98**	**-5.4**	**0.00**
	R65/B35	2.07	-1.2	0.18
	R50/B50	**2.13**	**1.8**	**0.05**
D2	CARB reference fuel	2.01	-	-
	R100	**1.91**	**-4.9**	**0.00**
	R65/B35	2.01	0.0	0.97
	R50/B50	**2.09**	**4.2**	**0.02**

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

4.1.2 On-Road NTDE NOx Emissions

The NOx emission results for the on-road NTDE are presented in Figure 4-2 on a g/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 for each of the test cycles. It should be noted that for the on-road NTDE, a subset of outlier tests were observed over the FTP that were not include in the data presented in this subsection. These data are discussed in greater detail in Appendix A.

For the on-road NTDE, no statistically significant differences were found between the CARB reference fuel and R100 for either the FTP or RMC cycles. The FTP cycle showed statistically significant increases of 46.6% for R65/B35 blend and 49.5% for the R50/B50 blend. The RMC showed statistically significant increases of 14.2% for the R65/B35 blend and 15.4% for the R50/B50 blend compared to the CARB reference fuel.

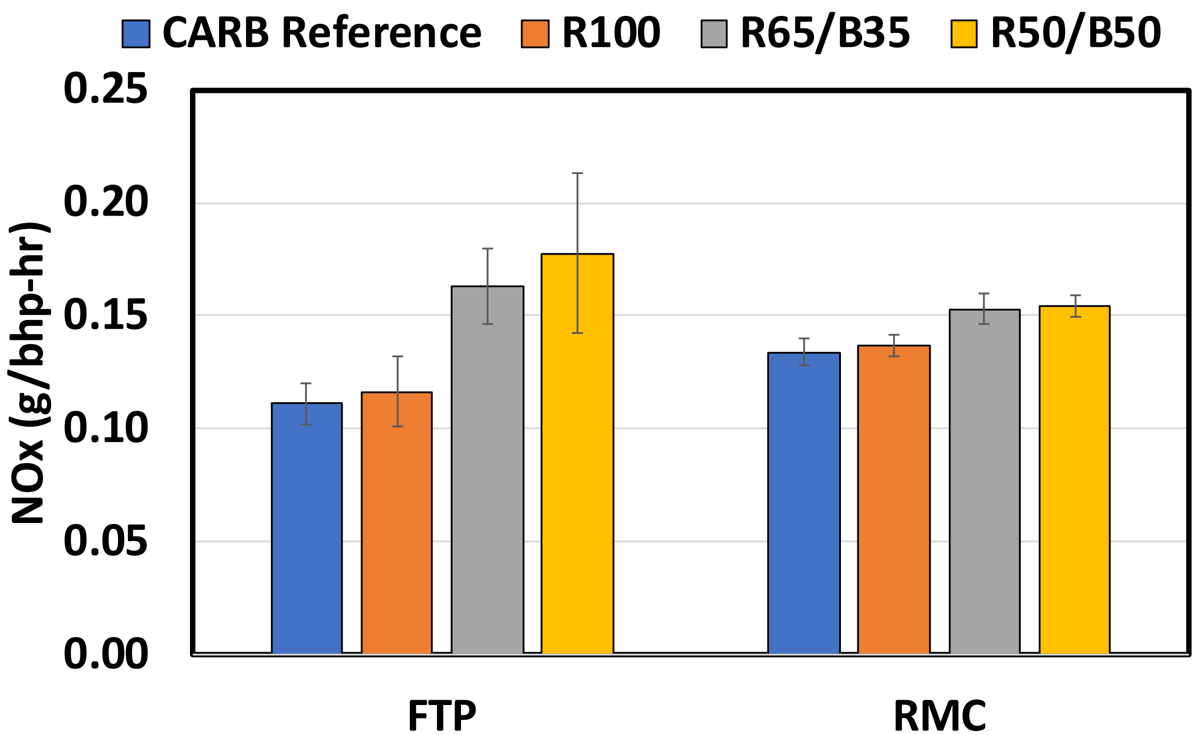

Figure 4-2. Average NOx Emission Results for the On-Road NTDE Testing

Table 4-2. NOx Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the On-Road NTDE Testing

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
FTP	CARB reference fuel	0.11	-	-
	R100	0.12	4.8	0.34
	R65/B35	**0.16**	**46.6**	**0.00**
	R50/B50	**0.17**	**49.5**	**0.00**
RMC	CARB reference fuel	0.13	-	-
	R100	0.14	2.3	0.19
	R65/B35	**0.15**	**14.2**	**0.00**
	R50/B50	**0.15**	**15.4**	**0.00**

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

Additional engine out NOx data was obtained from the engine out NOx sensor equipped on the engine for a subset of RMC tests. Figure 4-3 shows the engine out NOx sensor emissions for the on-road NTDE over the RMC cycle compared to the tailpipe NOx emissions measured with the MEL. Table 4-3 also shows the engine-out emissions (g/bhp-hr) for the RMC, and percentage differences and the associated p-values for statistical comparisons between the CARB reference fuel and the biofuels for the RMC, and Table 4-4 shows a comparison between the engine out and tailpipe emissions for the RMC cycle. Note that the FTP cycle NOx sensor data is not available as it is a hot-start cycle and the NOx sensor did not reach its operation temperature until approximately 300 seconds into the cycle. The engine out NOx sensor data showed no statistically significant difference between R100 and CARB reference fuel. The R65/B35 and R50/B50 blends, on the other hand, showed statistically significant increases in engine out NOx levels compared to the CARB reference fuel. The trends for the engine-out emissions are consistent with the tailpipe-out emissions data, which showed that the R100 fuel was not statistically significantly different from the CARB reference fuel, but the R65/B35 and R50/B50 emissions were higher at a statistically significant level than those for the CARB reference fuel. This suggests the increase in engine-out NOx emissions for the renewable diesel/biodiesel blends is likely a key factor contributing to the higher tailpipe emissions for the renewable diesel/biodiesel blends. Comparison of the engine out and tailpipe out (after emissions control system) NOx data showed that the SCR provided a 95% to 96% reduction in NOx emissions for the different fuels.

Table 4-3. NOx Engine-Out Emissions (g/bhp-hr), Percentage Differences Between the Biofuels and the CARB reference fuel, and Statistical Significance for On-Road NTDE Testing

	Fuel Type	Engine-Out NOx Emissions (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
RMC	CARB reference fuel	3.02	-	-
	R100	2.93	-3.1	-
	R65/B35	**3.68**	**21.9**	**0.00**
	R50/B50	**3.85**	**27.5**	**0.00**

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

Table 4-4. Average NO_x Engine-Out Emissions (g/bhp-hr) Compared to Tailpipe-Out Emissions Percentage Differences Between Biofuels and the CARB Reference Fuel for the On-Road NTDE RMC Testing

Cycle	Fuel Type	Engine-Out NOx Emissions (g/bhp-hr)	Tailpipe-Out NOx Emissions (g/bhp-hr)	Percent NOx Reduction from SCR
RMC	CARB reference fuel	3.02	0.13	96
	R100	2.93	0.14	95
	R65/B35	**3.68**	**0.15**	**96**
	R50/B50	**3.85**	**0.15**	**96**

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

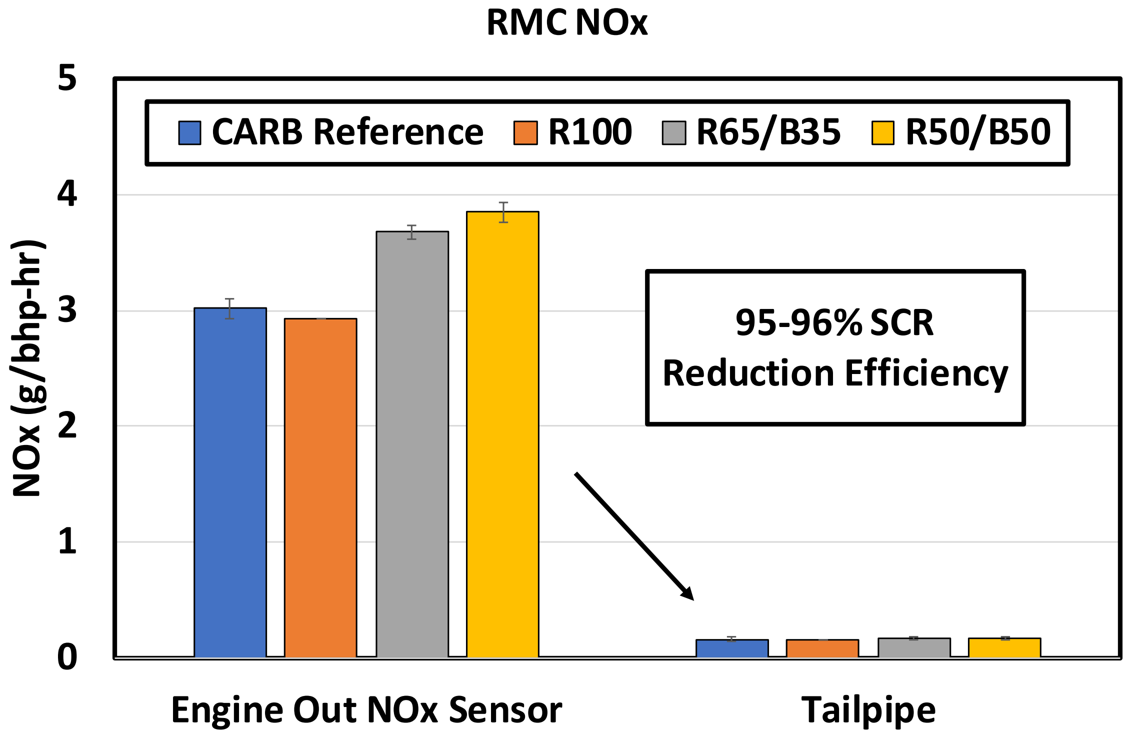

Figure 4-3. Average Sensor-Based NOx Emissions for the On-Road NTDE RMC cycle

4.1.3 Off-Road NTDE NOx Emissions

The NOx emission results for the off-road NTDE are presented in Figure 4-4 on a g/bhp-hr basis. Table 4-5 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 for each of the test cycles. In general, emissions were more variable for this engine, as shown by the large error bars in Figure 4.4, and the engine and aftertreatment showed less consistent operation.

For the off-road NTDE, no statistically significant differences were found between the CARB reference fuel and R100 for the NRTC or C1 cycles. The NRTC cycle showed statistically significant increases of 88.3% for R65/B35 blend and 149.6% for the R50/B50 blend. The C1 cycle showed statistically significant increases of 55.1% for the R65/B35 blend and 119.4% for the R50/B50 blend. It should be noted that the emissions for the C1 cycle were very low on an absolute basis, ranging on average from 0.014 g/bhp-hr to 0.030 g/bhp-hr, so the emissions differences between the CARB reference fuel and the renewable diesel/biodiesel blends were also low on an absolute basis, on the order of 0.007 g/bhp-hr to 0.016 g/bhp-hr.

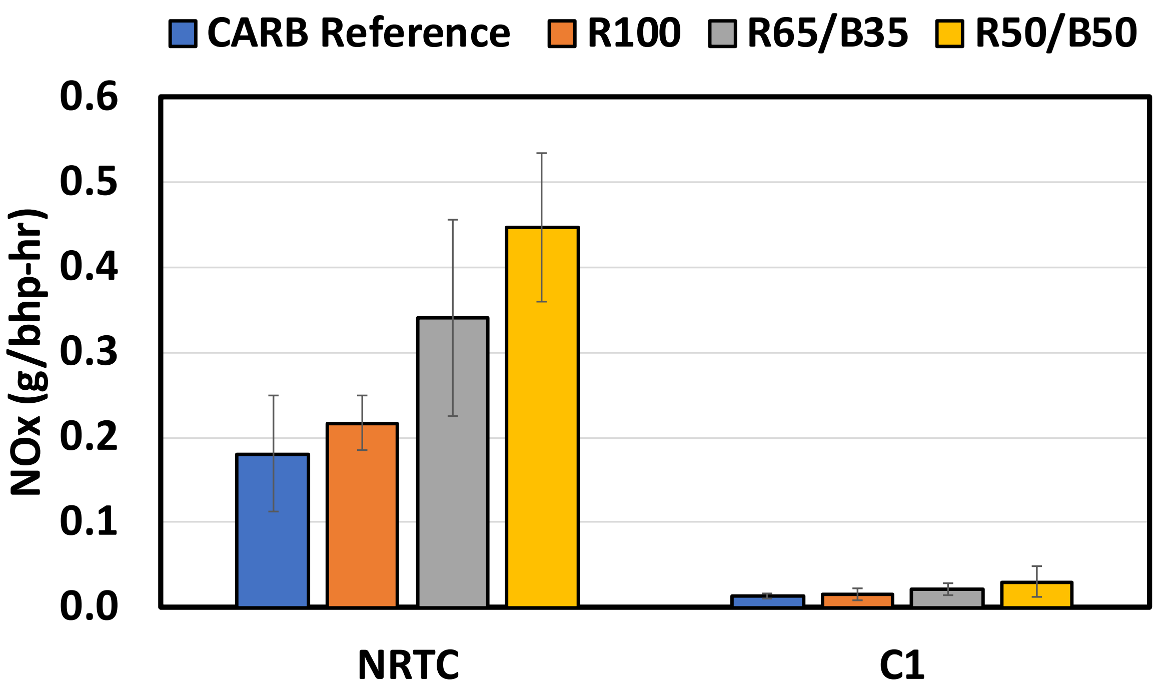

Figure 4-4. Average NOx Emission Results for the Off-Road NTDE Testing

Table 4-5. NOx Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road NTDE Testing

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	0.18	-	-
	R100	0.22	20.1	0.11
	R65/B35	**0.34**	**88.3**	**0.00**
	R50/B50	**0.45**	**146.9**	**0.00**
C1	CARB reference fuel	0.014	-	-
	R100	0.015	10.5	0.56
	R65/B35	**0.021**	**55.1**	**0.01**
	R50/B50	**0.030**	**119.4**	**0.01**

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

Engine out along with tailpipe NOx are presented in Figure 4-5. The engine-out data seen in Table 4-6 did not show any statistically significant differences between the R100 and the CARB reference fuel for either cycle. The engine-out data did show statistically significant increases in NOx emissions for the NRTC of 12.3% for R65/B35 and 15.9% for R50/B50 fuels compared with the CARB reference fuel. There are also statistically significant increases in engine-out NOx emissions for the C1 cycle of 18.8% for R65/B35 and 23.6% for R50/B50.

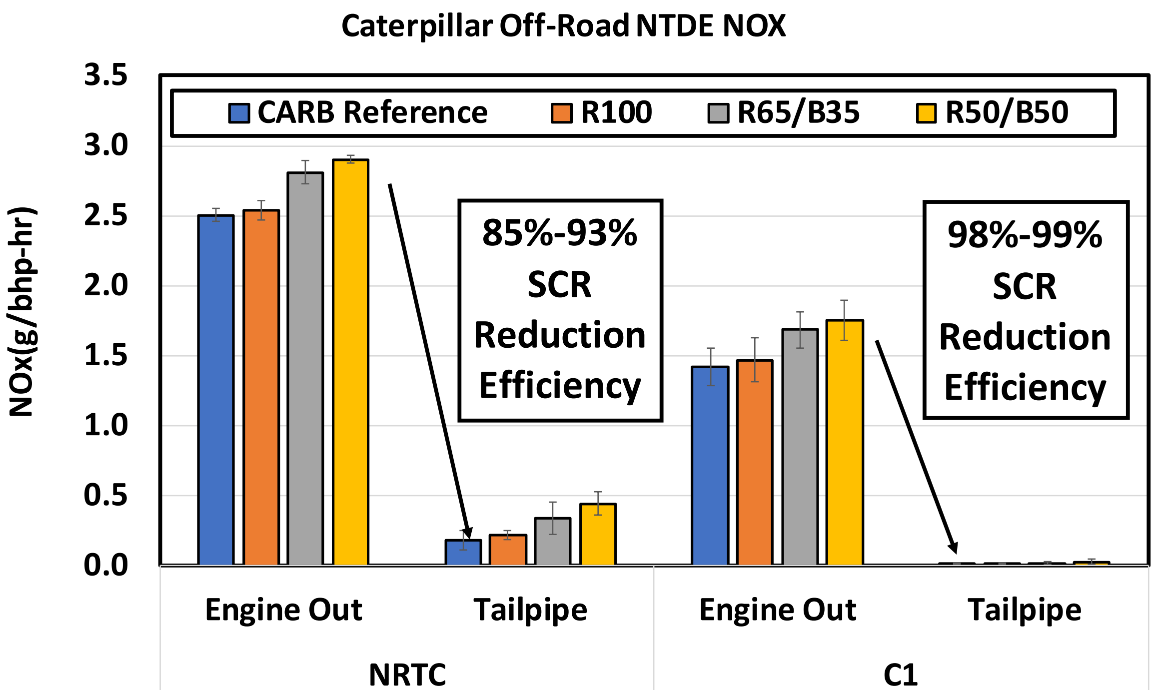

Figure 4-5. Average Engine Out and Tailpipe NOx Emissions for the Off-Road NTDE

Table 4-6. Engine Out NOx Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road NTDE Testing

Cycle	Fuel Type	Engine-Out NOx Emissions (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	2.50		
	R100	2.54	1.4	0.17
	R65/B35	**2.81**	**12.3**	**0.00**
	R50/B50	**2.90**	**15.9**	**0.00**
C1	CARB reference fuel	1.42		
	R100	1.47	3.5	0.45
	R65/B35	**1.69**	**18.8**	**0.00**
	R50/B50	**1.75**	**23.6**	**0.00**

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

Engine out NOx emissions along with tailpipe NOx emissions are presented in Table 4-7. Comparison of the engine-out and tailpipe NOx for the NRTC showed SCR reduction efficiencies of 93% for the CARB reference fuel, 91% for R100, 88% for R65/B35, and 85% for R50/B50. The SCR provided NOx reductions of 98% to 99% for the C1 cycle for all fuels.

