For the CE-CERT Engine Testing Portion for the CARB Assessment of the Emissions from the Use of Biodiesel as a Motor Vehicle Fuel in California "Biodiesel Characterization and NO$_x$ Mitigation Study"

Testing on 2006 Cummins ISM

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Abstract

California currently has several legislative initiatives that promote increased alternative fuels use to reduce oil dependency, greenhouse gases, and air pollution. CARB is conducting a comprehensive study of biodiesel and other alternative diesel fuels to better understand and, to the extent possible, mitigate any impact that biodiesel has on NO_x emissions from diesel engines. This memorandum summarizes the results from the first test engine, a 2006 Cummins ISM, under this comprehensive program. The testing included a baseline CARB ultralow sulfur diesel (ULSD) fuel, two biodiesel feedstocks (one soy-base and one animal-based) tested on blend levels of B5, B20, B50, and B100, and a renewable and a GTL diesel fuel tested at 20%, 50%, and 100% blend levels. Testing was also conducted on up to 4 different engine test cycles including a light loaded UDDS cycle, the FTP, and 40 mph and 50 mph CARB cruise cycles. These cycles represent different operating conditions, and low, medium, and high loads.

The results showed that average NO_x emissions increase with increasing biodiesel blend level, but the magnitude of the effects differ between the different feedstocks. The soy-based biodiesel blends showed a higher increase in NO_x emissions for essentially all blend levels and test cycles in comparison with the animal-based biodiesel blends. The trends for other emissions components were similar to those from previous studies, with biodiesel providing reductions in THC and PM, while increasing fuel consumption. CO emissions showed consistent reductions for the animal-based biodiesel, but not for the soy-based biodiesel.

For the renewable and GTL diesel fuels, the results show a steady decrease in NO_x emissions with increasingly higher levels of renewable diesel fuel. In comparison with the biodiesel feedstocks, the levels of NO_x reduction for the renewable and GTL fuels are less than the corresponding increases in NO_x seen for the soy-base biodiesel, but are more comparable to the increases seen for the animal-based biodiesel blends. This suggests that the renewable and GTL diesel fuel levels need to be blended at slightly higher levels than the corresponding biodiesel in order to mitigate the associated NO_x increase, especially for the soy-based biodiesel blends. The renewable and GTL fuels also provided reductions in PM and CO emissions, with the GTL fuel also providing reductions in THC. The renewable and GTL fuels provided a slight reduction in CO_2 emissions at the higher blends, with a slight, but measureable, increase in fuel consumption.

Several NO_x mitigation formulations were evaluated, including those that utilized renewable and GTL diesel fuels, and additives. Successful formulations included those with higher levels of renewable diesel (R80 or R55) with a B20-soy biodiesel. Blends of 15% renewable or GTL diesel were also proved successful in mitigating NO_x for a B5 soy blend, giving a formulation more comparable to what might be implemented with the low carbon fuel standard. A 1% di tertiary butyl peroxide (DTBP) additive blend was found to fully mitigate the NO_x impacts for a B20 and B10 soy biodiesel, while 2-ethylhexyl nitrate (2-EHN) blends had little impact on improving NO_x emissions. It was found that the level of renewable or GTL diesel fuels needed for blending can be reduced if a biodiesel fuel with more favorable NO_x characteristics is used or if an additive is used that can also provide an improvement in NO_x, such as the DTBP in this study.

Acronyms and Abbreviations

ARB ....Air Resources Board
CARB...California Air Resources Board
CEC...California Energy Commission
CE-CERT..College of Engineering-Center for Environmental Research
and Technology (University of California, Riverside)
CFR...Code of Federal Regulations
CO...carbon monoxide
COV ....coefficient of variation
CO2...carbon dioxide
CVS...constant volume sampling
DPF ....diesel particulate filter
DR..dilution ratio
ECM...engine control module
FTP...Federal Test Procedure
g/mi ....grams per mile
g/bhp-hr...grams per brake horsepower hour
GTL..gas-to-liquid
GVWR ....gross vehicle weight rating
HDDT ....Heavy-Duty Diesel Truck
HDETL ....CARB's Heavy-Duty Emissions Testing Laboratory
HDV...heavy-duty vehicle
LDV ....light-duty vehicle
lpm ....liters per minute
MDL...minimum detection limit
MEL ....CE-CERT's Mobile Emissions Laboratory
nm ....nanometers
NMHC...non-methane hydrocarbons
NO_x ....nitrogen oxides
NO_2 ....nitrogen dioxide
PM..particulate matter
QA..quality assurance
QC..quality control
scfm..standard cubic feet per minute
THC..total hydrocarbons
UDDS..Urban Dynamometer Driving Schedule
ULSD ....ultralow sulfur diesel

Executive Summary

California as well as the United States as a whole is making a concerted effort to increase the use of alternative fuels in transportation and other areas. In California, the legislature passed AB1007 that requires the California Air Resources Board (CARB) and California Energy Commission (CEC) to develop a plan to increase alternative fuels use in California to reduce oil dependency and air pollution. The California Governor has also established aggressive greenhouse emission reduction targets for which CARB has identified potential strategies such as biodiesel. Biodiesel is an alternative diesel fuel that has the potential to reduce greenhouse gas emissions, other pollutants, and can partially offset our use of petroleum-based fuels.

Although biodiesel has been studied extensively over the past 20 years, knowledge gaps still exist and further research is needed to fully characterize the impact biodiesel has on oxides of nitrogen (NO_x) emissions and the effects various feedstocks have on air emissions. A comprehensive assessment of the impact of biodiesel on pre 2002 engines was conducted by the US Environmental Protection Agency in 2002 (US EPA, 2002), which estimated that a soy-based biodiesel at a B20 level would increase NO_x emissions about 2% compared to an average Federal base fuel. Additional analyses in this same study did indicate that the impacts of biodiesel on NO_x emissions using a cleaner base fuel, more comparable to that utilized in California, could be greater than that found for the average Federal fuel, but data was more limited in this area. Researchers at the National Renewable Energy Laboratory (NREL) conducted further analysis of more recent engine and chassis dynamometer test results (McCormick et al., 2006). They found that the impact of biodiesel on NOx emissions in more recent studies was varied and did not show a consistent trend of increasing NOx emissions with biodiesel use. The US EPA in a more recent study also found that the impact of biodiesel on NOx emissions can be a function of cycle load, with greater impacts found at higher loads (Sze et al. 2007). A number of researchers have also studied mechanisms via which biodiesel might impact NO_x emissions (McCormick et al., 2001; Ban Weiss et al., 2005, Szybist et al., 2003 a,b, Cheng et al. 2007, Eckerle et al. 2008).

In order to better characterize the emissions impacts of renewable fuels under a variety of conditions, CARB is conducting a comprehensive study of biodiesel and other alternative diesel fuels. The goal of this study is to understand and, to the extent possible, mitigate any impact that biodiesel has on NO_x emissions from diesel engines. The full test matrix of the program includes testing on 2 heavy-duty engines, 4 heavy-duty vehicles, and 2 off-road engines. This memorandum summarizes the results from the first test engine, a 2006 Cummins ISM, under this comprehensive program.

Test Fuels and Cycles

The test fuels for this program included 5 primary fuels that were subsequently blended at various levels to comprise the full test matrix. A CARB-certified ultralow sulfur diesel (ULSD) fuel was the baseline for testing. Two biodiesel feedstocks were utilized for testing, including one soy-based and animal-based biodiesel fuel. These fuels were selected to provide a range of properties that are representative of typical feedstocks, but also to have feedstocks representing different characteristics of biodiesel in terms of cetane number and degree of saturation. A

renewable feedstock and a GTL diesel were also used for testing. The renewable feedstock was provided by Neste Oil, and it is known as NExBTL. This fuel is denoted as the renewable diesel in the following results sections. This fuel is produced from renewable biomass sources such as fatty acids from vegetable oils and animal fats via a hydrotreating process (Rantanen et al. 2005; Kuronen et al. 2007). The two biodiesel feedstocks (one soy-base and one animal-based) tested on blend levels of B5, B20, B50, and B100, and a renewable and a GTL diesel fuel tested at 20%, 50%, and 100% blend levels.

Testing was conducted on up to 4 different engine test cycles including a light loaded Urban Dynamometer Driving Schedule (UDDS) cycle, the Federal Test Procedure (FTP), and 40 mph and 50 mph CARB heavy heavy-duty diesel truck (HHDDT) cruise cycles. These cycles were selected to represent different operating conditions, and low, medium, and high loads. The engine dynamometer test cycles for the UDDS, and 40 and 50 mph cruise cycles were developed from torque and engine rpm data from the engine's ECM while it was driven on a chassis dynamometer. The UDDS and 40 mph cruise cycles were developed from data taken on the actual 2006 Cummins ISM being tested for this program. The 50 mph cruise cycle was developed under the ACES program utilizing collected through the E55/59 chassis dynamometer study of heavy-duty trucks (Clark et al., 2007), and was utilized as is for this study.

Biodiesel Characterization Results

Tables ES-1 and ES-2 show the percentage differences for the soy-based and animal-based biodiesel feedstocks, respectively, compared with the CARB ULSD for different blend levels and test cycles, along with the associated p-values for statistical comparisons using a 2-tailed, 2 sample equal variance t-test. For the discussion in this memorandum, results are considered to be statistically significant for p values ≤ 0.05.

The NO_x emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock are presented in Figures ES-1 and ES-2, respectively, on a gram per brake horsepower hour (g/bhp-hr) basis. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination. The error bars represent one standard deviation on the average value.

The average NO_x emissions show trends of increasing NO_x emissions with increasing biodiesel blend level, but the magnitude of the effects differ between the different feedstocks. The soy-based biodiesel blends showed a higher increase in NO_x emissions for essentially all blend levels and test cycles in comparison with the animal-based biodiesel blends.

For the soy-based biodiesel over the FTP, the NO_x impact ranged from an increase of 2.2% at the B5 level, to 6.6% at the B20 level, to 27% at the B100 level. The biodiesel emissions impacts for the other cycles were comparable to but less than those found for the FTP for the different blend levels. These increases were higher than the EPA base case estimates for all of the test cycles. The NO_x impacts found for the soy-based biodiesel were consistent, however, with the EPA estimates for the "clean base fuel" case, which would be more representative of a CARB diesel fuel.

		THC		CO		NO$_x$		PM		CO$_2$		BSFC	
		% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
UDDS	B20	-12%	0.000	5%	0.115	4.1%	0.002	-24%	0.002	0.8%	0.448	1.8%	0.093
	B50	-28%	0.000	26%	0.000	9.8%	0.000	-30%	0.000	2.5%	0.055	5.1%	0.001
	B100	-55%	0.000	62%	0.000	17.4%	0.000	-33%	0.000	4.2%	0.003	9.8%	0.000
FTP	B20	-11%	0.000	-3%	0.078	6.6%	0.000	-25%	0.000	0.4%	0.309	1.4%	0.001
	B50	-29%	0.000	-4%	0.038	13.2%	0.000	-46%	0.000	0.5%	0.159	3.1%	0.000
	B100	-63%	0.000	3%	0.163	26.6%	0.000	-58%	0.000	1.5%	0.007	6.8%	0.000
40 mph Cruise	B5	-1%	0.573	2%	0.427	1.7%	0.135	-6%	0.101	1.7%	0.085	1.9%	0.065
	B20	-16%	0.000	-3%	0.160	3.9%	0.000	-26%	0.000	0.8%	0.056	1.8%	0.001
	B50	-36%	0.000	0%	0.986	9.1%	0.000	-48%	0.000	1.3%	0.053	3.8%	0.000
	B100	-70%	0.000	0%	0.868	20.9%	0.000	-69%	0.000	3.0%	0.000	8.4%	0.000
50 mph Cruise	B5	-2%	0.222	1%	0.649	-1.1%	0.588	-5%	0.036	0.0%	0.959	0.3%	0.690
	B20	-12%	0.000	-2%	0.330	0.5%	0.800	-18%	0.000	0.6%	0.227	1.6%	0.002
	B50	-31%	0.000	-6%	0.002	6.3%	0.001	-43%	0.000	1.2%	0.008	3.8%	0.000
	B100	-68%	0.000	-14%	0.000	18.3%	0.000	-50%	0.000	2.6%	0.000	8.0%	0.000

Table ES-1. Percentages changes for Soy-Biodiesel blends relative to CARB and associated statistical p values

		THC		CO		NO$_x$		PM		CO$_2$		BSFC	
		% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
UDDS	B20	-16%	0.000	-10%	0.000	-1.5%	0.376	-10%	0.009	-0.6%	0.640	1.2%	0.404
	B50	-38%	0.000	-12%	0.000	0.1%	0.935	-24%	0.001	1.2%	0.201	3.1%	0.005
	B100	-73%	0.000	-20%	0.000	1.9%	0.243	-31%	0.000	2.5%	0.016	6.7%	0.000
FTP	B5	-3%	0.011	-4%	0.008	0.3%	0.298	-9%	0.000	-0.3%	0.191	2.9%	0.031
	B20	-13%	0.000	-7%	0.000	1.5%	0.000	-19%	0.000	0.1%	0.733	1.4%	0.145
	B50	-36%	0.000	-14%	0.000	6.4%	0.000	-42%	0.000	0.4%	0.117	1.8%	0.038
	B100	-71%	0.000	-27%	0.000	14.1%	0.000	-64%	0.000	0.7%	0.018	4.4%	0.001
Cruise	B20	-14%	0.000	-7%	0.003	-2.3%	0.151	-16%	0.000	0.7%	0.170	2.6%	0.010
	B50	-37%	0.000	-9%	0.066	0.8%	0.588	-35%	0.000	1.5%	0.014	3.5%	0.000
	B100	-73%	0.000	-25%	0.000	5.3%	0.000	-59%	0.000	1.6%	0.008	5.9%	0.000

Table ES-2. Percentages changes for Animal-Biodiesel blends relative to CARB and associated statistical p values