Table 4-7. NOx Engine-Out Emissions (g/bhp-hr) Compared to Tailpipe-Out Emissions Percentage Differences Between Biofuels and the CARB Reference Fuel for Caterpillar Off-Road NTDE Testing

Cycle	Fuel Type	Engine-Out NOx Emissions (g/bhp-hr)	Tailpipe-Out NOx Emissions (g/bhp-hr)	Percent NOx Reduction from SCR
NRTC	CARB reference fuel	2.50	0.18	93
	R100	2.54	0.22	91
	R65/B35	2.81	0.34	88
	R50/B50	2.90	0.45	85
C1	CARB reference fuel	1.42	0.014	99
	R100	1.47	0.015	99
	R65/B35	1.69	0.021	99
	R50/B50	1.75	0.030	98

4.2 PM Emissions

4.2.1 Off-Road Legacy Engine PM Emissions

The PM emission results for the testing on the off-road legacy engine are presented in Figure 4-6 on a g/bhp-hr basis. Table 4-8 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 for each of the test cycles.

PM emissions showed decreases for the renewable diesel and the renewable diesel/biodiesel blends for both the NRTC and the D2. The reductions for the NRTC compared to the CARB reference fuel were 38% for R100, 53% for R65/B35, and 63% for R50/B50. The reductions for the D2 compared to the CARB reference fuel were 27% for R100, 51% for R65/B35, and 58% for R50/B50 fuel.

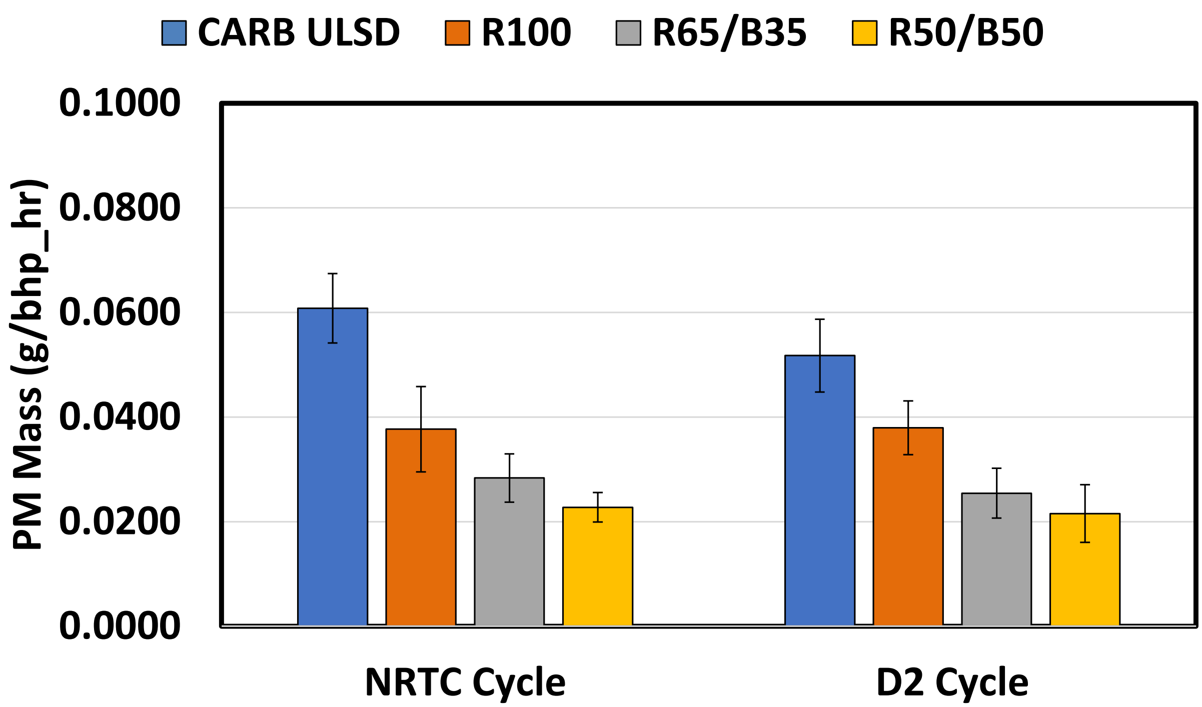

Figure 4-6. Average PM Emission Results for the Off-Road Legacy Engine Testing

Table 4-8. PM Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine

Cycle	Fuel Type	PM Emissions (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	0.061	-	-
	R100	**0.038**	**-38**	**0.00**
	R65/B35	**0.028**	**-53**	**0.00**
	R50/B50	**0.023**	**-63**	**0.00**
D2	CARB reference fuel	0.052	-	-
	R100	**0.038**	**-27**	**0.00**
	R65/B35	**0.025**	**-51**	**0.00**
	R50/B50	**0.022**	**-58**	**0.00**

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

4.2.2 On-Road NTDE PM Emissions

PM mass emissions for the on-road NTDE are presented in Figure 4-7 for all valid tests. Table 4-9 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 for each of the test cycles. It should be noted that for the on-road NTDE, a subset of outlier tests were observed over the FTP that were not included in the data presented in this subsection. These data are discussed in greater detail in Appendix A. PM mass emissions in general were low and near background levels, and averaged less than 0.001 g/bhp-hr for all tests conditions and both cycles. As the PM standard for heavy-duty on-road engines is 0.01 g/bhp-hr, the PM emissions observed are for the most part at least 20-fold lower than the PM standard. The PM emissions for the different fuels generally did not show statistically significant differences, with the exception of the R50/B50, which had emissions that were lower than those for the CARB reference fuel at a marginally statistically significant level over the FTP cycle.

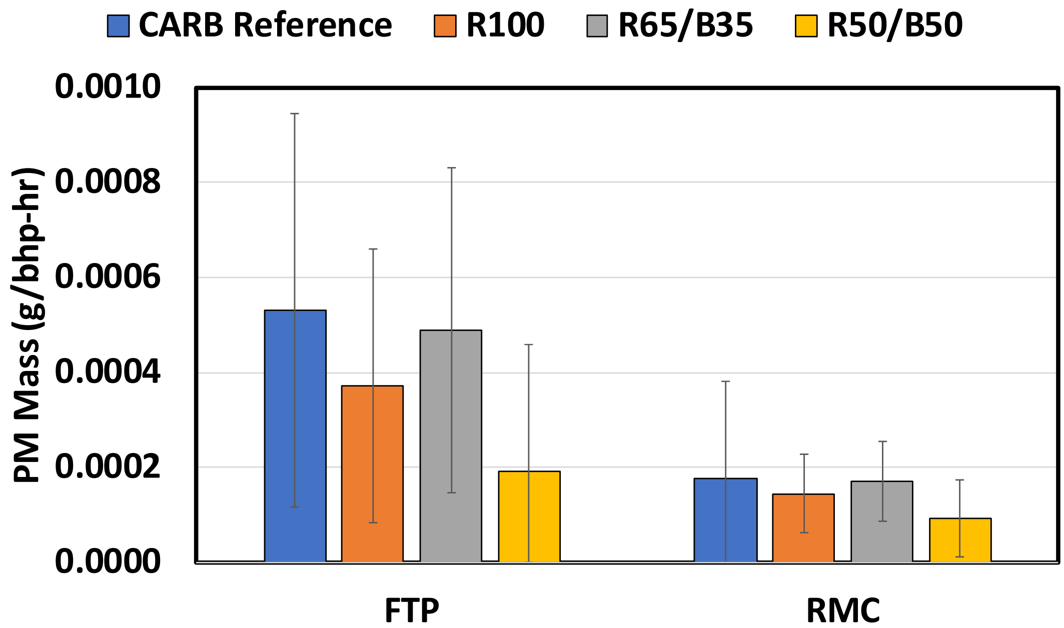

Figure 4-7. Average PM Emission Results for the On-Road NTDE Testing

Table 4-9. PM Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the On-Road NTDE

Cycle	Fuel Type	PM Emissions (g/bhp-hr)	% Diff vs. CARB	p-value (t-test)
FTP	CARB reference fuel	0.00049	-	-
	R100	0.00036	-28	0.38
	R65/B35	0.00052	6	0.86
	R50/B50	0.00018	-64	0.06*
RMC	CARB reference fuel	0.00018	-	-
	R100	0.00015	-18	0.66
	R65/B35	0.00017	-4	0.94
	R50/B50	0.00009	-47	0.26

Statistically significant results are bolded and their percent differences are shown in red text.
* Indicates marginally statistically significant result.

4.2.3 Off-Road NTDE PM Emissions

PM mass emissions for the off-road NTDE are presented in Figure 4-8. Table 4-10 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 for each of the test cycles. PM mass emissions were more than a factor of 30 below the 0.015 g/bhp-hr PM standard for Tier 4 off-road engines in this size category for all test conditions and both cycles. No statistically significant differences in PM mass emissions were seen between fuels for either test cycle.

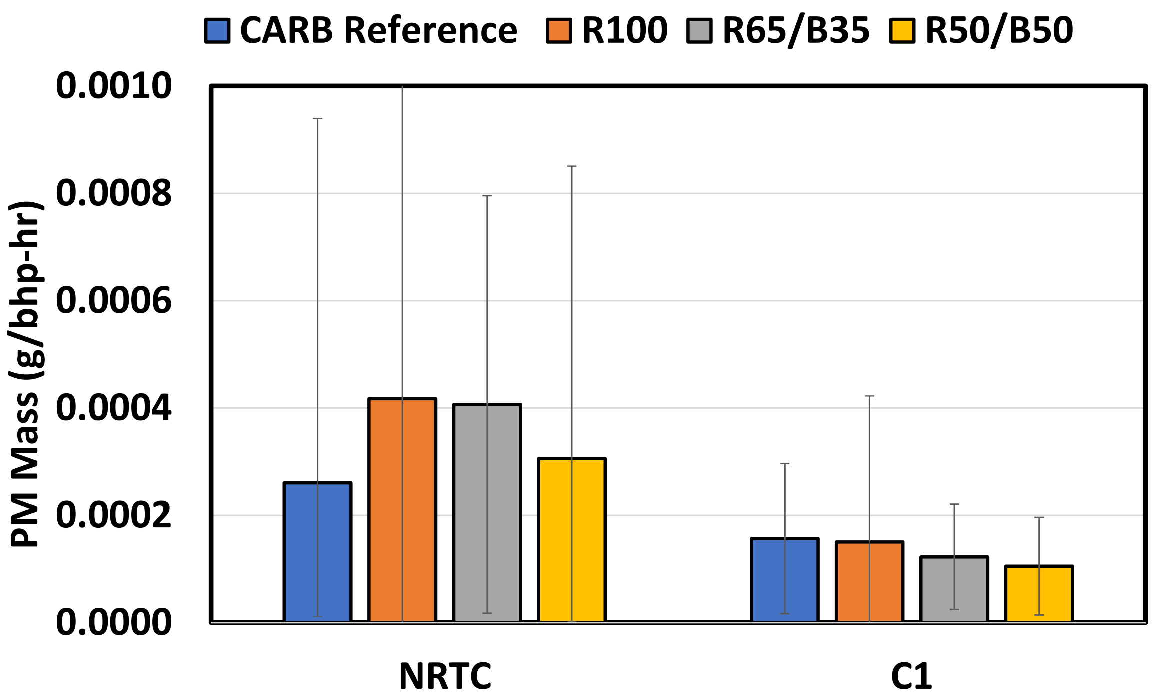

Figure 4-8. Average PM Emission Results for the Off-Road NTDE Testing

Table 4-10. PM Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road NTDE Testing

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	0.00026	-	-
	R100	0.00042	60	0.56
	R65/B35	0.00041	56	0.53
	R50/B50	0.00031	17	0.86
C1	CARB reference fuel	0.00016	-	-
	R100	0.00015	-4	0.95
	R65/B35	0.00012	-22	0.54
	R50/B50	0.00011	-33	0.43

4.3 THC Emissions

4.3.1 Off-Road Legacy Engine THC Emissions

The THC emission results for the testing on the off-road legacy engine are presented in Figure 4-9 on a g/bhp-hr basis. Table 4-11 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 for each of the test cycles.

THC emissions showed decreases for the renewable diesel and the renewable diesel/biodiesel blends for both the NRTC and the D2 cycles. The reductions for the NRTC compared to the CARB reference fuel were 45% for R100, 49% for R65/B35, and 66% for R50/B50. The reductions for the D2 compared to the CARB reference fuel were 35% for R100, 58% for R65/B35, and 71% for R50/B50.

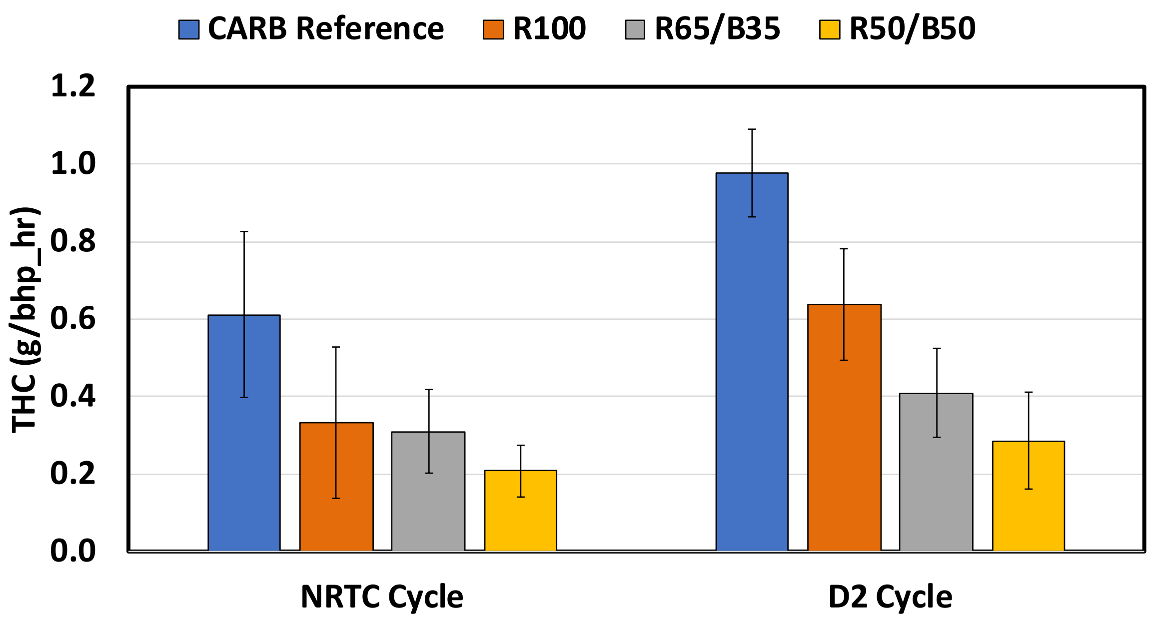

Figure 4-9. Average THC Emission Results for the Off-Road Legacy Engine Testing

Table 4-11. THC Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	0.61	-	-
	R100	**0.33**	**-45**	**0.00**
	R65/B35	**0.31**	**-49**	**0.00**
	R50/B50	**0.21**	**-66**	**0.00**
D2	CARB reference fuel	0.98	-	-
	R100	**0.64**	**-35**	**0.00**
	R65/B35	**0.41**	**-58**	**0.00**
	R50/B50	**0.29**	**-71**	**0.00**

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

4.3.2 On-Road NTDE THC Emissions

THC emissions for the on-road NTDE are presented in Figure 4-10 for all valid tests. Table 4-12 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 for each of the test cycles. It should be noted that for the on-road NTDE, a subset of outlier tests were observed over the FTP that were not include in the data presented in this subsection. These data are discussed in greater detail in Appendix A. THC emissions were near or below background levels for all tests conditions and both cycles. For the FTP, only R50/B50 showed a statistically significant reduction relative to the CARB reference fuel, with R100 and R65/B35 showing no statistically significant differences in THC emissions relative to the CARB reference fuel. For the RMC cycle, THC emissions levels were below the background levels for all tests, and hence did no show measurable THC emissions.

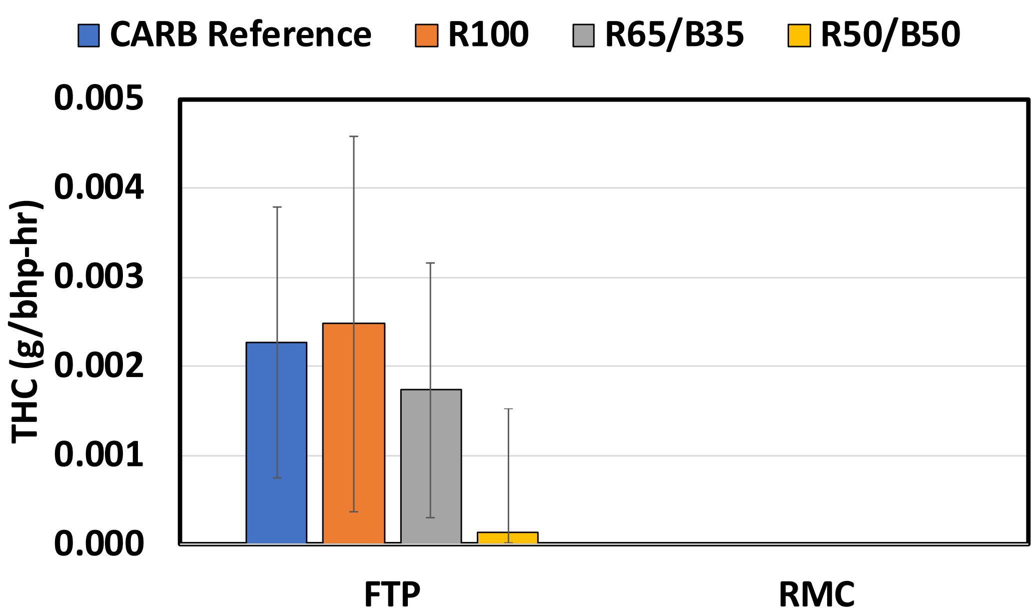

Figure 4-10. Average THC Emission Results for the On-Road NTDE Testing

Table 4-12. THC Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the On-Road NTDE Testing

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
FTP	CARB reference fuel	0.003	-	-
	R100	0.003	9	0.77
	R65/B35	0.002	-24	0.39
	R50/B50	**0.001**	**-71**	**0.01**
RMC	CARB reference fuel	0	-	-
	R100	0	-	-
	R65/B35	0	-	-
	R50/B50	0	-	-

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

4.3.3 Off-Road NTDE THC Emissions

THC emissions were below the background levels for all tests conditions and both the NRTC and C1 cycles, so the test results are reported as zeros, and no fuel differences were seen.

4.4 CO Emissions

4.4.1 Off-Road Legacy Engine CO Emissions

The CO emission results for the testing on the off-road legacy engine are presented in Figure 4-11 on a g/bhp-hr basis. Table 4-13 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 for each of the test cycles.

CO emissions showed statistically significant decreases for the renewable diesel and the renewable diesel/biodiesel blends for both the NRTC and D2 cycles. The reductions for the NRTC compared to the CARB reference fuel were 22% for R100, 26% for R65/B35, and 32% for R50/B50. The reductions for the D2 cycle compared to the CARB reference fuel were 14% for R100, 28% for R65/B35, and 32% for R50/B50.

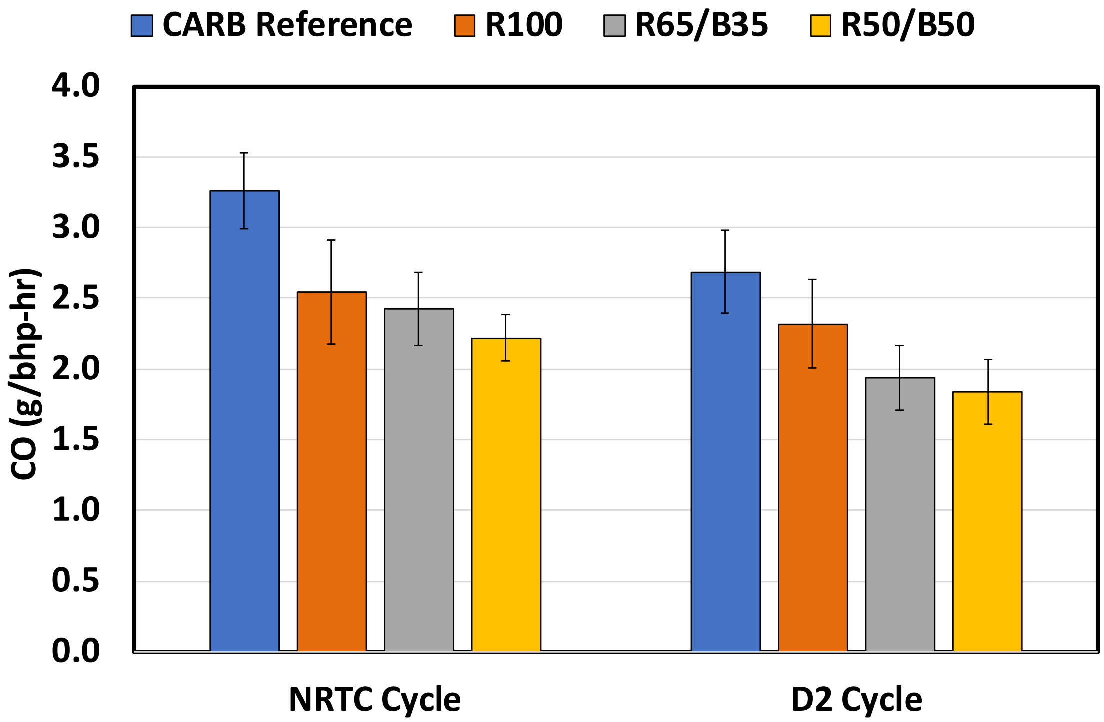

Figure 4-11. Average CO Emission Results for the Off-Road Legacy Engine Testing

Table 4-13. CO Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	3.26	-	-
	R100	**2.55**	**-22**	**0.00**
	R65/B35	**2.43**	**-26**	**0.00**
	R50/B50	**2.22**	**-32**	**0.00**
D2	CARB reference fuel	2.69	-	-
	R100	**2.32**	**-14**	**0.01**
	R65/B35	**1.94**	**-28**	**0.00**
	R50/B50	**1.84**	**-32**	**0.00**

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

4.4.2 On-Road NTDE CO Emissions

CO emissions for the on-road NTDE are presented in Figure 4-12 for all tests. Table 4-14 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 for each of the test cycles. It should be noted that for the on-road NTDE, a subset of outlier tests were observed over the FTP that were not include in the data presented in this subsection. These data are discussed in greater detail in Appendix A. For the FTP cycle, no statistically significant changes in CO emissions were found for any of the test biofuels relative to the CARB reference fuel. The RMC cycle showed a slight reduction of 5% with R100, with no statistical difference in CO emissions observed with the R65/B35 and R50/B50 blends.

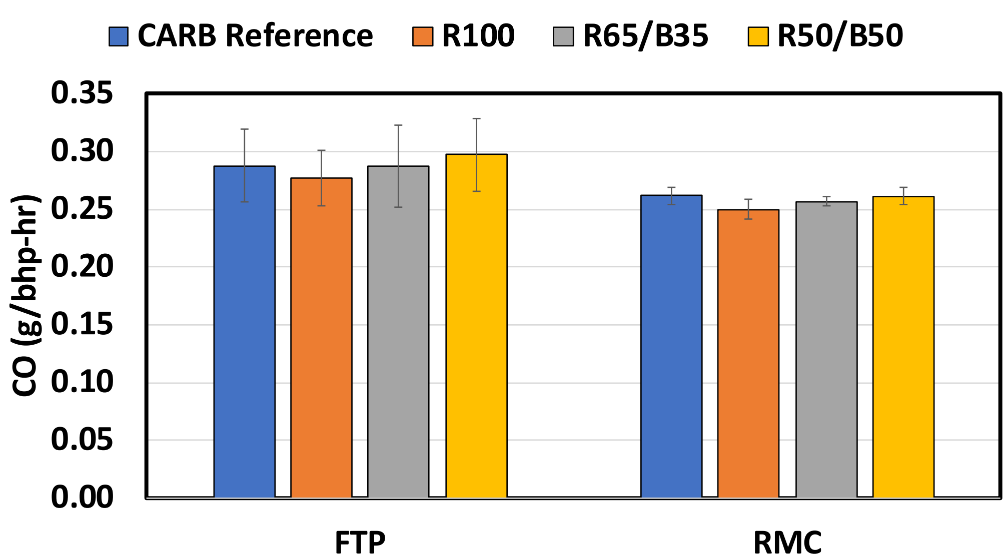

Figure 4-12. Average CO Emission Results for the On-Road NTDE Testing

Table 4-14. CO Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the On-Road NTDE Testing

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
FTP	CARB reference fuel	0.30	-	-
	R100	0.28	-5	0.21
	R65/B35	0.29	-2	0.74
	R50/B50	0.30	-2	0.75
RMC	CARB reference fuel	0.26	-	-
	R100	**0.25**	**-5**	**0.00**
	R65/B35	0.26	-2	0.11
	R50/B50	0.26	-0	0.93

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

4.4.3 Off-Road NTDE CO Emissions

CO emissions for the off-road NTDE are presented in Figure 4-13 for all tests. Table 4-15 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 for each of the test cycles. For the NRTC, measurable, but low CO emissions were found for the CARB reference fuel and R100. The NRTC CO emissions for the R100 fuel were 44% lower than those for the CARB reference fuel. The NRTC CO emissions for the R65/B35 and R50/B50 fuels were much lower than those for the CARB reference fuel and R100 fuels, and were near or below the background levels for all tests. The C1 CO emissions were at or below background levels for all tests. It should be noted that the engine out measurements showed measurable CO emissions were being generated by the engine during combustion for both test cycles and the different fuels, but that most of the CO emissions spikes were low enough that the CO emissions were eliminated by the DOC/DPF to levels where the CO tailpipe emissions were essentially only appreciably above the background levels for the CARB reference fuel and R100 tests for the NRTC cycle.

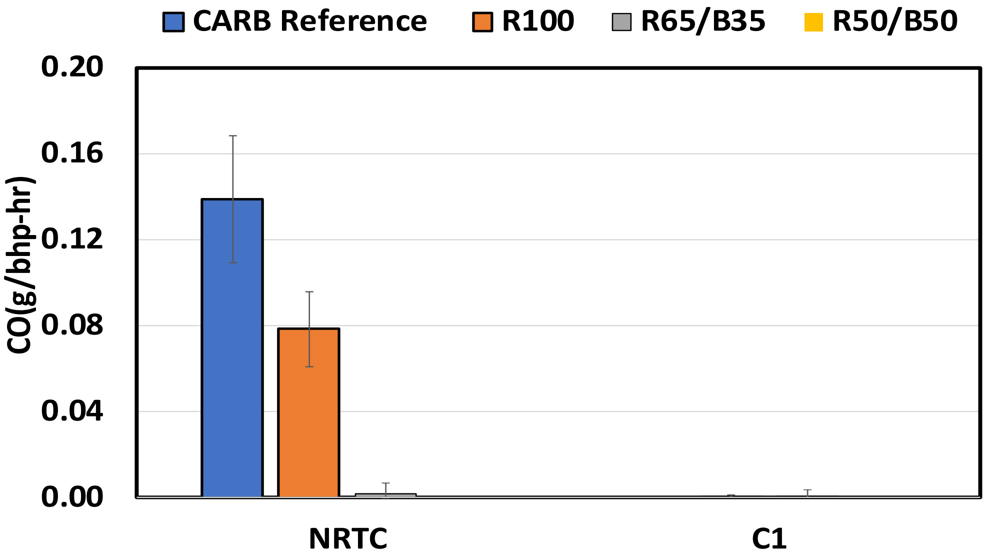

Figure 4-13. Average CO Emission Results for the Off-Road NTDE Testing

Table 4-15. CO Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road NTDE Testing

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	0.139	-	-
	R100	**0.078**	**-44**	**0.00**
	R65/B35	**0.002**	**-98**	**0.00**
	R50/B50	**0.000**	**-100**	**0.00**
C1	CARB reference fuel	0.000	-	-
	R100	0.000	-	-
	R65/B35	0.001	-	-
	R50/B50	0.000	-	-

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

4.5 CO_2 Emissions

4.5.1 Off-Road Legacy Engine CO_2 Emissions

The CO_2 emission results for the testing on the off-road legacy engine are presented in Figure 4-14 on a g/bhp-hr basis. Table 4-16 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 for each of the test cycles. For the NRTC, CO_2 emissions showed statistically significant reductions of 4.1% for R100, 2.6% for R65/B35, and 1.7% for R50/B50 compared to the CARB reference fuel. For the D2, R100 showed a statistically significant reduction in CO_2 emissions of 4.6% compared to the CARB reference fuel, while the R65/B35 and R50/B50 fuels did not show statistically significant differences compared to the CARB reference fuel.

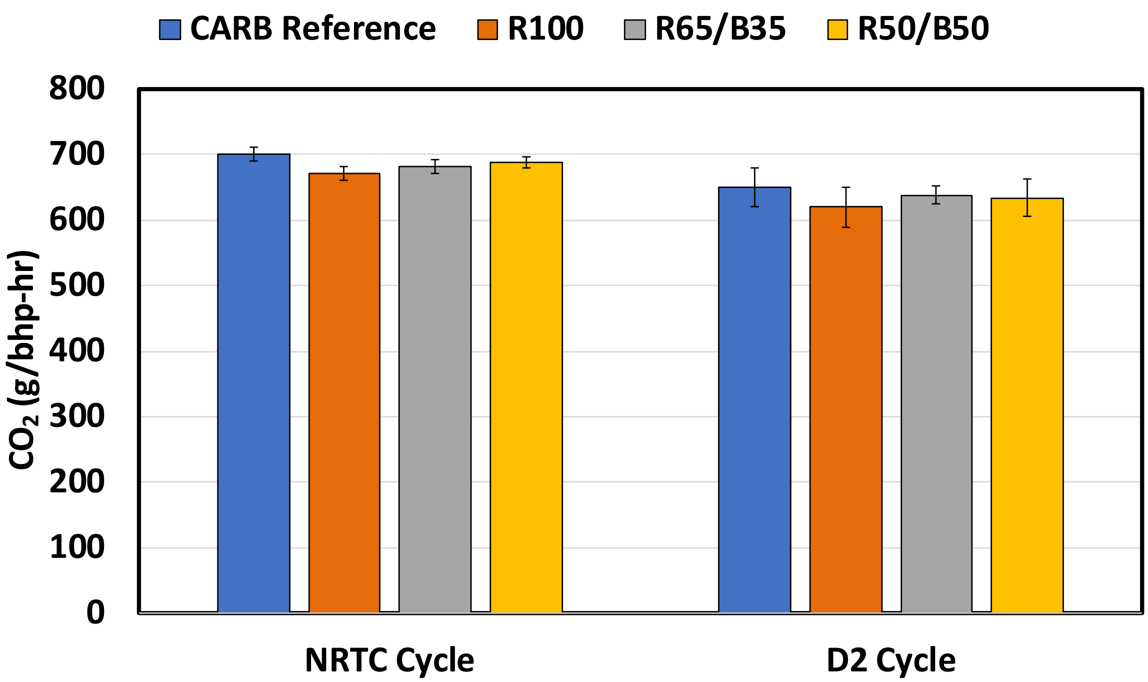

Figure 4-14. Average CO_2 Emission Results for the Off-Road Legacy Engine Testing

Table 4-16. CO_2 Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	700.1	-	-
	R100	**671.5**	**-4.1**	**0.00**
	R65/B35	**681.9**	**-2.6**	**0.00**
	R50/B50	**687.9**	**-1.7**	**0.01**
D2	CARB reference fuel	650.2	-	-
	R100	**620.5**	**-4.6**	**0.02**
	R65/B35	638.5	-1.8	0.26
	R50/B50	634.1	-2.5	0.18

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

4.5.2 On-Road NTDE CO_2 Emissions

The CO_2 emission results for the testing on the on-road NTDE are presented in Figure 4-15 on a g/bhp-hr basis. Table 4-17 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 for each of the test cycles. It should be noted that for the on-road NTDE, a subset of outlier tests were observed over the FTP that were not include in the data presented in this subsection. These data are discussed in greater detail in Appendix A.

For the on-road NTDE, CO_2 emissions from the FTP showed statistically significant decreases of 3.2% for R100, 0.9% for R65/B35, and 0.8% for R50/B50 compared to the CARB reference fuel. The RMC showed statistically significant decreases of 2.9% for R100 and 0.5% for R65/B35, and a marginally statistically significant increase of 0.3% for R50/B50 compared to the CARB reference fuel.

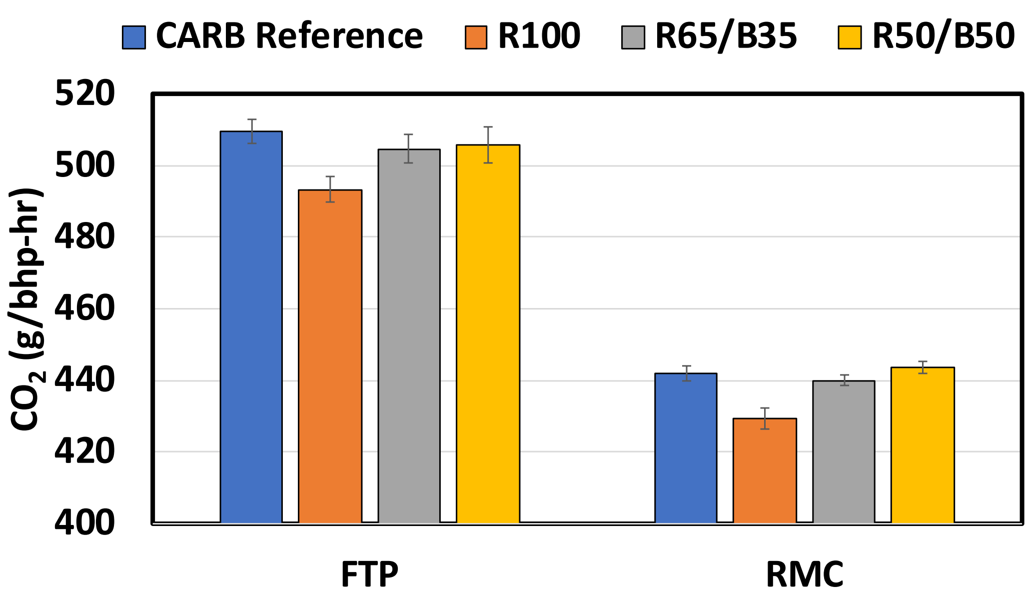

Figure 4-15. Emission Results for the On-Road NTDE Testing

Table 4-17. CO_2 Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel or the On-Road NTDE Testing

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
FTP	CARB reference fuel	509.4	-	-
	R100	**493.3**	**-3.2**	**0.00**
	R65/B35	**504.6**	**-0.9**	**0.01**
	R50/B50	**505.1**	**-0.8**	**0.04**
RMC	CARB reference fuel	442.0	-	-
	R100	**429.4**	**-2.9**	**0.00**
	R65/B35	**440.0**	**-0.5**	**0.02**
	R50/B50	443.5	0.3	0.08*

Statistically significant results are bolded and their percent differences are shown in red text.
*Indicates marginally statistically significant result.