NO$_x$ Emissions - Soy Biodiesel
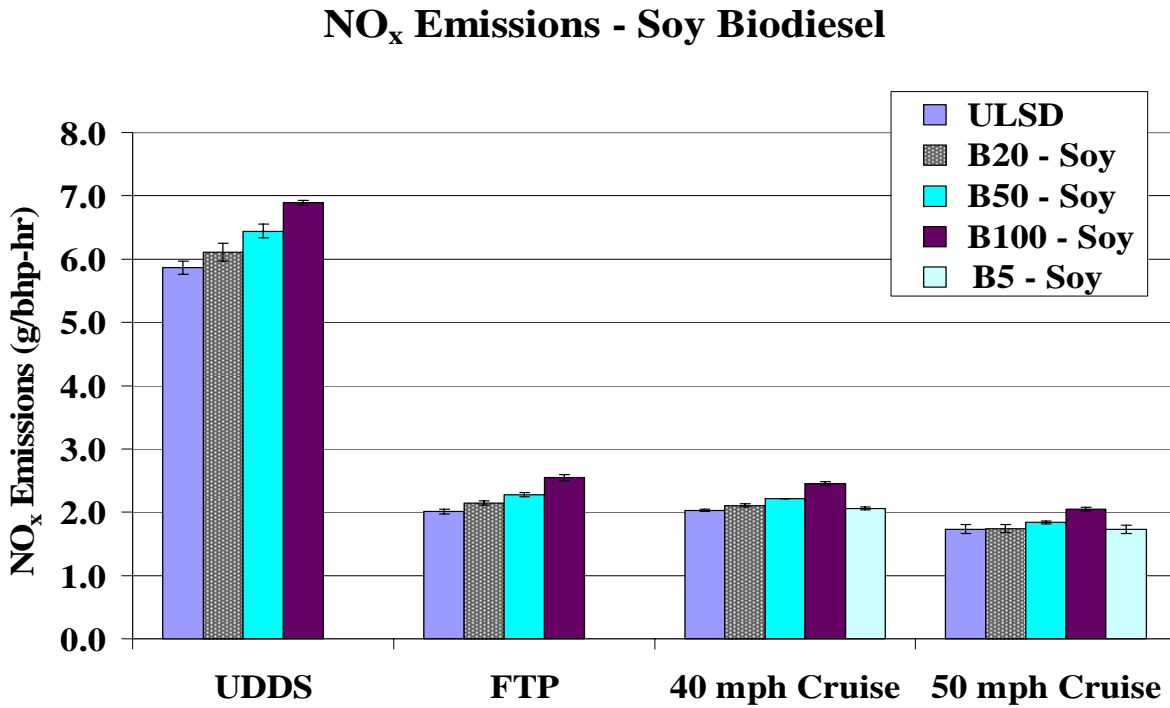
Figure ES-1. Average NO$_x$ Emission Results for the Soy-Based Biodiesel Feedstock

NO$_x$ Emissions - Animal Biodiesel
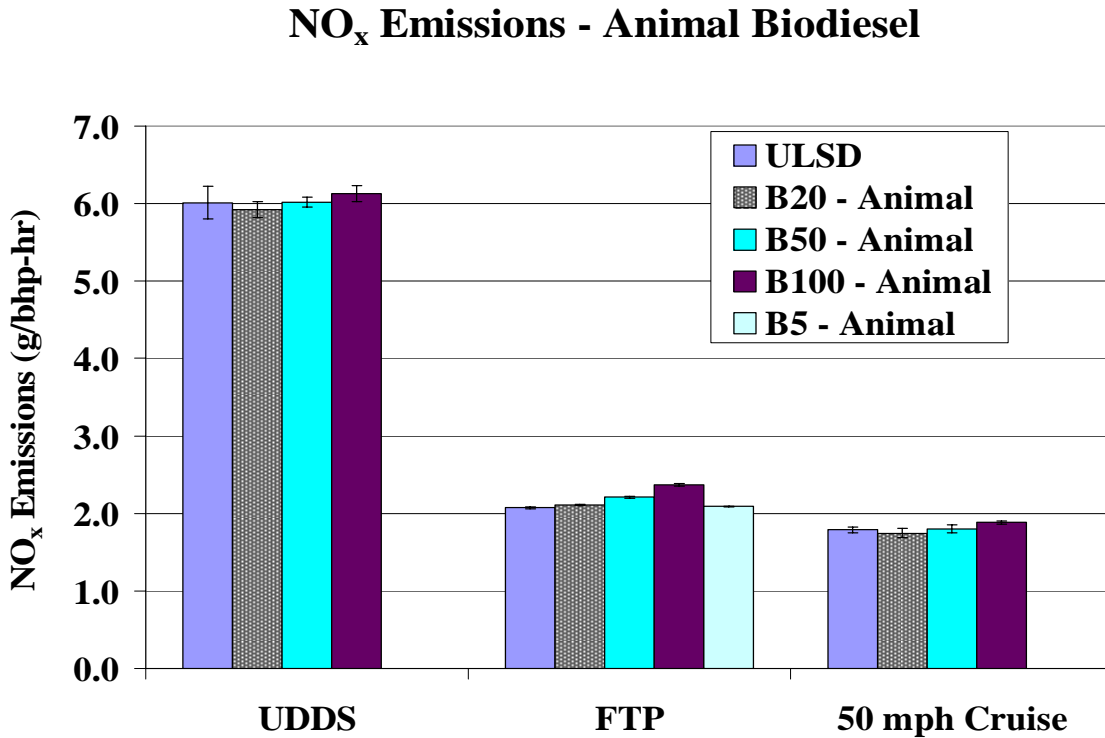
Figure ES-2. Average NO$_x$ Emission Results for the Animal-Based Biodiesel Feedstock

For the animal-based biodiesel feedstock, the NO_x emission increases with biodiesel for the FTP cycle were consistent with the EPA base case estimates. The NO_x impact for the animal-based biodiesel over the FTP ranged from an increase of 1.5% at the B20 level to 14% at the B100 level. For the lower load UDDS cycle for the animal-based biodiesel feedstock, the emissions differences were not statistically significant for any of the blend levels. For the 50 mph cruise cycle, a statistically significant increase in NO_x emissions was only found for the B100 animal-based biodiesel. The 50 mph cruise results were obscured, however, by changes in the engine control strategy that appeared to occur over a segment of this cycle.

NO_x emissions were found to increase as a function of engine load, as expected. Comparing different cycles, the FTP seemed to show the strongest NO_x increases for biodiesel for both soy-based and animal-based blends. The impact of biodiesel on NO_x emissions was not found to be a strong function of engine load, as was observed in previous studies by EPA (Sze et al., 2007). It is possible that different engine mapping procedures were utilized in the EPA study. Additionally, the results in this study for the highest load cycle are obscured by the differences in engine operation that were observed for the 50 mph cruise cycle.

PM emissions showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. This is consistent with a majority of the previous studies of emissions from biodiesel blends. The PM reductions for both the soy-based and animal-based biodiesel blends were generally larger than those found in the EPA study, and are closer to the estimates for an base case fuel than a clean base fuel. Over the FTP, the PM reductions for the soy-based biodiesel ranged from 6% for a B5 blend, to 25% for a B20 blend, to 58% for B100. For the animal-based biodiesel over the FTP, the PM reductions ranged from 19% for the B20 blend to 64% for B100.

For PM, the smallest reductions were seen for the UDDS, or the lightest loaded cycle. The PM reductions for biodiesel for the FTP and the cruise cycles were comparable for both fuels. Although there were some differences in the percent reductions seen for the soy-based and animal-based biodiesel fuels, there were no consistent differences in the PM reductions for these two feedstocks over the range of blend levels and cycles tested here.

THC emissions showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. The THC reductions over the FTP for the soy-based biodiesel ranged from 6% for a B10 blend, to 11% for a B20 blend, to 63% for B100. For the animal-based biodiesel over the FTP, the THC reductions ranged from 13% for the B20 blend to 71% for B100. Overall, the THC reductions seen in this study are consistent with and similar to those found by EPA. The THC reductions for both the soy-based and animal-based biodiesel blends for B100 were closer to those found in the EPA study for the B100 level for the base case fuels, while the lower blend levels (i.e., B20 and B50), were in between those estimated by EPA for the clean and base case fuels. For the soy-based biodiesel, the reductions are slightly less for the lower load UDDS, but for the animal-based biodiesel the THC reductions for all the test cycles were similar. There was not a strong trend in the THC reductions with biodiesel as a function of either power or fuel consumption.

CO emissions showed consistent and significant reductions for the animal-based biodiesel blends, consistent with previous studies. Over the FTP, the CO reductions for the animal-based biodiesel ranged from 7% for a B5 blend, to 14% for a B20 blend, to 27% for B100. The CO reductions seen for the animal-based biodiesel are comparable to those seen for the EPA clean base fuel estimates, but are lower than those for the EPA base case.

The CO trends for the soy-based biodiesel were less consistent. The CO emissions for the soy-based biodiesel did show consistent reductions with increasing biodiesel blend levels for the highest load, the 50 mph cruise cycle. For the FTP and 40 mph cruise cycles, the biodiesel blends did not show any strong trends relative to the CARB ULSD and a number of differences were not statistically significant. Interestingly, the CO emissions for the lowest load UDDS cycle showed higher emissions for the biodiesel blends, with the largest increase (62%) seen for the highest blend level. Additional testing would likely be needed to better understand the nature of these results, which are opposite the trends seen in most previous studies.

Throughout the course of testing on the first engine some outliers were observed in the testing that appeared to be related to conditions set within the engine control module (ECM). The first condition occurred when the temperature of the coolant water to the charge air cooler dropped below 68°F. These tests were removed from the subsequent analyses. A second condition was also observed where changes in engine operation were observed within the 50 mph CARB HHDDT cycle. For this test cycle, for a period of the test cycle from approximately 300 to 400 seconds, two distinct modes of operation were observed. These tests were not removed from the analysis, as it was surmised that these conditions could potentially occur in real-world operation.

The biodiesel fuels showed a slight increase in CO_2 emissions for the higher blends. This increase ranged from about 1-4% with the increases being statistically significant for the B100 fuels for all of the tests, and for the B50 fuel for the cruise cycles and some of the other cycles.

The biodiesel blends showed an increase in fuel consumption with increasing levels of biodiesel. This is consistent with expectations based on the lower energy density of the biodiesel. The fuel consumption differences were generally slightly higher for the soy-based biodiesel in comparison with the animal-based biodiesel. The increases in fuel consumption for the soy-based biodiesel blends range from 1.4 to 1.8% for the B20 to 6.8 to 9.8% for the B100. The increases in fuel consumption for the animal-based biodiesel blends range from no statistical difference to 2.6% for the B20 to 4.4 to 6.7% for the B100.

Renewable GTL Diesel Fuel Results

Tables ES-3 and ES-4 show the percentage differences for the renewable and the GTL fuels, respectively, compared with the CARB ULSD for different blend levels and test cycles, along with the associated p-values for statistical comparisons using a 2-tailed, 2 sample equal variance t-test.

		THC		CO		NO$_x$		PM		CO$_2$		BSFC	
		% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
UDDS	R20	-3%	0.018	-16%	0.000	-4.9%	0.000	-5%	0.401	-0.4%	0.595	1.0%	0.255
	R50	-6%	0.002	-23%	0.000	-10.2%	0.000	-12%	0.044	-0.7%	0.448	3.1%	0.007
	R100	-12%	0.000	-33%	0.000	-18.1%	0.000	-28%	0.000	-3.3%	0.002	5.1%	0.000
FTP	R20	0%	0.719	-4%	0.022	-2.9%	0.000	-4%	0.023	-0.3%	0.652	1.1%	0.117
	R50	0%	0.777	-8%	0.000	-5.4%	0.000	-15%	0.000	-1.0%	0.124	2.9%	0.001
	R100	-4%	0.057	-12%	0.000	-9.9%	0.000	-34%	0.000	-3.4%	0.000	5.2%	0.000
50 mph Cruise	R20	2%	0.207	0%	0.831	-3.8%	0.007	-3%	0.220	0.0%	0.972	1.4%	0.107
	R50	2%	0.230	1%	0.234	-7.8%	0.000	-14%	0.000	0.0%	0.996	4.0%	0.000
	R100	-1%	0.510	3%	0.022	-14.2%	0.000	-24%	0.000	-2.1%	0.011	6.6%	0.000

Table ES-3. Percentages changes for renewable blends relative to CARB and associated statistical p values

		THC		CO		NO$_x$		PM		CO$_2$		BSFC	
		% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
FTP	GTL20	-5%	0.000	-6%	0.000	-0.9%	0.053	-8%	0.000	0.0%	0.933	1.3%	0.001
	GTL50	-16%	0.000	-10%	0.000	-5.2%	0.000	-12%	0.000	-1.9%	0.001	1.4%	0.008
	GTL100	-28%	0.000	-14%	0.000	-8.7%	0.000	-29%	0.000	-3.5%	0.000	3.3%	0.000

Table ES-4. Percentages changes for GTL blends relative to CARB and associated statistical p values

For the renewable and GTL diesel fuels, the results show a steady decrease in NO_x emissions with increasingly higher levels of renewable diesel fuel. The NO_x emission results for the testing with the renewable diesel and the GTL diesel are presented in Figures ES-3 and ES-4, respectively, on a gram per brake horsepower hour (g/bhp-hr) basis. Over the FTP cycle, the NO_x reductions for the renewable and GTL diesel were comparable for each of the blend levels. For the FTP, the NO_x reductions for the renewable diesel ranged from 2.9% for the 20% blend to 9.9% for the 100% blend, while the NO_x reductions for the GTL ranged from ~1% for the 20% blend to 8.7% for the 100% blend. Larger emissions reductions were found over the UDDS and Cruise cycles, where only the renewable diesel fuel was tested. The reductions in NO_x for the renewable diesel fuel are comparable to those found in previous studies of heavy-duty engines.

NO_x Emissions - Renewable Blends
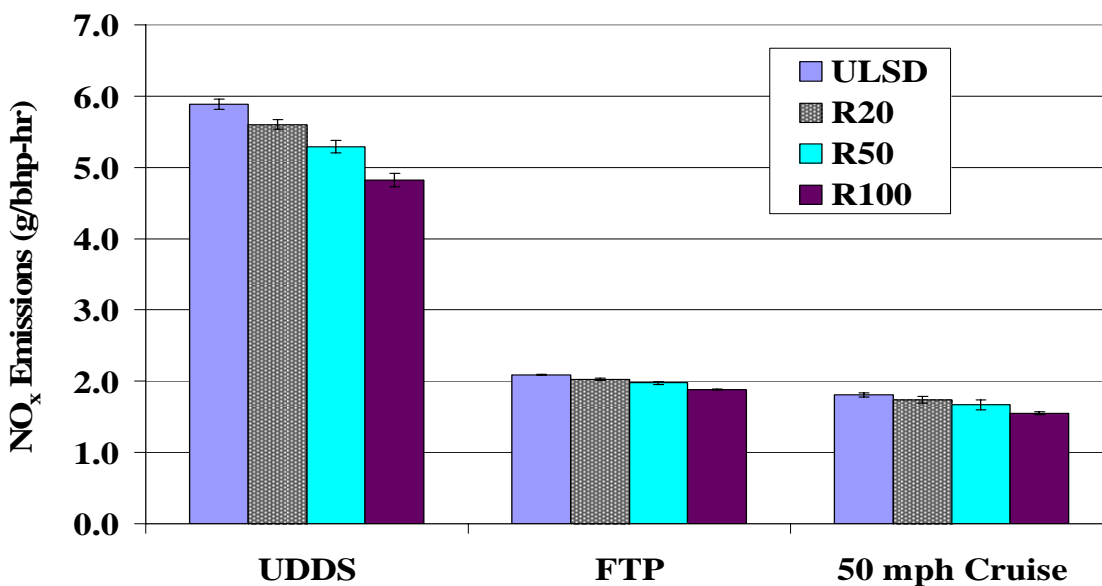
Figure ES-3. Average NO_x Emission Results for the Renewable Blends