4.5.3 Off-Road NTDE CO_2 Emissions

CO_2 results for the off-road NTDE are presented in Figure 4-16 on a gallons/bhp-hr basis. Table 4-18 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 for each of the test cycles. CO_2 emissions showed statistically significant reductions for the R100 fuel of 3.8% for the FTP and of 3.0% for the D2 cycle compared to the CARB reference fuel. CO_2 emissions did not show statistically significant differences for the R65/B35 and R50/B50 fuels compared to the CARB reference fuel for either the NRTC or C1 cycles.

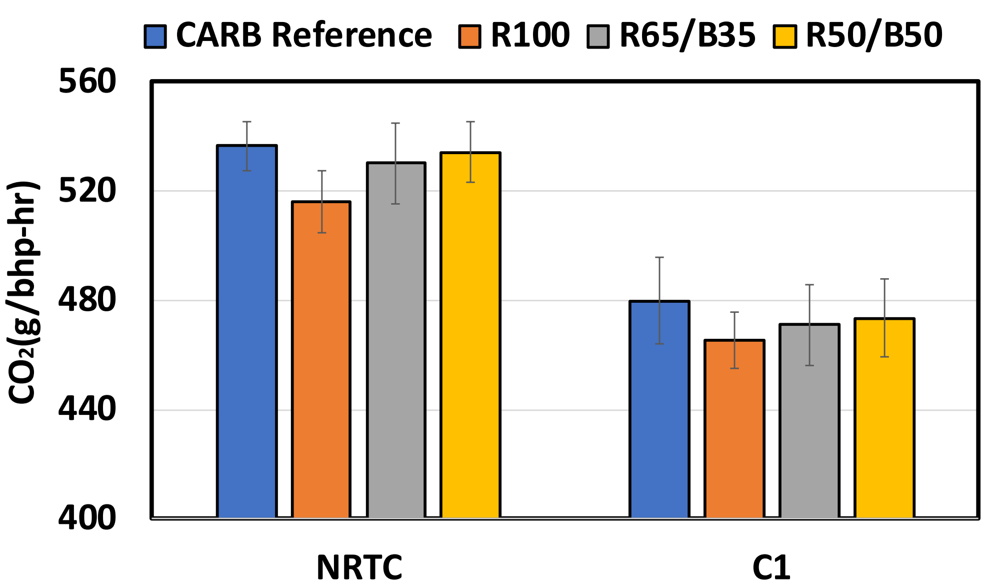

Figure 4-16. Average CO_2 Emission Results for the Off-Road NTDE Testing

Table 4-18. CO_2 Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road NTDE Testing

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	536.5	-	-
	R100	**516.0**	**-3.8**	**0.00**
	R65/B35	530.3	-1.2	0.24
	R50/B50	534.2	-0.4	0.59
C1	CARB reference fuel	479.9	-	-
	R100	**465.6**	**-3.0**	**0.03**
	R65/B35	471.0	-1.8	0.22
	R50/B50	473.5	-1.3	0.42

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

4.6 Brake Specific Fuel Consumption (BSFC)

4.6.1 Off-Road Legacy Engine BSFC

The BSFC results for the off-road legacy engine are presented in Figure 4-17 on a gallons/bhp-hr basis. BSFC was calculated via the carbon balance method. Table 4-19 shows the average BSFC values 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 for each of the test cycles. BSFC showed statistically significant increases ranging from 3.5% for R100, 3.8% for R65/B35, and 4.4% for R50/B50 compared to the CARB reference fuel for the NRTC cycle. For the D2 cycle, there was no statistically significant change in BSFC for R100. For the D2 cycle, the R65/B35 showed a statistically significant BSFC increase of 4.5% and the R50/B50 showed a marginally statistically significant BSFC increase of 3.4% compared to the CARB reference fuel.

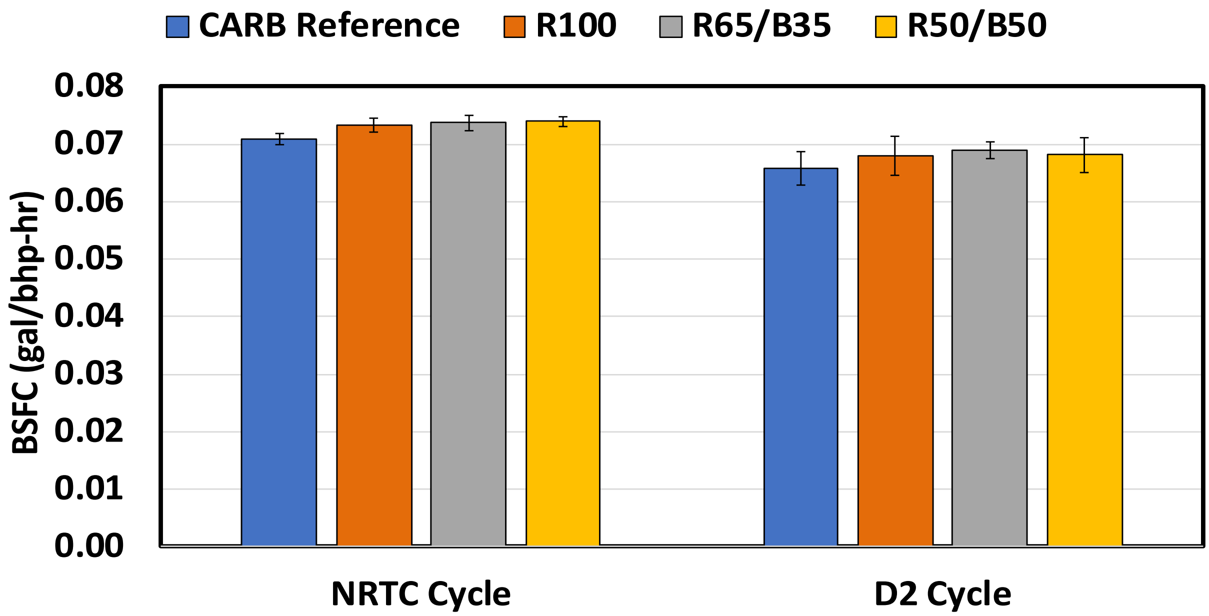

Figure 4-17. Average Brake Specific Fuel Consumption Results for the Off-Road Legacy Engine Testing

Table 4-19. BSFC (gal/bhp-hr), and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine

Cycle	Fuel Type	Ave. (gal/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	0.071	-	-
	R100	**0.073**	**3.5**	**0.00**
	R65/B35	**0.074**	**3.8**	**0.00**
	R50/B50	**0.074**	**4.4**	**0.00**
D2	CARB reference fuel	0.066	-	-
	R100	0.068	3.0	0.13
	R65/B35	**0.069**	**4.5**	**0.01**
	R50/B50	0.068	3.4	0.07*

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

4.6.2 On-Road NTDE BSFC

BSFC results for the on-road NTDE are presented in Figure 4-18 on a gallons/bhp-hr basis. BSFC was calculated via the carbon balance method. Table 4-20 shows the average BSFC values 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 for each of the test cycles. It should be noted that for the on-road NTDE, a subset of outlier tests were observed over the FTP that were not include in the data presented in this subsection. These data are discussed in greater detail in Appendix A.

BSFC for the FTP cycle showed statistically significant increases in fuel consumption per bhp-hr for all of the biofuels, ranging from 4.8% for R100, 6.0% for R65/B35, and 5.7% for R50/B50. The RMC cycle also showed statistically significant increases in fuel consumption for all of the biofuels, ranging from 5.1% for R100, 6.5% for R65/B35, and 7.0% for R50/B50 when compared to the CARB reference fuel.

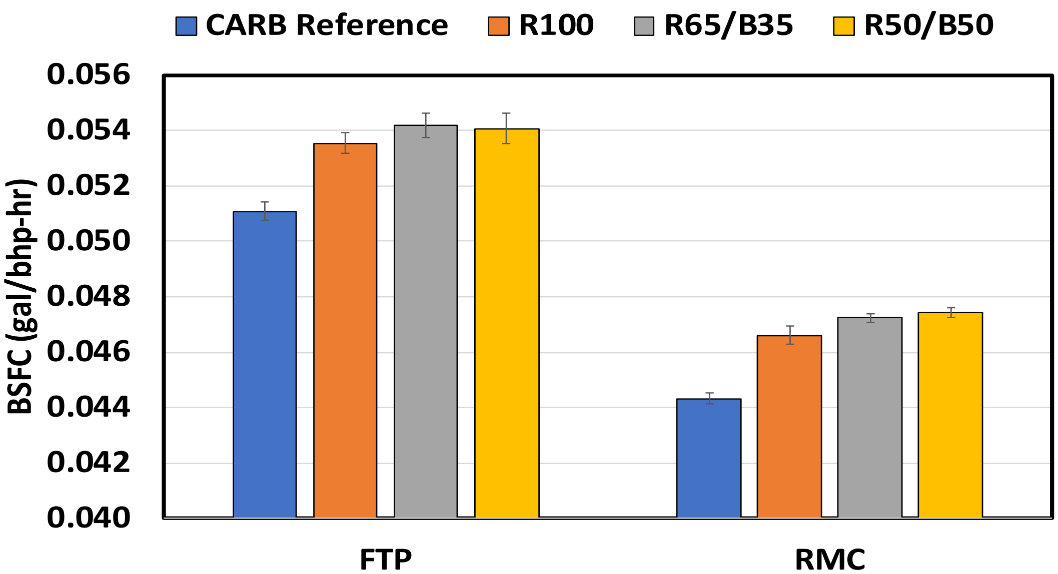

Figure 4-18. Average BSFC Results for the On-Road NTDE Testing

Table 4-20. BSFC, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the On-Road NTDE Testing

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
FTP	CARB reference fuel	0.051	-	-
	R100	**0.054**	**4.8**	**0.00**
	R65/B35	**0.054**	**6.0**	**0.00**
	R50/B50	**0.054**	**5.7**	**0.00**
RMC	CARB reference fuel	0.044	-	-
	R100	**0.047**	**5.1**	**0.00**
	R65/B35	**0.047**	**6.5**	**0.00**
	R50/B50	**0.047**	**7.0**	**0.00**

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

4.6.3 Off-Road NTDE BSFC

BSFC results for the off-road NTDE are presented in Figure 4-19 on a gallons/bhp-hr basis. BSFC was calculated via the carbon balance method. Table 4-21 shows the average BSFC values 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 for each of the test cycles. BSFC showed statistically significant increases for the NRTC cycle ranging from 4.1% for R100, 5.8% for R65/B35, and 6.1% for the R50/B50 fuels compared to the CARB reference fuel. For the C1 cycle, BSFC showed statistically significant increases ranging from 5.0% for R100, 5.1% for R65/B35, and 5.2% for the R50/B50 fuels when compared to the CARB reference fuel.

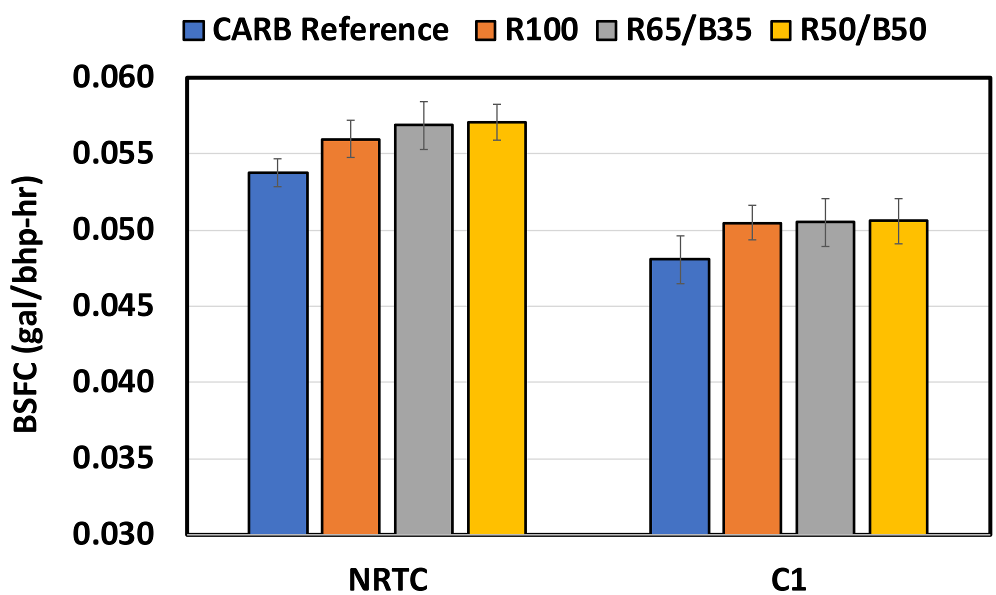

Figure 4-19. Average BSFC Results for the Off-Road NTDE Testing

Table 4-21. Average BSFC and Percentage Differences Between the Renewable/Biodiesel Fuels and the CARB Reference Fuel for the Off-Road NTDE Testing

Cycle	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	0.054	-	-
	R100	**0.056**	**4.1**	**0.00**
	R65/B35	**0.057**	**5.8**	**0.00**
	R50/B50	**0.057**	**6.1**	**0.00**
C1	CARB reference fuel	0.048	-	-
	R100	**0.050**	**5.0**	**0.00**
	R65/B35	**0.051**	**5.1**	**0.00**
	R50/B50	**0.051**	**5.2**	**0.01**

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

4.7 Total and Solid Particle Number Emissions

Measurements of total particle number (TPN) and solid particle number (SPN) emissions were made for the off-road legacy engine and on-road NTDE. SPNs represent measurements of solid particles above 23 nm in diameter, as defined by the European Union solid particle number emissions regulations. TPN and SPN emissions in #/bhp-hr for each engine, fuel, and cycle are shown in Figure 4-20. Note that the off-road legacy engine TPN and SPN emissions are divided by a factor of 1000 in order to effectively show both engines on the same figure. Table 4-22 and Table 4-23 show the average emissions for the legacy off-road engine 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 for each of the test cycles for the TPN and SPN, respectively. Table 4-24 and Table 4-25 show the average emissions for the off-road NTDE 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 for each of the test cycles for the TPN and SPN, respectively. It should be noted that for the on-road NTDE, a subset of outlier tests were observed over the FTP that were not include in the data presented in this subsection. These data are discussed in greater detail in Appendix A.

For both engines, the biofuel blends generally showed a reduction in both TPN and SPN emissions, with the exception of TPN for R100 fuel for the off-road legacy engine D2 cycle that also showed a relatively large measurement variability, as indicated by the wide error bar. TPN and SPN emissions for both engines were seen in lower levels for the higher biodiesel blends relative to R100 and CARB reference fuel. These trends are consistent with those seen for the PM mass from the off-road legacy engine, where the PM mass emissions are well above the background levels.

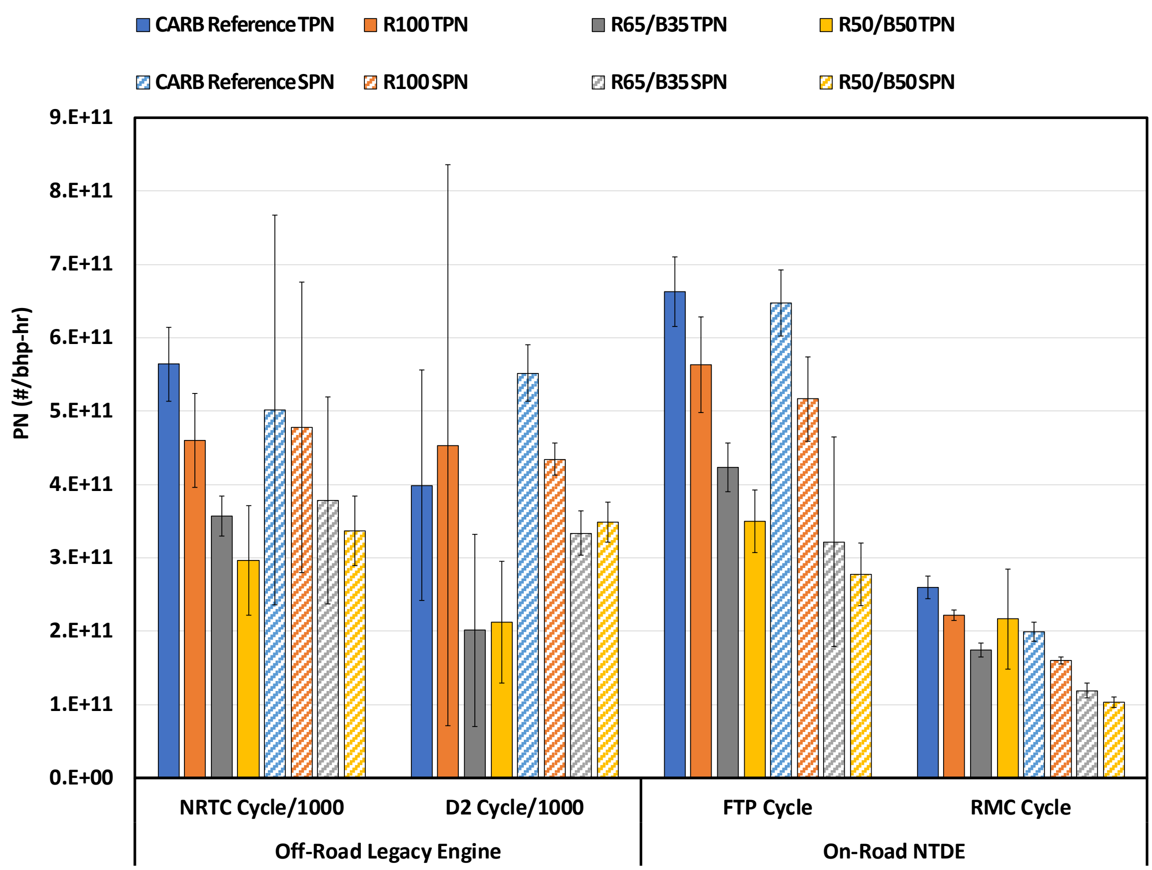

Figure 4-20. Average Total Particle Number and Solid Particle Number Emissions for the Off-Road Legacy Engine and On-Road NTDE Testing

Table 4-22. TPN Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Testing

Cycle	Fuel Type	Ave. (#/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	5.6E+14	-	-
	R100	**4.7E+14**	**-16**	**0.00**
	R65/B35	**3.6E+14**	**-37**	**0.00**
	R50/B50	**3.2E+14**	**-43**	**0.00**
D2	CARB reference fuel	4.0E+14	-	-
	R100	4.5E+14	14	0.61
	R65/B35	**2.0E+14**	**-50**	**0.02**
	R50/B50	**2.1E+14**	**-47**	**0.01**

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

Table 4-23. SPN Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the Off-Road Legacy Engine Testing

Cycle	Fuel Type	Ave. (#/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NRTC	CARB reference fuel	6.7E+14	-	-
	R100	**5.4E+14**	**-19**	**0.00**
	R65/B35	**4.2E+14**	**-37**	**0.00**
	R50/B50	**3.5E+14**	**-48**	**0.00**
D2	CARB reference fuel	5.5E+14	-	-
	R100	**4.3E+14**	**-21**	**0.00**
	R65/B35	**3.3E+14**	**-40**	**0.00**
	R50/B50	**3.5E+14**	**-37**	**0.00**

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

Table 4-24. TPN Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the On-Road NTDE Testing

Cycle	Fuel Type	Ave. (#/bhp.hr)	% Diff vs. CARB	p-value (t-test)
FTP	CARB reference fuel	6.7E+11	-	-
	R100	**5.6E+11**	**-16**	**0.00**
	R65/B35	**4.2E+11**	**-37**	**0.00**
	R50/B50	**3.5E+11**	**-48**	**0.00**
RMC	CARB reference fuel	2.6E+11	-	-
	R100	**2.2E+11**	**-14**	**0.00**
	R65/B35	**1.7E+11**	**-33**	**0.00**
	R50/B50	**2.2E+11**	**-16**	**0.03**

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

Table 4-25. SPN Emissions, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the On-Road NTDE Testing

Cycle	Fuel Type	Ave. (#/bhp.hr)	% Diff vs. CARB	p-value (t-test)
FTP	CARB reference fuel	6.6E+11	-	-
	R100	**5.2E+11**	**-22**	**0.00**
	R65/B35	**3.2E+11**	**-51**	**0.00**
	R50/B50	**2.8E+11**	**-57**	**0.00**
RMC	CARB reference fuel	2.0E+11	-	-
	R100	**1.6E+11**	**-19**	**0.00**
	R65/B35	**1.2E+11**	**-40**	**0.00**
	R50/B50	**1.0E+11**	**-48**	**0.00**

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

4.8 Particle Size Distributions

4.8.1 Off-Road Legacy Engine PSDs

Figure 4-21 shows the particle size distributions (PSD) of all fuels/test cycle combinations for the off-road legacy engine. Diesel-generated combustion particles are typically divided into three modes, including the nucleation mode (5-50 nm diameter), the accumulation mode (50-1,000 nm diameter), and the coarse mode (1,000-10,000 nm diameter). The nucleation mode typically consists of organic volatile compounds and can contain ash and soot particles. Most soot particles agglomerate, however, and are usually found in the accumulation mode. Coarse mode particles are typically from larger soot particles breaking off of the exhaust walls.

For the off-road legacy engine, the R100, R65/R35, and R50/B50 fuels showed reductions in particle counts per bhp-hr over most of the particle size range compared to the CARB reference fuel for both cycles. These reductions were most significant for the larger particles in the accumulation mode, although reductions were also found in the nucleation size range, peaking around 30 nm, for most of the biofuels relative to the CARB reference fuel. The R100 showed higher particle counts than the R65/B35 and R50/B50 fuels in the nucleation mode size range for both cycles and in the accumulation mode particle size range for the NRTC.

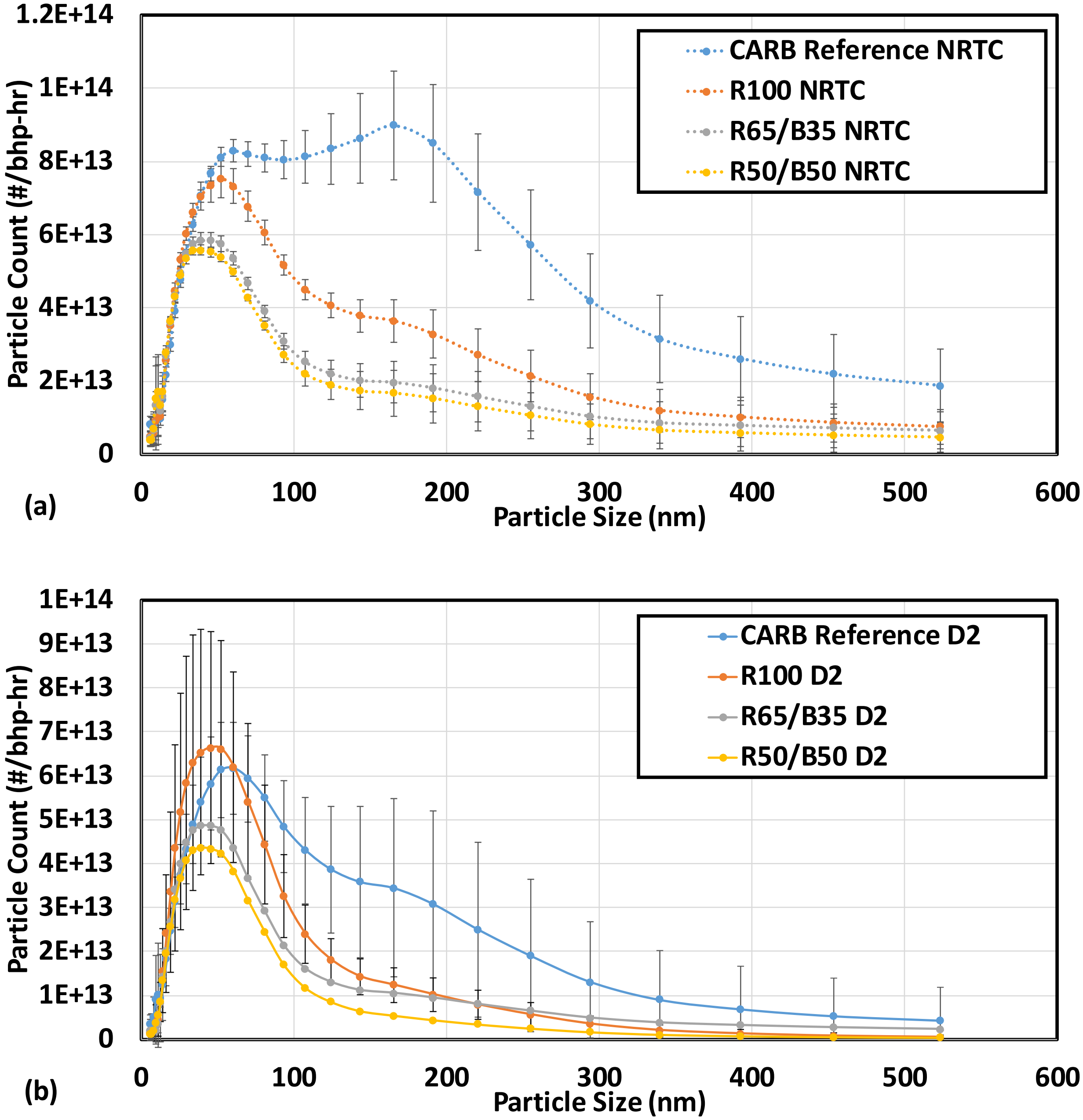

Figure 4-21. Particle Size Distributions for the Off-Road Legacy Engine Testing on (a) NRTC cycle and (b) D2 cycle

4.8.2 On-Road NTDE PSDs

Figure 4-22 shows the PSDs of all fuels/test cycle combinations for the on-road NTDE. The on-road NTDE generally only showed particle sizes less than 100 nm, suggesting the DPF effectively reduced the accumulation and coarse particles. Figure 4-22 was shortened to only show particle size range from 0 to 200 nm in order to better show emission differences between fuels. Nucleation mode particles were about an order of magnitude lower than those measured for the off-road legacy engine. The lower nucleation mode particles for the on-road NTDE were a consequence of the DPF/DOC system. Surprisingly, the R65/B35 fuel showed the highest emissions for the FTP cycle, but also showed large measurement variability, as indicated by the wide error bars. Over the full test matrix, however, the use of biofuel blends generally resulted in lower particle counts in the different size ranges compared to the CARB reference fuel.

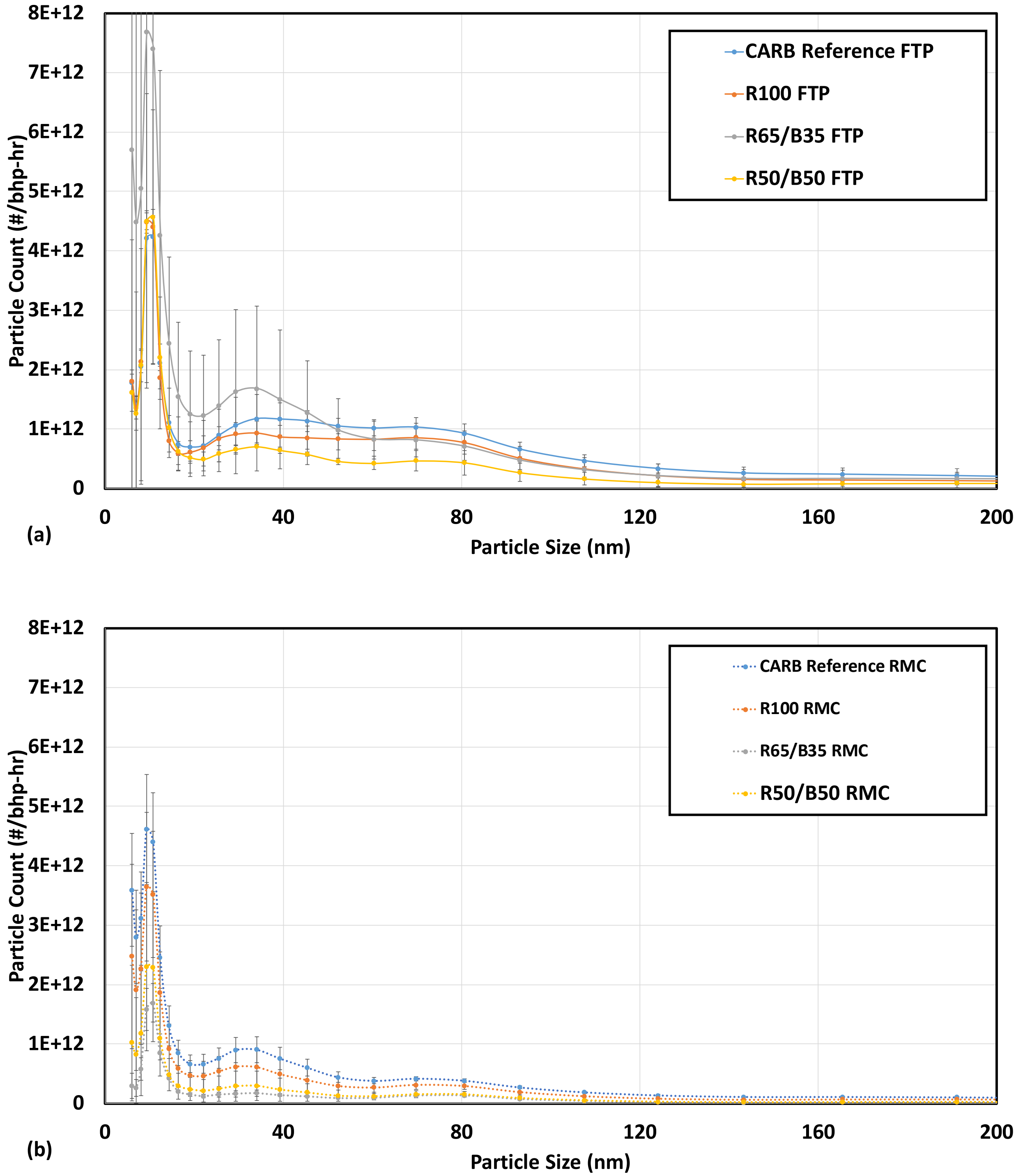

Figure 4-22. Particle Size Distributions for the On-Road NTDE (a) on FTP cycle and (b) RMC cycle

5 Summary and Conclusions

CARB is evaluating the potential for use of renewable diesel and renewable diesel/biodiesel blends to reduce NOx and PM for on-road and off-road diesel-powered vehicles and equipment. The goal of this study was the characterize the emissions and performance of renewable diesel and renewable diesel/biodiesel blends in legacy engines and NTDEs. For this study, emissions testing was conducted on renewable diesel and renewable diesel/biodiesel blends in an off-road legacy engine and heavy-duty on-road and off-road NTDEs using an engine dynamometer. This study focused on engine dynamometer measurements. The engine dynamometer testing included two off-road engines with different levels of emissions control technology (i.e., one legacy and one NTDE) and one on-road heavy-duty NTDE. Testing was conducted on a CARB reference fuel, pure renewable diesel, and two renewable diesel/biodiesel blends. Testing was conducted on at least two test cycles per engine, including the NRTC or FTP transient cycles and different steady state ramped modal cycles.

A summary of the results is below for each of the pollutants measured. It should be noted that for the on-road NTDE, a subset of outlier tests were observed over the FTP that were not included in the data presented in the Summary and Conclusions section. These data are discussed in greater detail in Appendix A.

NOx Emissions

NOx emissions results for the testing on the off-road legacy engine showed the lowest emissions for the R100 for both the NRTC and D2 cycles. R100 showed statistically significant reductions of 5.4% for the NRTC and 4.9% for the D2 cycle compared to the CARB reference fuel. The R65/B35 showed no statistically significant differences compared to the CARB reference fuel for either the NRTC or the D2 cycles. The R50/B50 showed statistically significant increases of 1.8% for the NRTC and 4.2% for the D2 cycle compared to the CARB reference fuel.

For the on-road NTDE, no statistically significant differences in NOx emissions were found between the CARB reference fuel and R100 over either the FTP or RMC cycles. The FTP cycle showed statistically significant increases of 46.6% for R65/B35 and 49.5% for R50/B50. The RMC cycle showed statistically significant increases of 14.2% for R65/B35 and 15.4% for R50/B50. Engine out NOx sensor data for the RMC cycle showed that there are increases in engine out NOx levels for the biodiesel blends, which is likely a key factor contributing to the higher tailpipe emissions for the renewable diesel/biodiesel blends. Comparison of the engine out and tailpipe NOx data showed that the SCR provided a 95% to 96% reduction in NOx emissions for the different fuels.

For the off-road NTDE, no statistically significant differences in NOx emissions were found between the CARB reference fuel and R100 for the NRTC or C1 cycles. The NRTC showed statistically significant increases of 88.3% for R65/B35 blend and 149.6% for the R50/B50 blend. The C1 cycle showed statistically significant increases of 55.1% for the R65/B35 blend and 119.4% for the R50/B50 blend. The engine out data show consistently higher emissions for the R65/B35 and R50/B50 fuels compared with the CARB reference fuel for both cycles. The engine out data did not show any statistically significant differences between the R100 and the CARB reference fuel for either cycle. Comparison of the engine out and tailpipe NOx data showed that the SCR provided NOx reduction efficiencies of 93% for the CARB reference fuel, 91% for R100, 88% for R65/B35, and 85% for R50/B50. The SCR provided NOx reductions of 98% to 99% for all fuels for the C1 cycle.

PM Emissions

For the off-road legacy engine, PM emissions showed decreases for the renewable diesel and the renewable diesel/biodiesel blends for both the NRTC and the D2 cycle. The reductions for the NRTC compared to the CARB reference fuel were 38% for R100, 53% for R65/B35, and 63% for R50/B50. The reductions for the D2 compared to the CARB reference fuel were 27% for R100, 51% for R65/B35, and 58% for R50/B50 fuel.

For the on-road NTDE, PM mass emissions in general were low and near background levels, and averaged less than 0.001 mg/bhp-hr for all tests conditions and both cycles. As the PM standard for heavy-duty on-road engines is 0.01 g/bhp-hr, the PM emissions observed are for the most part at least 20-fold lower than the PM standard. The PM emissions for the different fuels generally did not show statistically significant differences, with the exception of the R50/B50, which had emissions that were lower than those for the CARB reference fuel at a marginally statistically significant level over the FTP cycle.