NO_x Emissions - GTL Blends
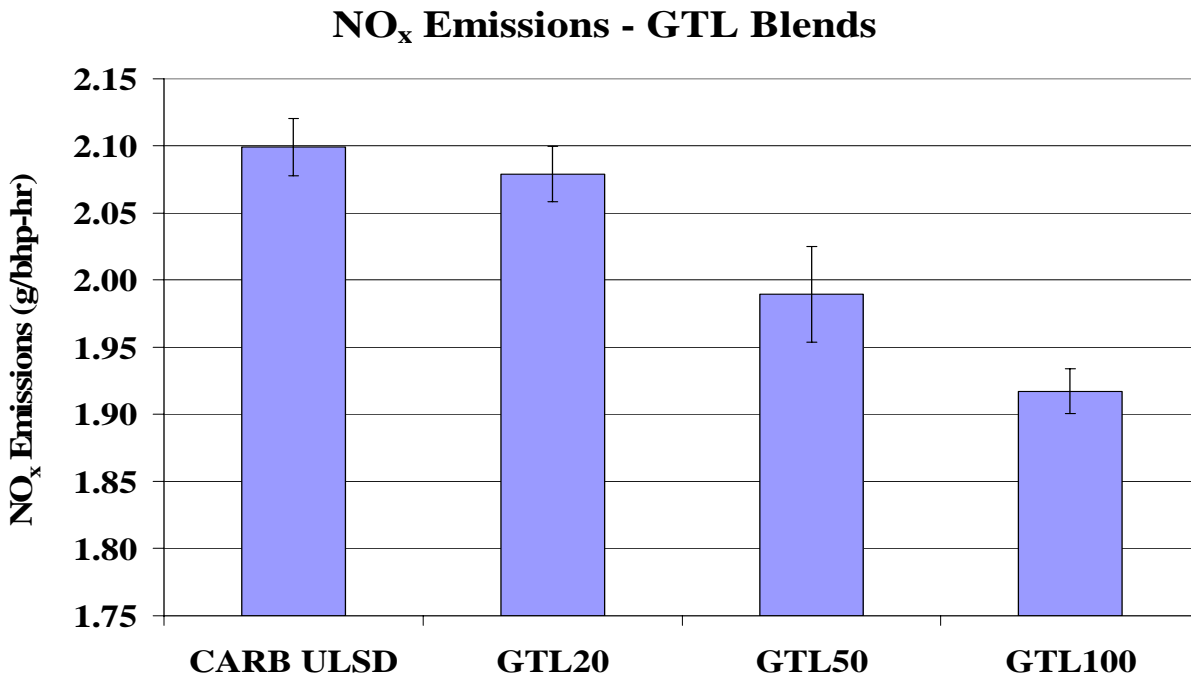
Figure ES-4. Average NO_x Emission Results for the GTL Blends

In comparison with the biodiesel feedstocks, the levels of NO_x reduction for the renewable and GTL fuels are less than the corresponding increases in NO_x seen for the soy-base biodiesel, but are more comparable to the increases seen for the animal-based biodiesel blends. With respect to NO_x mitigation, this suggests that the renewable and GTL diesel fuel levels need to be blended at slightly higher levels than the corresponding biodiesel in order to mitigate the associated NO_x increase, as discussed in further detail below. This is especially true for the soy-based biodiesel blends.

PM emissions showed consistent and significant reductions for the renewable blends, with the magnitude of the reductions increasing with blend level. The reductions for the renewable diesel were statistically significant for the higher blends and ranged from 12-15% for the R50 and from 24-34% for the R100. A statistically significant 4% reduction was also found for the R20 over the FTP. The GTL fuel showed a statistically significant reduction over the FTP, with reductions ranging from 8% for the 20% blend to 29% for the 100% blend. Similar reductions are found for the UDDS, FTP, and Cruise cycles indicating that cycle load does not have a significant impact on the PM reductions.

For the THC emissions, the GTL fuel showed statistically significant reductions over the FTP that increased with increasing blend level. These reductions ranged from 5% for the 20% blend to 28% for the 100% blend. The renewable diesel did not show consistent trends for THC emissions over the different test cycles. This finding was consistent with predictions based on the EPA's Unified Model and the associated distillation temperatures and other parameters of the fuels that showed there should not be any significant differences between the THC emissions for the CARB fuel in comparison with the renewable winter blend used in the study (Hodge, 2009). Statistically significant THC reductions were found for the renewable diesel fuel for the lowest

load UDDS cycle, with the THC reductions increasing with increasing levels of the renewable diesel fuel.

Reductions in CO emissions with the renewable diesel fuel were found for the UDDS and FTP cycles, but not for the cruise cycle. Over these cycles, the percentage reductions increased with increasing renewable diesel fuel blend. Over the FTP, these reductions ranged from 4% for the R20 to 12% for the R100. The comparisons of CO emissions over the 50 mph cruise may have been complicated by the changes in engine operation that were seen for that cycle. The GTL fuel also showed similar reductions over the FTP, with reductions ranging from 6% for the 20% blend to 14% for the 100% blend.

The CO_2 emissions for the neat or 100% blend renewable and GTL fuels were lower than those for the CARB ULSD for each of the test cycles. The reduction was on the order of 2-4% for the 100% blends. This slight reduction in CO_2 emissions is consistent and comparable to previous studies of the renewable diesel fuel.

The brake specific fuel consumption data showed increasing fuel consumption with increasing levels of renewable and GTL fuels. The increases in fuel consumption range from 1.0-1.4% for the R20 and 5.1 to 6.6% for the R100. The increases in fuel consumption with blend level are slightly higher for the cruise cycle compared to the lower load UDDS and FTP. The fuel consumption increases for the GTL ranged from 1.3% for the 20% blend to 3.3% for the 100% blend. The fuel consumption differences are consistent with the results from previous studies, and can be attributed to the lower density or energy density of the renewable and GTL fuels compared to the CARB baseline fuel.

NO_x Mitigation Results

Table ES-5 shows the percentage differences for the NO_x mitigation formulations compared with the CARB ULSD for different blend levels and test cycles, along with the associated p-values for statistical comparisons using a 2-tailed, 2 sample equal variance t-test. The shaded regions represent the formulations that provided NO_x neutrality relative to the CARB ULSD. The NO_x emission results for the various mitigation strategies are presented in Figure ES-5 on a gram per brake horsepower hour basis. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination within a particular test period. The NO_x mitigation testing was conducted over three separate test periods, the results of which are separated by the vertical lines in the figure. All comparisons with the CARB diesel are based on the CARB diesel results from that specific test period, so that the impacts of drift between different test periods was minimized.

The impact of biodiesel on NO_x emissions depends on the feedstock or fundamental properties of the biodiesel being blended. Blends of two biodiesels with different emissions impacts for NO_x provides a blend that shows a NO_x impact that is intermediate between the two primary biodiesel feedstocks. This indicates that the NO_x impact for a particular biodiesel feedstock can be mitigated in part by blending with another biodiesel feedstock with a lower tendency for increasing NO_x.