For the off-road NTDE, PM mass emissions were more than a factor of 30 below the 0.015 g/bhp-hr PM standard for Tier 4 off-road engines in this size category for all test conditions and both cycles. No statistically significant differences in PM mass emissions were seen between fuels for either test cycle.

THC Emissions

For the off-road legacy engine, THC emissions showed significant decreases for renewable diesel and the renewable diesel/biodiesel blends for both the NRTC and D2 cycles. The reductions for the NRTC compared to the CARB reference fuel were 45% for R100, 49% for R65/B35, and 66% for R50/B50. The reductions for the D2 compared to the CARB reference fuel were 35% for R100, 58% for R65/B35, and 71% for R50/B50.

For the on-road NTDE, THC emissions were near or below background levels for all tests conditions and both cycles. For the FTP, only R50/B50 showed a statistically significant reduction relative to the CARB reference fuel, with R100 and R65/B35 showing no statistically significant differences in THC emissions relative to the CARB reference fuel. For the RMC cycle, THC emissions levels were below the background levels for all tests, and hence there were no measurable THC emissions.

For the off-road NTDE, THC emissions were below the background levels for both the NRTC and C1 cycles and for all fuels, so no fuel differences were seen.

CO Emissions

For the off-road legacy engine, CO emissions showed statistically significant decreases for the renewable diesel and the renewable diesel/biodiesel blends for both the NRTC and D2 cycles. The reductions for the NRTC compared to the CARB reference fuel were 22% for R100, 26% for

R65/B35, and 32% for R50/B50. The reductions for the D2 cycle compared to the CARB reference fuel were 14% for R100, 28% for R65/B35, and 32% for R50/B50.

For the on-road NTDE, the FTP showed no statistically significant changes in CO emissions for any of the test biofuels relative to the CARB reference fuel. The RMC showed a slight reduction of 5% with R100, with no statistical difference in CO emissions observed with the R65/B35 and R50/B50 blends.

For the off-road NTDE, for the NRTC, measurable, but low CO emissions were found for the CARB reference fuel and R100. The NRTC CO emissions for the R100 fuel were 44% lower than those for the CARB reference fuel. The NRTC CO emissions for the R65/B35 and R50/B50 fuels were much lower than those for the CARB reference fuel and R100 fuels, and were near or below the background levels for all tests. For the C1 cycle, CO emissions were near or below background levels for all tests.

CO_2 Emissions

For the off-road legacy engine, for the NRTC, CO_2 emissions showed statistically significant reductions of 4.1% for R100, 2.6% for R65/B35, and 1.7% for R50/B50 compared to the CARB reference fuel. For the D2 cycle, R100 showed a statistically significant reduction in CO_2 emissions of 4.6% compared to the CARB reference fuel, while the R65/B35 and R50/B50 fuels did not show statistically significant differences compared to the CARB reference fuel.

For the on-road NTDE, CO_2 emissions from the transient cycle showed statistically significant decreases of 3.2% for R100, 1.0% for R65/B35, and 0.9% for R50/B50 compared to the CARB reference fuel. The steady state cycle showed statistically significant decreases of 2.9% for R100 and 0.5% for R65/B35, and a marginally statistically significant increase of 0.3% for R50/B50 compared to the CARB reference fuel.

For the off-road NTDE, CO_2 emissions showed statistically significant reductions for the R100 of 3.8% for the FTP and of 3.0% for the D2 cycle compared to the CARB reference fuel. CO_2 emissions did not show statistically significant differences for the R65/B35 and R50/B50 fuels compared to the CARB reference fuel for either the NRTC or C1 cycles.

Brake Specific Fuel Consumption (BSFC)

For the off-road legacy engine, BSFC showed statistically significant increases ranging from 3.5% for R100, 3.8% for R65/B35, and 4.4% for R50/B50 compared to the CARB reference fuel for the NRTC cycle. For the D2 cycle, there was no statistically significant change in BSFC for R100. For the D2 cycle, the R65/B35 showed a statistically significant BSFC increase of 4.5% and the R50/B50 showed a marginally statistically significant BSFC increase of 3.4% compared to the CARB reference fuel.

For the on-road NTDE, BSFC for the transient cycle showed statistically significant increases in fuel consumption per bhp-hr for all of the biofuels, ranging from 4.8% for R100, 6.0% for R65/B35, and 57% for R50/B50. The steady state cycle also showed statistically significant increases in fuel consumption for all of the biofuels, ranging from 5.1% for R100, 6.6% for R65/B35, and 7.0% for R50/B50 when compared to the CARB reference fuel.

For the off-road NTDE, BSFC showed statistically significant increases for the NRTC BSFC ranging from 4.1% for R100, 5.8% for R65/B35, and 6.1% for the R50/B50 fuels compared to the CARB reference fuel. For the C1 cycle, BSFC showed statistically significant increases ranging from 5.0% for R100, 5.1% for R65/B35, and 5.2% for the R50/B50 fuels when compared to the CARB reference fuel.

Total and Solid Particle Number Emissions

Additional measurements of total and solid particle number emissions were made for the off-road legacy engine and on-road NTDE. Solid particle number represent measurements of solid particles greater than 23 nm in diameter, as defined by the European Union solid particle number emissions regulations. For both engines, the biofuel blends generally showed a reduction in both TPN and SPN emissions, with the exception of total particle number for R100 fuel for the D2 cycle that also showed a relatively large measurement variability. TPN and SPN emissions for the higher biodiesel blends were lower than the R100 and CARB reference fuel. These trends are consistent with those seen for the PM mass from the off-road legacy engine, where the PM mass emissions are well above the background levels.

Particle Size Distributions

For the off-road legacy engine, the R100, R65/R35, and R50/B50 fuels showed reductions in particle counts per bhp-hr over most of the particle size range compared to the CARB reference fuel for both cycles. These reductions were most significant for the larger particles in the accumulation mode (50-1,000 nm), although reductions were also found in the nucleation size range (5-50 nm), peaking around 30 nm, for most of the biofuels relative to the CARB reference fuel. The R100 showed higher particle counts than the R65/B35 and R50/B50 fuels in the nucleation mode size range for both cycles and in the accumulation mode particle size range for the NRTC.

For the on-road NTDE, nucleation mode particles were about an order of magnitude lower than those measured for the off-road legacy engine. The R65/B35 fuel showed the highest emissions for the FTP cycle, but also showed large measurement variability. Over the full test matrix, however, the use of biofuel blends generally resulted in lower particle counts in the different size ranges compared to the CARB reference fuel.

Conclusions

For NOx emissions, the results for this legacy engine are consistent with previously observed reductions in NOx emissions with R100 as the test fuel, and increased emissions of NOx from the use of biodiesel in fuel. They are also consistent with the observations that renewable diesel in a renewable diesel/biodiesel blend can reduce NOx emissions arising from the use of biodiesel, with the highest ratio of renewable diesel to biodiesel (R65/B35) in this study resulting in NOx emissions that were not significantly different from CARB reference fuel (also referred to as a NOx-neutral ratio), while the R50/B50 blend (the lowest ratio of renewable diesel to biodiesel) did result in higher NOx emissions than CARB reference fuel. Therefore, the renewable diesel in the R50/B50 blend did not sufficiently reduce NOx emissions from biodiesel such that emissions are NOx neutral, while the R65/B35 blend did result in NOx-neutral emissions.

NOx emissions from both NTDEs with R100 as the test fuel were not statistically different than the CARB reference fuel. NOx emissions in the renewable diesel/biodiesel blends were statistically higher than the CARB reference fuel for both NTDEs, with emissions increasing as the renewable diesel to biodiesel ratio decreased (i.e., biodiesel concentration increased and renewable diesel concentrations decreased), although the NOx emissions increases were not linear. These results indicate that in these particular NTDEs, equipped with state-of-the-art emissions control systems, NOx emissions resulting from the two renewable diesel/biodiesel blends tested (R65/B35 and R50/B50) were not completely controlled, i.e., were not NOx-neutral relative to CARB reference fuel, although the NOx emissions overall in the NTDE engines were orders of magnitude lower than those from the legacy engine.

PM emissions in the legacy off-road engine showed statistically significant reductions in comparison to the CARB reference fuel for all test biofuels and both cycles, with the greatest PM reductions observed in the blends with the renewable diesel/biodiesel ratios (highest biodiesel concentrations), confirming previous observations that biodiesel does act to reduce PM emissions in legacy diesel engines. There were no statistical differences in PM emissions in the NTDEs observed in any test fuel or test cycle compared to the CARB reference fuel, indicating that PM emissions are effectively controlled by the exhaust aftertreatment systems, no matter the biofuel blend or test cycle.

Appendix A: Cummins FTP Outlier Discussion

It should be noted that for the on-road NTDE, there were a number of outlier tests for the FTP, where the engine appeared to be running in a slightly different operating mode compared to the other tests. The NOx emissions for these outlier tests showed emissions that were on the order of twice the NOx emissions for the non-outlier tests, with these differences being statistically significant for the test fuels that showed multiple outlier points. These same test points also showed statistically significant differences for CO and CO_2 emissions, and brake specific fuel consumption, as shown below. The FTP outlier tests also showed some differences in the ECM parameters for the engine, as shown below in Figure A-1 for the average turbocharger actuator position.

Table A-1 shows the average emissions for the FTP outlier tests for each of the measured pollutants for each test fuel, and percentage differences and the associated p-values for statistical comparisons between the CARB reference fuel and the biofuels for each of the test cycles. It should be noted that only a single outlier test was found for the R100 and R65/B35 fuels, so statistical comparisons could not be made for those fuels.

The NOx emission results for the on-road NTDE FTP outlier tests are presented in Figure A-2 on a g/bhp-hr basis. The R50/B50 showed statistically significant increases in NOx emissions compared to the CARB reference fuel, consistent with the results in section 4.1.2. For the other measurements, only BSFC showed statistically significant increases for the R50/B50 compared to the CARB reference fuel, consistent with the results in section 4.1.2

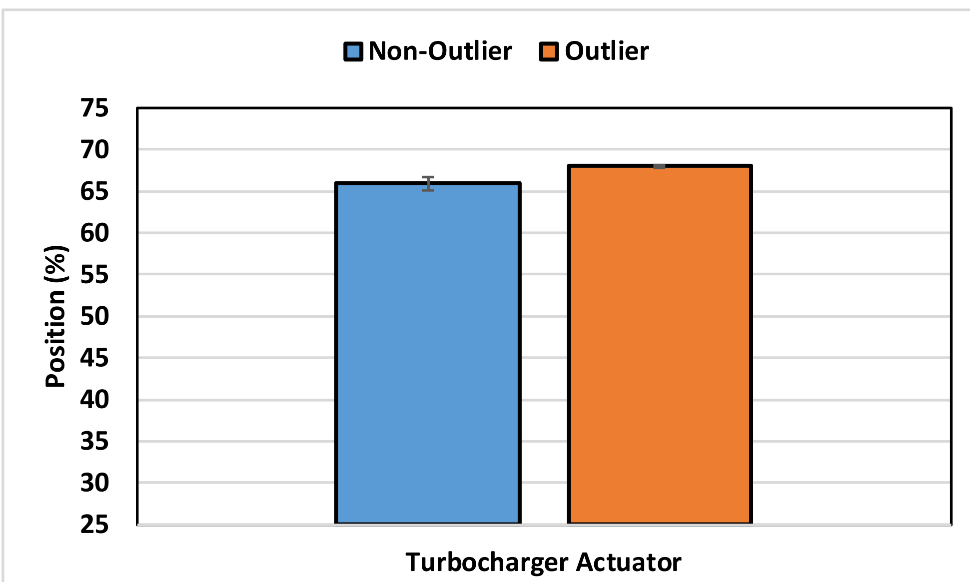

Figure A-1. Average Turbo Actuator Valve Position for the Non-Outlier and Outlier FTP Tests for the On-Road NTDE Testing

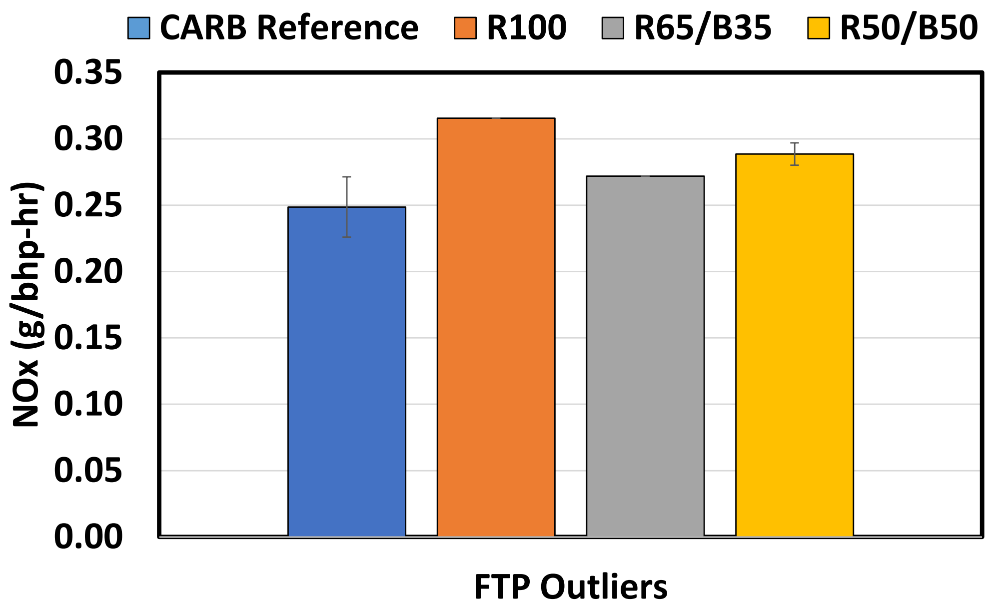

Figure A-2. Average FTP Outlier NOx Emission Results for the On-Road NTDE Testing

Table A-1. FTP Outlier Emissions for NOx, PM, THC, CO, CO2, BSFC, TPN, and SPN, and Percentage Differences and Statistical Comparisons Between Biofuels and the CARB Reference Fuel for the On-Road NTDE

Emissions	Fuel Type	Ave. (g/bhp.hr)	% Diff vs. CARB	p-value (t-test)
NOx	CARB reference fuel	0.25	-	-
	R100	0.32	26.9	-
	R65/B35	0.27	9.3	-
	R50/B50	0.28	13.5	0.09*
PM	CARB reference fuel	0.00069	-	-
	R100	0.00050	-27	-
	R65/B35	0.00021	-69	-
	R50/B50	0.00022	-67	0.29
THC	CARB reference fuel	0.001	-	-
	R100	0.000	-84	-
	R65/B35	0.000	-72	-
	R50/B50	0.000	-100	0.12
CO	CARB reference fuel	0.25	-	-
	R100	0.25	-3	-
	R65/B35	0.26	1	-
	R50/B50	0.29	13	0.13
CO_2	CARB reference fuel	495.4	-	-
	R100	486.2	-1.9	-
	R65/B35	501.3	1.2	
	R50/B50	503.9	1.7	0.15
BSFC	CARB reference fuel	0.050	-	-
	R100	0.053	6.2	-
	R65/B35	0.054	8.3	-
	R50/B50	**0.054**	**8.5**	**0.00**
TPN	CARB reference fuel	6.3E+11	-	-
	R100	-	-	-
	R65/B35	-	-	-
	R50/B50	-	-	-
SPN	CARB reference fuel	6.1E+11	-	-
	R100	-	-	-
	R65/B35	-	-	-
	R50/B50	2.2E+11	-63	-

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

Appendix B: 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 C: Southwest Research Institute Fuel Analysis Results

Table C-1. Fuel Analysis Results for CARB Diesel, B100, and R100

	Project Name		ODDB	ODDB	ODDB
	Lab Number		51651	51694	51695
Method	Sample Code		Biodiesel 100%	CARB ULSD	Renewable 100%
D1160	IBP	Deg C	330		
	05% AET	Deg C	348		
	10% AET	Deg C	348		
	20% AET	Deg C	350		
	30% AET	Deg C	350		
	40% AET	Deg C	351		
	50% AET	Deg C	351		
	60% AET	Deg C	351		
	70% AET	Deg C	352		
	80% AET	Deg C	353		
	90% AET	Deg C	354		
	95% AET	Deg C	356		
	FBP	Deg C	360		
	Pressure	mm Hg	10.0		
D287	API_60F	degAPI	28.6	38.0	49.1
	Specific Gravity	.	0.8838	0.8348	0.7835
	Density	g/ml	0.8833	0.8344	0.7831
D445 40c	Viscosity	cSt	4.399	2.544	3.031
D4629	Nitrogen	ppm	13.8	4.9	<1.0
D5186	Total Aromatics	Mass%		9.9	1.2
	MonoAromatics	Mass%		8.7	0.9
	PolyAromatics	Mass%		1.2	0.2
D5291	Carbon	wt%	77.30	86.30	84.96
	Hydrogen	wt%	12.07	13.86	15.01
D5453	Sulfur	ppm	3.03	<0.5	<0.5
D613	Cetane Number		56.7	48.1	79.6
	Cetane Number		55.8	48.3	80.1
	Cetane Number		56.6	48.2	79.8
D86	PCorrIBP	degF		395.5	285.8
	PCorrD05	degF		428.0	433.8
	PCorrD10	degF		435.7	487.7
	PCorrD15	degF		442.0	513.5
	PCorrD20	degF		448.6	526.2
	PCorrD30	degF		461.0	541.2
	PCorrD40	degF		473.9	548.1
	PCorrD50	degF		486.5	552.3
	PCorrD60	degF		499.1	555.8
	PCorrD70	degF		513.6	558.8
	PCorrD80	degF		532.4	562.1
	PCorrD90	degF		559.3	566.9
	PCorrD95	degF		581.9	573.7
	PCorrFBP	degF		601.6	586.9
	Recoverd	mL		98.0	97.6
	Residue	mL		1.2	1.3
	Loss	mL		0.8	1.1
D93	Flash Point	degF	326.0	189.0	146.0
		degC	163.0	87.0	63.0
EN14331	Ester Content	wt%	97.3		
	Methyl Linolenate	wt%	9.2		

Table C-2. Fuel Analysis Results for R65/B35 and R50/B50 Blends

	Project Name		ODDB	ODDB
	Lab Number		51652	51696
Method	Sample Code		R65/B35	R50/B50
D287	API_60F	degAPI	41.5	38.4
	Specific Gravity	.	0.8179	0.8328
	Density	g/ml	0.8175	0.8324
D445 40c	Viscosity	cSt	3.370	3.552
D4629	Nitrogen	ppm	4.8	6.8
D5453	Sulfur	ppm	1.34	1.60
D613	Cetane Number		68.4	67.6
	Cetane Number		67.6	67.7
	Cetane Number		67.1	67.7
D86	PCorrIBP	degF	315.5	332.1
	PCorrD05	degF	491.1	514.8
	PCorrD10	degF	528.3	546.5
	PCorrD15	degF	545.2	561.6
	PCorrD20	degF	553.7	570.0
	PCorrD30	degF	565.9	580.9
	PCorrD40	degF	574.5	589.0
	PCorrD50	degF	580.6	597.8
	PCorrD60	degF	587.6	606.3
	PCorrD70	degF	597.5	616.4
	PCorrD80	degF	610.8	627.9
	PCorrD90	degF	630.0	639.4
	PCorrD95	degF	645.3	650.3
	PCorrFBP	degF	654.0	659.6
	Recoverd	mL	97.6	98.2
	Residue	mL	1.1	1.2
	Loss	mL	1.3	0.6
D93	Flash Point	degF	164.0	175.0
		degC	74.0	80.0
EN14078	FAME Content	vol%	34.8	49.1

Appendix D: 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 D-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 D-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 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 is 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 D-2. CE-CERT's Heavy-Duty Engine Dynamometer Facility

Appendix E: 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 E-1.