	THC	CO	NO_x	PM	CO_2	BSFC

	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value	% diff	P value
B5 - S	-1%	0.087	-1%	0.471	2.2%	0.000	-6%	0.000	0.1%	0.816	0.3%	0.228
B10 - S	-6%	0.000	-2%	0.171	2.6%	0.000	-17%	0.000	-0.1%	0.569	0.3%	0.167
B20 – S*	-11%	0.000	-3%	0.078	6.6%	0.000	-25%	0.000	0.4%	0.309	1.4%	0.001
B20-S 1% DTBP	-16%	0.000	-19%	0.000	0.0%	0.959	-16%	0.000	-0.9%	0.000	0.1%	0.748
B10-S 1% DTBP	-9%	0.000	-14%	0.000	-1.1%	0.002	-6%	0.000	-0.2%	0.258	0.2%	0.445
B20-S 1% 2-EHN	-16%	0.000	-15%	0.000	6.3%	0.000	-17%	0.000	0.2%	0.362	1.2%	0.000
B5-S 1% 2-EHN	-6%	0.000	-12%	0.000	3.1%	0.000	-4%	0.007	-0.1%	0.782	0.1%	0.564
R80/B20-soy	-13%	0.000	-16%	0.000	-3.0%	0.000	-47%	0.000	-2.0%	0.000	5.7%	0.000
C25/R55/B20-S	-12%	0.000	-13%	0.000	-0.8%	0.029	-40%	0.000	-1.5%	0.000	4.1%	0.000
C70/R20/B10-S	-8%	0.000	-3%	0.013	0.9%	0.014	-17%	0.000	-0.4%	0.059	1.7%	0.000
C75/R20/B5-S	-3%	0.014	-3%	0.048	0.2%	0.674	-11%	0.000	0.3%	0.309	2.2%	0.000
C80/B10-S/B10-A	-12%	0.000	-6%	0.000	3.9%	0.000	-26%	0.000	1.2%	0.003	2.2%	0.000
C80/R15/B5-S	-3%	0.024	-4%	0.000	0.7%	0.117	-11%	0.000	0.2%	0.686	1.6%	0.000
C80/R13/B3-S/B4-A	-2%	0.039	-4%	0.005	-0.3%	0.501	-9%	0.000	0.4%	0.251	1.9%	0.000
C53/G27/B20-S	-21%	0.000	-10%	0.000	2.1%	0.000	-32%	0.000	-1.4%	0.001	1.3%	0.002
C80/G10/B10-S	-7%	0.000	-5%	0.000	2.4%	0.000	-18%	0.000	0.6%	0.150	1.7%	0.000
C80/G15/B5-S	-7%	0.000	-5%	0.000	-0.7%	0.068	-9%	0.000	-0.6%	0.018	0.6%	0.010
C80/R10/B10-S 0.25% DTBP	-9%	0.000	-11%	0.000	-1.3%	0.002	-11%	0.000	-0.8%	0.006	0.5%	0.081

Table ES-4. Percentages changes for GTL blends relative to CARB and associated statistical p values

Notes: C = CARB ULSD; R = renewable, G = GTL; Bxx = biodiesel blend level; S = soy biodiesel; A = animal biodiesel
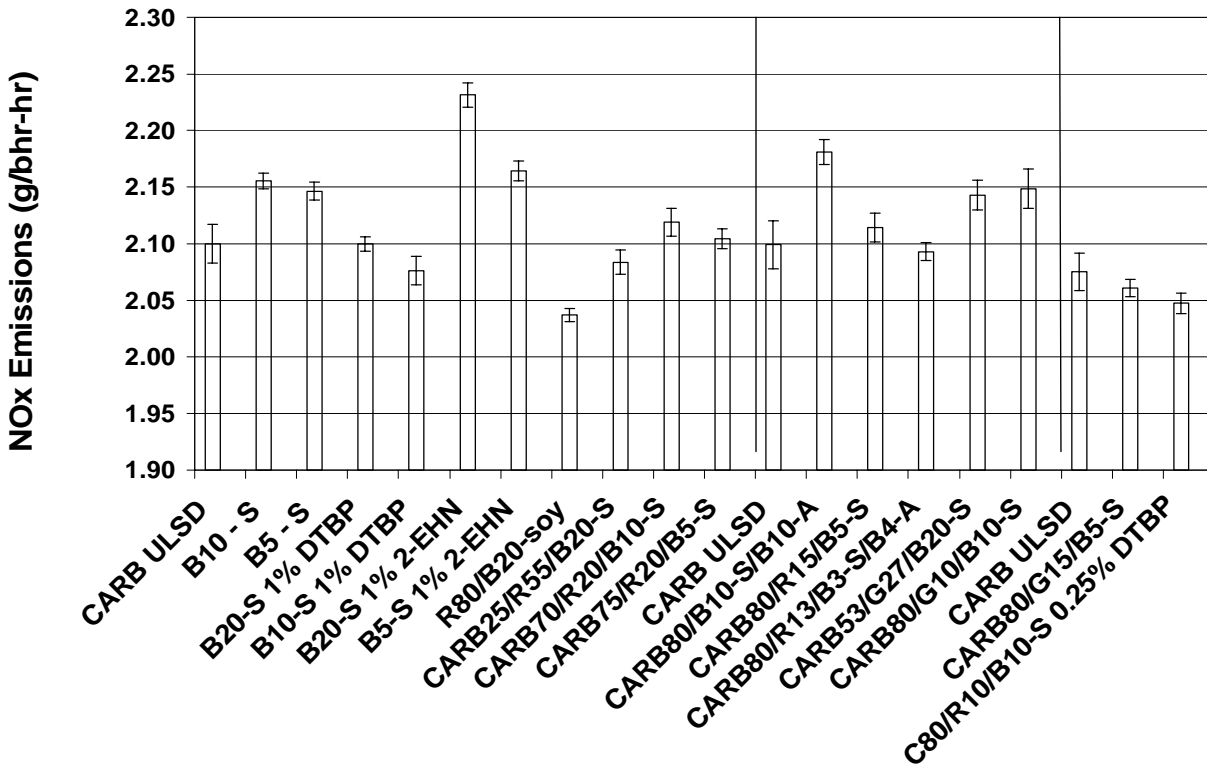
Figure ES-5. Average NO$_x$ Emission Results for the NO$_x$ Mitigation Formulations

Two additives were tested for NO$_x$ mitigation, 2-EHN and DTBP. Of these two additives, the DTBP was the most effective in this testing configuration. A 1% DTBP additive blend was found to fully mitigate the NO$_x$ impacts for a B20 and B10 soy biodiesel. The 2-EHN was tested at 1% level in both a B20-soy and B5-soy blend and did not show any significant NO$_x$ reductions from the pure blends.

The testing showed that renewable diesel fuels can be blended with biodiesel to mitigate the NO$_x$ impact. This included higher levels of renewable diesel (R80 or R55) with a B20-soy biodiesel. Several lower level blends, designed to be more comparable to those that could potentially be used to meet the low carbon fuel standard, also showed NO$_x$ neutrality, including a CARB75/R20/B5-soy blend, a CARB80/R13/B3-soy/B4-animal blend, a CARB80/R15/B5-soy blend, and a CARB80/GTL15/B5-soy blend. Overall, the renewable and GTL diesels provide comparable levels of reductions for NO$_x$ neutrality at the 15% blend level with a B5-soy.

The level of renewable or GTL diesel fuels can be reduced if a biodiesel fuel with more favorable NO$_x$ characteristics is used. This is demonstrated by the success of the CARB80/R13/B3-S/B4-A blend that combined both the soy and animal-based biodiesel. The use of an additive in conjunction with lower levels of renewable diesel and GTL can also be used to provide NO$_x$ neutrality, as shown by the success of the CARB80/R10/B10-S 0.25% DTBP blend.

The PM emissions for all of the NO$_x$ mitigation formulations all showed reductions in PM for both the additive blends and the renewable blends. The largest reductions were found for the formulations with higher percentages of both biodiesel (B20) and the renewable diesel (55%-

80%). Most of the other blends provided PM reductions that are slightly greater than those found for the corresponding B20 or lower soy biodiesel blends.

THC emissions showed consistent reductions for most of the NO_x mitigation blends ranging from 3 to 21%. These reductions were highest for the blends with the B20 blend level. Generally, the blends of biodiesel with either a renewable diesel, a GTL diesel, or an additive showed THC reductions that were either higher than or equivalent to the levels found for the biodiesel by itself at a particular blend level.

All formulations used for the NO_x mitigation showed reductions in CO compared to the CARB fuel ranging from 3 to 19%. The formulations with higher percentages of renewable diesel fuel (R80, R55, and GTL27) with B20 and those with additives all showed statistically significant reductions in CO emissions of 10% or greater.

The NO_x mitigation formulations showed statistically significant changes in CO_2 for about half of the formulations tested. The statistically significant changes were all reductions in CO_2 that were 2% or less. This included some for the formulations with higher blends (55 and 80%) of renewable diesel. This is consistent with the CO_2 reductions seem for the higher blends of the renewable diesel and GTL fuels discussed above.

The fuel consumption for the NO_x mitigations formations was either higher than or not statistically different from the CARB fuel. The increase in fuel consumption was highest for the fuels with the highest combined percentages of the renewable diesel and biodiesel. This is consistent with the fuel consumption increased seen for the higher blend levels of the biodiesel fuels, the renewable diesel, and the GTL diesel.

1.0 Introduction

The legislature passed AB1007 that requires the California Air Resources Board (CARB) and California Energy Commission (CEC) to develop a plan to increase alternative fuels use in California to reduce oil dependency and air pollution. Also, the Governor has established aggressive greenhouse emission reduction targets for which CARB has identified potential strategies such as biodiesel. Biodiesel is an alternative diesel fuel that has the potential to reduce greenhouse gas emissions, other pollutants, and can partially offset our use of petroleum-based fuels. However, knowledge gaps exist and further research is needed in characterizing the impact biodiesel has on oxides of nitrogen (NO_x) emissions, the effects various feedstocks have on air emissions, and the effect biodiesel has on emissions from off road and post 1997 on road diesel engines. This research is needed to conduct lifecycle analyses and to determine the potential health and environmental benefits and disbenefits of biodiesel. Additionally, for the conditions under which NO_x is found to increase, it is important to identify methods which can mitigate the NO_x increases.

The impact of biodiesel on emissions has been the subject of numerous studies over the past 20 years. The US EPA conducted a comprehensive assessment of the impact of biodiesel on pre 2002 engines (US EPA, 2002). Most of the studies cited in this report were on soy-based biodiesel in comparison with an average federal diesel base fuel. Based on this analysis, it was estimated that a soy-based biodiesel at a B20 level would increase NO_x emissions about 2% compared to an average Federal base fuel. Additional analyses in this same study did indicate that the impacts of biodiesel on NO_x emissions using a cleaner base fuel, more comparable to that utilized in California, could be greater than that found for the average Federal fuel, but data was more limited in this area.

Researchers at the National Renewable Energy Laboratory (NREL) conducted further analysis of more recent engine and chassis dynamometer test results (McCormick et al., 2006). These researchers noted that the nearly half of the data observations used for the EPA's analysis were 1991-1997 DDC engines, with a majority of these being the Series 60 model, so the analysis might not be representative of a wider range of technologies. They also noted that the engine testing results were highly variable for NO_x, with percentage changes for NO_x ranging from -7% to +7%. Reviewing more recent studies of newer engines, these researchers found an average change in NO_x emissions for the more recent engine studies of -0.6%±2.0%. Similar results were found for recent chassis dynamometer tests, which when the results were combined yielded an average change of 0.9%±1.5%. The US EPA conducted some more extensive analysis of the impact of test cycle on biodiesel emissions impacts (Sze et al. 2007). They found that biodiesel increased NO_x emissions over different test cycles from 0.9 to 6.6% for a B20 blend, with the change in NO_x emissions increasing linearly with the average cycle load.

Looking at the available literature as a whole, studies have generally shown hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) are reduced using biodiesel, while trends for NO_x emissions have been less clear. While many studies have shown slight increases in NO_x with biodiesel, results over a wide range of studies are varied. Some research has also suggested that the impact of biodiesel on NO_x emissions can depend on operating conditions, load, or engine configuration (McCormick et al. 2006; Sze et al. 2007). Studies have also shown that

operating condition and load can impact the effects of biodiesel on emissions and NO_x. Many studies are also limited in their direct application to California because exhaust emissions from diesel engines fueled with biodiesel were not compared to these engines fueled with CARB diesel or because they use only soy-based biodiesel that may not be the major feedstock used in California.

Some studies have also examined mechanisms via which biodiesel might impact NO_x emissions. Researchers have suggested a number of explanations including chemical structure (McCormick et al., 2001; Ban Weiss et al., 2005), such as fatty chain length and number of double bonds, an advancement in timing which could be related to bulk modulus (Szybist et al., 2003 a,b), and/or increases in combustion temperature (Cheng et al. 2007). Researchers at Cummins Inc. have also shown that both the combustion process and the engine control system must be taken into account when determining the net NO_x effect of biodiesel compared to conventional diesel fuel (Eckerle et al. 2008). If biodiesel blends are determined to increase NO_x emissions then it is important to find mitigation strategies that make biodiesel NO_x neutral or better when compared to CARB diesel use. It is known that the properties of diesel fuel can affect the emissions of NO_x as well as other emission components (Miller, 2003). It is possible that the fuel specifications of diesel fuel can be altered such that any negative impacts of the biodiesel in the blend could be overcome or such that the properties of the biodiesel blend could be made such that the blend would have the same properties as a typical diesel fuel. Biodiesel could potentially even be incorporated into more traditional petroleum refinery processes as a feedstock. The use of additives and cetane improvers has also shown some potential for reducing NO_x emissions from biodiesel blends (McCormick et al., 2002, 2005; Sharp, 1994).

To facilitate the introduction of a larger percent of renewable fuels into use and better characterize the emissions impacts of renewable fuels under a variety of conditions, CARB has implemented one of the most comprehensive studies of renewable fuels to date. The focus of this research study is on understanding and, to the extent possible, mitigating any impact that biodiesel has on NO_x emissions from diesel engines. This program incorporates engine testing, chassis dynamometer testing, and testing of off-road engines on a range of biodiesel and renewable diesel fuels. This will include heavy-duty diesel engines from different vintages, including a 2007 engine, a 2004-2006 engine, a retrofitted engine, and two non-road engines. The testing will also include at least two biodiesel feedstocks tested on blend levels of B5, B20, B50, and B100, one or more renewable diesel fuels and various blends of these fuels, and other fuel formulations/additive combinations designed to mitigate any potential increases in NO_x emissions. Testing will also be conducted on several cycles designed to represent low, medium, and high power engine operation such that the effects of biodiesel on NO_x emissions can be understood over a range of different operating conditions.

This memorandum summarizes the results from some of the initial testing under this comprehensive program. The testing described in this memorandum was conducted on a 2006 Cummins ISM engine in CE-CERT's engine dynamometer laboratory. The testing included a baseline CARB ultralow sulfur diesel (ULSD) fuel, two biodiesel feedstocks (one soy-base and one animal-based) tested on blend levels of B5, B20, B50, and B100, and a renewable and a gas-to-liquid (GTL) diesel fuel tested at 20%, 50%, and 100% blend levels. Testing was also conducted on up to 4 different engine test cycles to represent different operating conditions and

low, medium, and high loads. The results of this study provide an initial assessment of the potential impact of renewable fuel use in California and provide a basis for the development of NO_x mitigation strategies for the upcoming portions of the comprehensive CARB study.