Table E-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 in H_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 F: Test Cycles

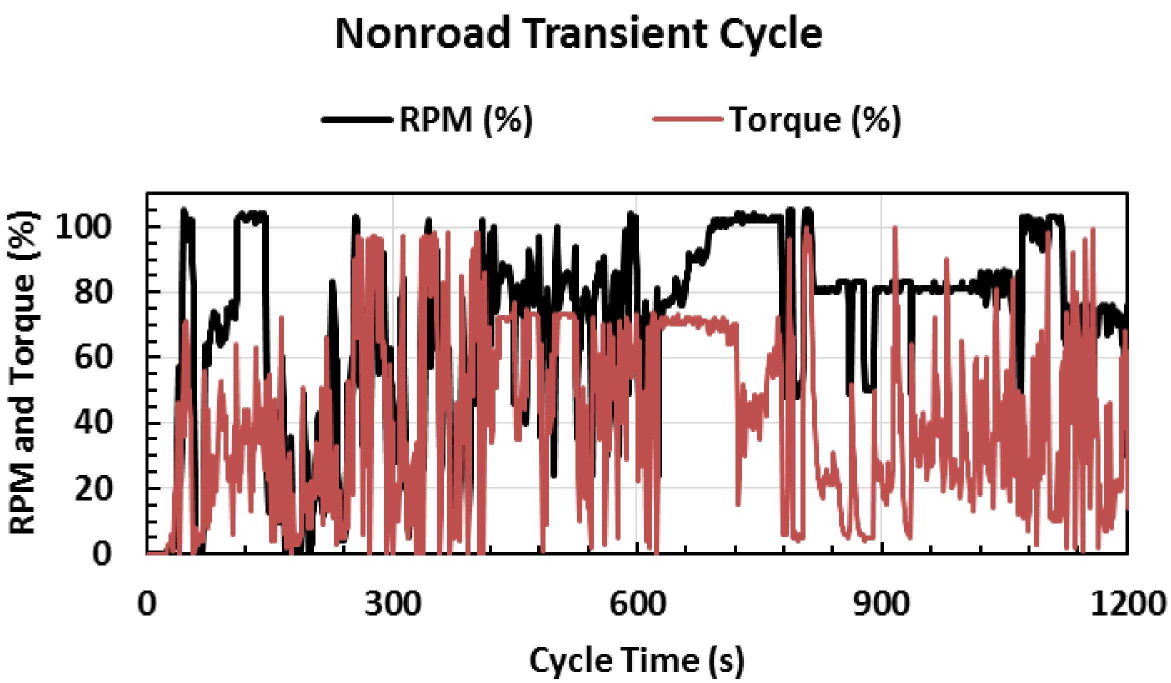

Figure F-1. Nonroad Transient Cycle (NRTC) for off-road engines

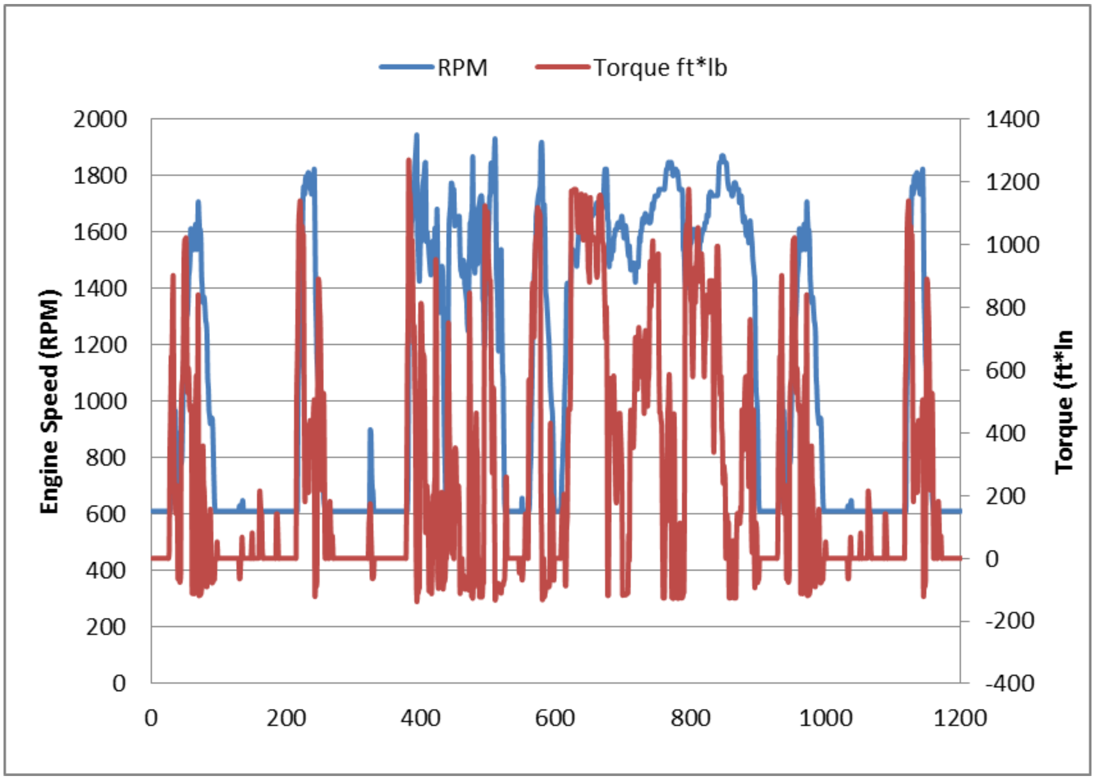

Figure F-2. Federal Test Procedure (FTP) certification cycle for on-highway engines

RMC mode	Time in mode (seconds)	Engine speed	Torque (percent) [1,2]
1a Steady-state	53	Engine governed	100.
1b Transition	20	Engine governed	Linear transition.
2a Steady-state	101	Engine governed	10.
2b Transition	20	Engine governed	Linear transition.
3a Steady-state	277	Engine governed	75.
3b Transition	20	Engine governed	Linear transition.
4a Steady-state	339	Engine governed	25.
4b Transition	20	Engine governed	Linear transition.
5 Steady-state	350	Engine governed	50.

Figure F-3. Test Points and Sequence for D2 RMC Off-Road Legacy Engine

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

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

Figure F-4. Test Points and Sequences for SET Ramped Modal On-Road NTDE

(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 F-5. Test Points and Sequences for C1 RMC for Off-Road NTDE

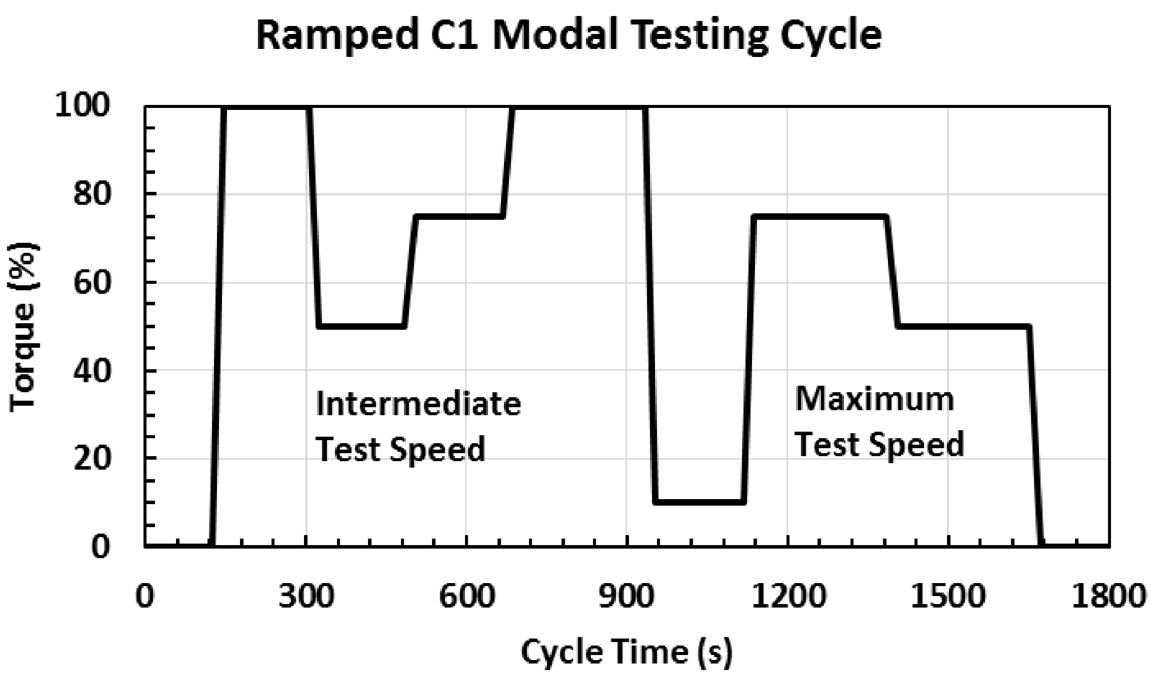

Figure F-6. Graphical Presentation of the C1 RMC for Off-Road NTDE

Appendix G: Detailed Emissions Test Results

Appendix G-1: Detailed Off-Road Legacy Engine Emissions Test Results (D2 Cycle)

File ID	Work (bhp-hr)	CO2 (g/bhp-hr)	CO (g/bhp-hr)	Nox (g/bhp-hr)	THC (g/bhp-hr)	PM (mg/bhp-hr))	F.C. (gal/bhp-hr))
Carb ULSD							
20200115_0654	17.9	608.2	2.32	1.97	0.86	58.64	0.062
20200115_0749	17.1	634.4	1.85	2.06	1.01	59.46	0.064
20200115_0833	17.5	621.7	2.31	2.01	0.94	57.91	0.063
20200116_1039	17.2	637.6	2.83	2.09	0.98	63.81	0.065
20200116_1127	17.8	621.2	2.77	1.95	1.02	58.00	0.063
20200116_1218	17.0	655.2	2.97	2.01	1.03	63.61	0.066
20200117_1505	17.3	646.8	2.49	2.00	0.80	45.03	0.065
20200117_1556	17.3	654.3	2.72	1.98	0.83	46.90	0.066
20200117_1731	17.8	636.9	2.55	1.93	0.81	44.23	0.065
20200124_1031	16.5	721.9	2.93	2.19	1.01	47.00	0.073
20200124_1120	16.9	700.3	2.80	2.14	0.93	45.99	0.071
20200124_1208	17.8	666.6	2.81	2.02	1.01	46.04	0.068
20200127_0555	18.2	632.6	2.66	1.94	0.94	43.79	0.064
20200127_0641	17.0	684.1	2.89	2.03	0.97	48.54	0.069
20200127_1014	18.3	638.4	2.68	1.93	0.98	44.32	0.065
20200127_1735	17.4	664.7	3.05	2.02	1.21	54.73	0.067
20200127_1824	18.1	642.4	2.92	1.94	1.16	52.58	0.065
20200127_1911	18.3	637.4	2.83	1.92	1.10	50.84	0.065
R100							
20200115_1100	16.9	620.9	2.19	1.97	0.66	38.69	0.068
20200115_1152	16.4	636.2	2.20	2.01	0.67	39.50	0.070
20200115_1241	17.7	591.3	1.91	1.87	0.58	34.57	0.065
20200116_1619	17.9	590.6	2.24	1.87	0.57	35.50	0.065
20200116_1712	17.9	590.5	2.04	1.87	0.41	32.28	0.065
20200116_1801	17.8	593.4	2.17	1.86	0.50	33.93	0.065
20200124_0617	17.9	638.6	2.76	1.87	0.86	44.83	0.070
20200124_0704	17.7	651.2	2.60	1.89	0.66	35.04	0.071
20200124_0800	17.1	671.5	2.78	1.98	0.83	47.19	0.074
R65/B35							
20200115_1514	16.7	637.8	1.75	2.07	0.43	26.43	0.069
20200115_1607	17.1	623.3	1.77	2.02	0.46	28.00	0.067
20200115_1653	16.9	627.6	1.77	2.04	0.43	27.32	0.068
20200117_0632	17.7	624.4	1.87	1.93	0.31	21.34	0.067
20200117_0721	17.5	632.8	1.84	1.97	0.32	21.34	0.068
20200117_0808	17.1	649.9	1.90	2.01	0.32	22.65	0.070
20200127_1242	17.7	641.4	2.09	1.97	0.41	23.26	0.069
20200127_1416	17.5	643.2	2.00	2.00	0.34	22.41	0.069
20200127_1502	17.0	665.8	2.46	2.04	0.67	36.25	0.072
R50/B50							
20200116_0635	17.3	616.0	1.94	2.21	0.31	26.99	0.066
20200116_0723	18.1	591.5	1.68	2.12	0.20	25.10	0.064
20200116_0811	17.2	624.9	1.73	2.20	0.21	25.84	0.067
20200117_1100	17.5	635.4	1.72	2.02	0.22	17.09	0.068
20200117_1151	18.1	614.8	1.71	1.94	0.24	16.76	0.066
20200117_1239	17.9	624.3	1.72	1.97	0.24	16.44	0.067
20200124_1447	17.2	677.1	2.40	2.15	0.61	30.57	0.073
20200124_1536	17.8	653.0	1.79	2.09	0.28	17.51	0.070
20200124_1623	17.5	670.2	1.85	2.11	0.28	17.53	0.072

Appendix G-2: Detailed Off-Road Legacy Engine Emissions Test Results (NRTC Cycle)

File ID	Work (bhp-hr)	CO2 (g/bhp-hr)	CO (g/bhp-hr)	Nox (g/bhp-hr)	THC (g/bhp-hr)	PM (mg/bhp-hr))	F.C. (gal/bhp-hr))
		Carb ULSD					
20200128_0550	16.0	695.4	3.33	2.16	0.75	69.24	0.070
20200128_0634	15.9	707.8	3.42	2.18	0.70	68.73	0.072
20200128_0717	16.0	704.7	3.40	2.15	0.74	69.00	0.071
20200129_0940	15.9	702.1	3.07	2.13	0.43	57.90	0.071
20200129_1023	15.8	708.6	3.18	2.13	0.50	60.16	0.072
20200129_1111	15.9	699.9	3.25	2.10	0.57	56.81	0.071
20200130_1407	15.9	688.7	2.78	2.09	0.41	50.84	0.070
20200130_1450	15.9	688.2	2.77	2.08	0.40	48.62	0.070
20200130_1534	16.2	680.8	2.74	2.03	0.40	47.95	0.069
20200131_0946	15.9	701.1	3.09	2.10	0.49	56.71	0.071
20200131_1030	15.9	705.4	3.31	2.07	0.67	61.02	0.071
20200131_1117	15.9	700.8	3.31	2.08	0.74	60.56	0.071
20200203_1032	15.9	699.7	3.38	2.01	0.67	62.94	0.071
20200203_1120	15.7	714.6	3.56	2.05	0.76	63.71	0.072
20200203_1203	16.3	683.2	3.51	2.03	0.91	63.71	0.069
20200203_1812	16.0	690.6	3.44	2.06	0.89	63.08	0.070
20200203_1855	15.6	712.6	3.57	2.13	0.88	65.84	0.072
20200203_1938	15.7	716.9	3.54	2.11	0.11	67.18	0.072
		R100					
20200128_0931	16.3	657.9	3.00	1.93	0.56	47.86	0.072
20200128_1015	15.7	683.9	3.16	1.97	0.63	53.38	0.075
20200128_1101	16.2	661.6	2.86	1.89	0.57	41.40	0.072
20200129_1352	16.0	669.4	2.55	2.01	0.27	36.35	0.073
20200129_1440	15.9	671.1	2.36	2.01	0.21	33.41	0.073
20200129_1526	15.8	673.5	2.22	2.01	0.18	31.02	0.073
20200131_0558	16.1	669.9	2.31	2.00	0.20	32.37	0.073
20200131_0642	16.4	662.3	2.21	1.97	0.19	30.61	0.072
20200131_0725	15.6	693.4	2.24	2.05	0.19	32.64	0.076
		R65/B35					
20200128_1314	16.3	675.2	2.45	2.04	0.35	31.20	0.073
20200128_1357	15.7	705.3	2.59	2.11	0.36	32.79	0.076
20200128_1441	16.0	689.5	2.54	2.08	0.37	30.79	0.074
20200130_0559	16.1	672.5	2.06	2.11	0.17	21.81	0.072
20200130_0644	16.0	680.8	2.09	2.11	0.17	22.31	0.073
20200130_0731	16.0	684.0	2.13	2.09	0.17	22.65	0.074
20200203_1435	16.2	671.0	2.65	2.04	0.41	30.99	0.073
20200203_1519	16.2	671.3	2.62	2.02	0.39	30.97	0.073
20200203_1601	15.9	687.3	2.70	2.03	0.40	31.64	0.074
		R50/B50					
20200129_0601	16.0	693.6	2.14	2.19	0.17	20.89	0.075
20200129_0643	15.9	696.2	2.08	2.16	0.18	21.54	0.075
20200129_0727	15.8	700.9	2.19	2.17	0.18	22.35	0.075
20200130_1000	15.9	685.8	2.13	2.13	0.17	20.69	0.074
20200130_1045	15.9	682.6	2.09	2.09	0.17	20.47	0.073
20200130_1130	15.9	680.0	2.06	2.10	0.17	19.68	0.073
20200131_1330	16.0	687.5	2.47	2.12	0.34	26.76	0.074
20200131_1415	16.2	672.9	2.36	2.09	0.31	25.63	0.072
20200131_1502	15.9	691.8	2.46	2.15	0.18	26.63	0.074

Appendix G-3: Detailed On-Road NTDE Emissions Test Results (FTP Cycle)

File ID	Work (bhp-hr)	CO_2 (g/bhp-hr)	CO (g/bhp-hr)	NOx (g/bhp-hr)	THC (g/bhp-hr)	PM (mg/bhp-hr)	F.C. (gal/bhp-hr)
CARB ULSD							
202010191014	31.0	488.3	0.26	0.27	0.00	0.68	0.049
202010191056	30.9	499.4	0.26	0.25	0.00	1.30	0.050
202010191141	30.9	507.8	0.27	0.13	0.00	1.01	0.051
202010211246	30.5	510.5	0.27	0.10	0.00	0.36	0.051
202010211327	30.6	510.0	0.27	0.10	0.00	0.32	0.051
202010211410	30.8	506.2	0.27	0.10	0.00	0.67	0.051
202010230755	30.8	509.7	0.27	0.13	0.00	0.14	0.051
202010230837	30.5	515.5	0.27	0.11	0.00	0.44	0.052
202010230920	30.9	498.5	0.25	0.22	0.00	0.08	0.050
202010261329	30.5	506.9	0.33	0.11	0.00	0.10	0.051
202010261411	30.8	504.8	0.34	0.11	0.00	0.78	0.051
202010261453	30.7	506.5	0.33	0.11	0.01	0.31	0.051
202010280944	30.5	515.7	0.32	0.11	0.00	0.34	0.052
202010281026	30.8	509.8	0.31	0.12	0.00	0.12	0.051
202010281108	30.8	509.5	0.32	0.11	0.00	1.31	0.051
R100							
202010191442	30.8	494.8	0.28	0.10	0.00	0.30	0.054
202010191525	30.7	499.0	0.28	0.11	0.00	0.72	0.054
202010191607	31.0	489.0	0.27	0.10	0.00	0.81	0.053
202010220801	30.6	486.2	0.25	0.32	0.00	0.50	0.053
202010220843	30.4	494.0	0.26	0.15	0.00	0.23	0.054
202010220925	30.5	495.5	0.26	0.12	0.00	0.62	0.054
202010221007	30.6	493.3	0.26	0.13	0.00	0.13	0.054
202010271411	31.1	488.2	0.31	0.12	0.01	0.00	0.053
202010271454	30.8	495.7	0.31	0.11	0.01	0.39	0.054
202010271535	31.0	490.7	0.31	0.11	0.00	0.00	0.053
R65/B35							
202010210803	30.5	504.9	0.27	0.19	0.00	0.44	0.054
202010210844	30.6	502.8	0.27	0.16	0.00	1.02	0.054
202010210926	30.6	502.5	0.26	0.15	0.00	0.75	0.054
202010231230	31.0	501.3	0.26	0.27	0.00	0.21	0.054
202010231312	30.9	501.5	0.26	0.16	0.00	0.84	0.054
202010231354	30.5	509.6	0.26	0.14	0.00	0.59	0.055
202010270915	31.0	498.5	0.33	0.18	0.00	0.12	0.054
202010270957	30.5	509.9	0.34	0.16	0.00	0.42	0.055
202010271039	30.8	507.2	0.33	0.17	0.00	0.00	0.054
R50/B50							
202010221258	30.8	501.0	0.25	0.29	0.00	0.47	0.054
202010221340	30.5	509.8	0.26	0.17	0.00	0.00	0.055
202010221422	30.5	506.5	0.26	0.16	0.00	0.75	0.054
202010221502	30.5	509.2	0.26	0.16	0.00	0.53	0.054
202010260920	30.5	505.2	0.33	0.17	0.00	0.07	0.054
202010261002	30.7	500.7	0.33	0.16	0.00	0.09	0.054
202010261044	30.9	497.5	0.33	0.15	0.00	0.00	0.053
202010281342	30.9	500.5	0.31	0.28	0.00	0.20	0.054
202010281424	30.4	511.7	0.32	0.18	0.00	0.00	0.055
202010281548	30.4	510.2	0.30	0.27	0.00	0.00	0.055
202010281506	31.1	500.2	0.31	0.17	0.00	0.00	0.053

Appendix G-4: Detailed On-Road NTDE Emissions Test Results (RMC Cycle)

File ID	Work (bhp-hr)	CO_2 (g/bhp-hr)	CO (g/bhp-hr)	NOx (g/bhp-hr)	THC (g/bhp-hr)	PM (mg/bhp-hr)	F.C. (gal/bhp-hr)
CARB ULSD							
202010300744	135.0	441.3	0.27	0.14	0.00	0.79	0.044
202010300907	134.9	443.4	0.27	0.13	0.00	0.36	0.044
202010301029	135.0	444.4	0.27	0.14	0.00	0.38	0.045
202011021259	135.2	441.9	0.26	0.14	0.00	0.15	0.044
202011021421	135.0	441.5	0.26	0.14	0.00	0.08	0.044
202011021548	135.0	442.3	0.26	0.13	0.00	0.02	0.044
202011040748	135.1	440.9	0.25	0.13	0.00	0.08	0.044
202011040912	135.0	442.1	0.25	0.13	0.00	0.01	0.044
202011041043	135.1	441.9	0.25	0.14	0.00	0.17	0.044
202011051235	135.0	442.6	0.27	0.13	0.00	0.14	0.044
202011051355	135.1	447.2	0.27	0.14	0.00	0.00	0.045
202011051519	135.1	442.0	0.27	0.14	0.00	0.07	0.044
202011090830	135.1	438.2	0.26	0.12	0.00	0.24	0.044
202011090954	135.1	439.4	0.26	0.13	0.00	0.06	0.044
202011091117	135.0	441.5	0.27	0.12	0.00	0.09	0.044
R100							
202010301304	135.1	427.9	0.26	0.14	0.00	0.33	0.046
202010301428	135.1	433.5	0.26	0.14	0.00	0.17	0.047
202010301605	135.2	434.6	0.26	0.14	0.00	0.19	0.047
202011030744	135.1	428.1	0.25	0.13	0.00	0.14	0.046
202011030909	135.0	430.1	0.25	0.14	0.00	0.13	0.047
202011031034	135.2	427.3	0.24	0.14	0.00	0.12	0.046
202011061301	135.1	429.1	0.25	0.13	0.00	0.05	0.047
202011061428	135.1	428.8	0.24	0.14	0.00	0.12	0.047
202011061552	135.2	425.2	0.24	0.14	0.00	0.06	0.046
R65/B35							
202011020915	134.8	440.5	0.26	0.17	0.00	0.15	0.047
202011021041	135.0	439.4	0.26	0.15	0.00	0.08	0.047
202011041238	135.2	438.0	0.26	0.15	0.00	0.23	0.047
202011041406	135.0	440.4	0.26	0.15	0.00	0.11	0.047
202011041530	135.0	439.8	0.26	0.15	0.00	0.26	0.047
202011060803	135.0	438.5	0.25	0.16	0.00	0.28	0.047
202011060927	135.0	442.8	0.26	0.15	0.00	0.07	0.048
202011061049	135.0	440.3	0.25	0.15	0.00	0.19	0.047
R50/B50							
202011031231	135.0	444.1	0.25	0.16	0.00	0.11	0.047
202011031358	135.1	443.5	0.25	0.16	0.00	0.10	0.047
202011031521	135.0	445.1	0.25	0.16	0.00	0.21	0.048
202011050752	135.3	443.6	0.27	0.15	0.00	0.04	0.047
202011050916	135.0	445.4	0.26	0.16	0.00	0.07	0.048
202011051039	135.0	444.9	0.26	0.15	0.00	0.02	0.048
202011100807	135.0	440.6	0.26	0.15	0.00	0.06	0.047
202011100930	135.1	441.4	0.26	0.15	0.00	0.23	0.047
202011101054	135.1	443.2	0.27	0.15	0.00	0.00	0.047

Appendix G-5: Detailed Off-Road NTDE Emissions Test Results (NRTC Cycle)

File ID	Work (bhp-hr)	CO_2 (g/bhp-hr)	CO (g/bhp-hr)	NOx (g/bhp-hr)	THC (g/bhp-hr)	PM (mg/bhp-hr)	F.C. (gal/bhp-hr)
Carb ULSD							
202104171318	27.3	544.4	0.14	0.08	0.00	0.00	0.055
202104171358	27.4	544.6	0.16	0.10	0.00	0.00	0.055
202104171440	27.2	542.8	0.13	0.07	0.00	0.00	0.054
202104171523	27.2	542.5	0.12	0.18	0.00	0.31	0.054
202104171604	27.1	545.3	0.09	0.23	0.00	0.00	0.055
202104171648	27.1	542.8	0.11	0.27	0.00	0.01	0.054
202105101128	27.1	532.1	0.19	0.23	0.00	2.28	0.053
202105101211	27.6	522.6	0.15	0.19	0.00	0.01	0.052
202105101252	27.0	532.0	0.18	0.21	0.00	0.21	0.053
202105101333	27.4	522.7	0.14	0.23	0.00	0.05	0.052
202105101415	27.0	529.6	0.12	0.20	0.00	0.00	0.053
R100							
202104181111	26.5	533.0	0.07	0.25	0.00	0.49	0.058
202104181153	26.9	532.8	0.11	0.21	0.00	0.01	0.058
202104181235	27.6	505.1	0.08	0.13	0.00	1.94	0.055
202104181316	27.3	523.0	0.09	0.22	0.00	0.00	0.057
202104181357	27.1	527.3	0.06	0.22	0.00	0.42	0.057
202104181439	27.3	522.7	0.06	0.21	0.00	0.52	0.057
202105071152	27.4	505.1	0.09	0.23	0.00	0.00	0.055
202105071233	26.8	515.4	0.09	0.24	0.00	0.07	0.056
202105071316	27.2	505.7	0.07	0.24	0.00	1.21	0.055
202105071358	26.9	508.7	0.10	0.22	0.00	0.00	0.055
202105071439	27.4	501.8	0.07	0.21	0.00	0.32	0.054
202105071520	26.7	511.7	0.05	0.22	0.00	0.03	0.055
R65/B35							
202104191128	26.8	544.4	0.00	0.22	0.00	0.74	0.058
202104191209	27.4	539.3	0.01	0.17	0.00	0.92	0.058
202104191250	27.2	540.8	0.00	0.44	0.00	0.00	0.058
202104191331	26.8	550.7	0.01	0.50	0.00	0.10	0.059
202104191412	27.1	541.4	0.00	0.52	0.00	0.02	0.058
202104191453	27.0	545.6	0.00	0.48	0.00	0.00	0.059
202105091054	27.3	516.7	0.00	0.27	0.00	0.46	0.055
202105091135	27.2	517.2	0.00	0.25	0.00	0.64	0.055
202105091215	27.4	510.0	0.00	0.28	0.00	0.00	0.055
202105091256	27.2	514.5	0.00	0.33	0.00	0.39	0.055
202105091336	26.7	524.4	0.00	0.32	0.00	0.50	0.056
202105091417	26.9	518.2	0.00	0.30	0.00	1.10	0.056
R50/B50							
202104201137	27.1	542.1	0.00	0.57	0.00	1.08	0.058
202104201218	26.8	551.4	0.00	0.53	0.00	0.68	0.059
202104201259	27.0	544.6	0.00	0.49	0.00	1.63	0.058
202104201342	27.0	543.0	0.00	0.50	0.00	0.00	0.058
202104201422	27.2	541.2	0.00	0.55	0.00	0.25	0.058
202104201503	27.2	537.6	0.00	0.52	0.00	0.00	0.057
202105081105	26.9	527.4	0.00	0.37	0.00	0.00	0.056
202105081146	26.4	535.9	0.00	0.36	0.00	0.02	0.057
202105081226	27.1	520.4	0.00	0.36	0.00	0.00	0.056
202105081307	26.8	521.6	0.00	0.36	0.00	0.00	0.056
202105081348	27.0	517.0	0.00	0.36	0.00	0.00	0.055
202105081429	26.5	528.3	0.00	0.38	0.00	0.00	0.056

Appendix G-6: Detailed Off-Road NTDE Emissions Test Results (C1 Cycle)

File ID	Work (bhp-hr)	CO_2 (g/bhp-hr)	CO (g/bhp-hr)	NOx (g/bhp-hr)	THC (g/bhp-hr)	PM (mg/bhp-hr)	F.C. (gal/bhp-hr)
Carb ULSD							
202104121127	62.9	478.5	0.00	0.02	0.00	0.08	0.048
202104121224	62.3	489.6	0.00	0.02	0.00	0.17	0.049
202104121316	62.5	486.1	0.00	0.02	0.00	0.00	0.049
202104131512	63.0	484.7	0.00	0.02	0.00	0.14	0.049
202104131606	63.0	483.9	0.00	0.02	0.00	0.00	0.048
202104131659	62.0	490.6	0.00	0.02	0.00	0.24	0.049
202104151222	62.1	495.0	0.00	0.01	0.00	0.33	0.050
202104151317	62.3	491.4	0.00	0.01	0.00	0.01	0.049
202104161510	63.1	467.8	0.00	0.01	0.00	0.25	0.047
202104161607	62.6	471.5	0.00	0.01	0.00	0.41	0.047
202104161658	63.1	439.6	0.00	0.01	0.00	0.08	0.044
R100							
202104121625	62.4	471.3	0.00	0.02	0.00	0.07	0.051
202104121720	62.3	472.2	0.00	0.02	0.00	0.00	0.051
202104121815	62.0	471.6	0.00	0.02	0.00	0.03	0.051
202104141045	62.3	470.4	0.00	0.02	0.00	0.85	0.051
202104141139	62.1	474.3	0.00	0.02	0.00	0.02	0.051
202104141233	62.0	474.6	0.00	0.02	0.00	0.00	0.051
202105111246	62.1	450.6	0.00	0.01	0.00	0.10	0.049
202105111341	61.2	454.7	0.00	0.00	0.00	0.19	0.049
202105111435	61.6	450.7	0.00	0.01	0.00	0.10	0.049
R65/B35							
202104131046	61.6	483.9	0.01	0.03	0.00	0.03	0.052
202104131142	60.9	486.6	0.00	0.03	0.00	0.09	0.052
202104131235	61.5	478.4	0.00	0.03	0.00	0.12	0.051
202104151614	62.0	479.9	0.00	0.02	0.00	0.06	0.051
202104151708	61.9	481.4	0.00	0.02	0.00	0.00	0.052
202104151800	62.6	473.1	0.00	0.02	0.00	0.25	0.051
202105121707	61.5	451.1	0.00	0.02	0.00	0.17	0.048
202105121803	61.4	451.7	0.00	0.02	0.00	0.08	0.048
202105121858	61.4	453.3	0.00	0.02	0.00	0.29	0.049
R50/B50							
202104141528	61.2	485.0	0.00	0.04	0.00	0.23	0.052
202104141622	61.5	484.1	0.00	0.05	0.00	0.14	0.052
202104141715	60.7	489.6	0.00	0.05	0.00	0.11	0.052
202105121146	61.1	460.7	0.00	0.01	0.00	0.00	0.049
202105121240	60.8	461.7	0.00	0.01	0.00	0.15	0.049
202105121337	60.9	459.5	0.00	0.02	0.00	0.00	0.049