2.0 Experimental Procedures

2.1 Test Fuels

The test fuels for this program included 5 primary fuels that were subsequently blended at various levels to comprise the full test matrix.

A CARB-certified ultralow sulfur diesel (ULSD) fuel was the baseline for testing. The CARB fuel was obtained from a California refinery. The properties of the fuel were reviewed by CARB staff prior to selection to ensure they were consistent with those of a typical ULSD in California. The key target parameters evaluated included aromatics, sulfur, and cetane number.

Two biodiesel feedstocks were utilized for testing, including one soy-based and animal-based biodiesel fuel. These fuels were selected to provide a range of properties that are representative of typical feedstocks, but also to have feedstocks representing different characteristics of biodiesel in terms of cetane number and degree of saturation.

A renewable feedstock and a GTL diesel were also used for testing. The renewable feedstock was provided by Neste Oil, and it is known as NExBTL. This fuel is denoted as the renewable diesel in the following results sections. This fuel is produced from renewable biomass sources such as fatty acids from vegetable oils and animal fats via a hydrotreating process (Rantanen et al. 2005; Kuronen et al. 2007; Aatola et al. 2008; Erkkila and Nylund; Kleinschek 2005; Rothe et al. 2005). The GTL diesel fuel was provided by a petroleum company.

A summary of selected for properties for the neat fuels is provided in Table 2-1, with the full fuel characterization provided in Appendix A.

The biodiesel and renewable diesel feedstocks were blended with the ULSD base in different blending ratios. The soy-based and animal-based biodiesels were blended at levels of B5, B20, B50, as well as using the straight B100. The renewable and GTL diesel fuels were blended at 20% and 50% levels by blending with the CARB base fuel.

The ULSD and the renewable diesel were tested in triplicate upon arrival at the fuel storage facility for all properties under ASTM D975 and density. The GTL fuel was also tested for the ASTM D975 properties, density, and other properties by the fuel supplier. For the renewable diesel, the cetane number was also determined using the ignition quality test, since the accuracy of the D613 cetane number tests has limitations at cetane values above 60. The analyses for the ULSD, the renewable diesel, and the GTL diesel were all conducted at the Southwest Research Institute (SwRI) in San Antonio, TX. The pure biodiesel feedstocks were tested in triplicate upon arrival at the fuel storage facility for all properties under ASTM D6751 and for density. The biodiesel analyses were primarily conducted by Magellan Midstream Partners, L.P., with some testing also conducted by SwRI. The density was utilized for the fuel blending.

Blending of the biodiesel fuels was performed at the Interstate Oil Inc. fueling facility in Woodland, CA. The fuels were blended on a gravimetric basis to achieve the appropriate volumetric blend levels. After blending, the biodiesel blends were tested via ASTM-D7371 to

ensure the blending was uniform and consistent with the targeted blend values. Blending for the renewable diesel blends was conducted at the facilities at CE-CERT using a gravimetric method. The finished blends were tested in triplicate for the properties under ASTM D975. The GTL blends were also blended at CE-CERT, but on a volumetric basis and on a drum by drum basis since smaller quantities of this fuel are needed. Samples of the GTL blends were collected but not analyzed, except for one sample to characterize cetane number. The results of the fuel analyses for the blended fuels are provided in Appendix A.

Table 2-1. **Selected Fuel Properties**

	CARB ULSD	NExBTL Renewable Diesel	GTL	Soy-biodiesel	Animal-biodiesel
API gravity (@ 60ºF)	39.0	51.3	48.4	28.5	28.5
Aromatics, vol. %	18.6	0.4	0.5	NA	NA
PNAs, wt. %	1.6	0.1	<0.27	NA	NA
Cetane number, D613	57.4	72.3	>74.8	47.7	57.9
Cetane number, IQT		74.7			
Distillation, IBP	337	326	419		
T10, ºF	408	426	482		
T50,ºF	526	521	568		
T90, ºF	615	547	648	350ºC	347.5ºC
IBP	661	568	673		
Free glycerin, mass %	NA	NA	NA	0.001	0.008
Total glycerin, mass %	NA	NA	NA	0.080	0.069
Sulfur, ppm	3.3	0.3	0.9	0.7	2

Notes: NA = either Not Available or Applicable; IQT = ignition quality test derived cetane number
Distillation temperature for biodiesel samples provided in degrees C for comparison with D675

2.2 Engine Selection

The engines were selected from 2 model year categories; 2002-2006 and 2007+. The 2002-2006 engines are estimated to represent an important contribution to the emissions inventory from the present through 2017. The 2007 engine model year represents the latest technology that is available at present. The results for the 2007 engine will be discussed in an additional memorandum.

The 2002-2006 engine was a 2006 model year Cummins engine. This engine was pulled from a truck that was purchased specifically for this project and run at CARB's chassis dynamometer laboratory in Los Angeles, CA to obtain the engine operating parameters (as discussed below). The specifications of the engine are provided in **Error! Reference source not found.**. The results presented in this memorandum are all for this 2006 engine.

Table 2-2. Test Engine Specifications

Engine Manufacturer	Cummins, Inc.
Engine Model	ISM 370
Model Year	2006
Engine Family Name	6CEXH0661MAT
Engine Type	In-line 6 cylinder, 4 stroke
Displacement (liter)	10.8
Power /Torque Rating	370 hp / 1450 ft-lbs @ 1200 rpm
Fuel Type	Diesel
Induction	Turbocharger with charge air cooler

2.3 Test Cycles

The test cycles included the standard Federal Testing Procedure (FTP) for heavy-duty engines and three other cycles based on engine parameters collected over standard cycles on chassis dynamometer. Initially, two additional cycles were selected for testing that included a lightly loaded Urban Dynamometer Driving Schedule (UDDS) cycle and a 40 miles per hour (mph) CARB heavy heavy-duty diesel truck (HHDDT) cruise cycle. The different cycles were initially selected to provide a range of operating conditions and operational loads and some connection to the chassis dynamometer testing being conducted in CARB's Los Angeles laboratory.

The chassis dynamometer cycles were developed utilizing engine parameters downloaded when the light UDDS and the 40 mph CARB cruise cycle were run with the test vehicle on the chassis dynamometer. The light UDDS cycle was run over the standard UDDS cycle, with the test vehicle loaded at the weight of the truck cab itself with no trailer. This represents the most lightly loaded test cycle. The 40 mph CARB cruise cycle represented a heavier load cycle and was based on the vehicle being run at its fully loaded weight.

The torque and engine rpm were directly obtained from the J1939 signal for the test vehicle while it was driven on the chassis dynamometer. These cycles were then programmed into the CE-CERT engine dynamometer software prior to engine testing. In the process of translating the cycles from the chassis to the engine dynamometer, the cycles were optimized by setting the torque and engine RPM values equal to zero during periods of idle operation and the regression validation criteria were modified to account for the differences between the test cycles developed using chassis dynamometer data and the standard FTP. The procedures for the development of these cycles are described in greater detail in Appendix B.

After the initial round of testing on the soy-based biodiesel, it was determined that the loads for the FTP and the 40 mph CARB cruise cycle were very similar, and hence did not provide a sufficient load range to meet the program goals. It was decided that an additional higher load cycle was needed to provide a larger range of load conditions. The cycle that was selected was the 50 mph CARB HHDDT cruise cycle, but with an average speed of 50 mph instead of 40 mph.

This cycle was used for an additional round of supplementary tests on the soy-based biodiesel, and then it was substituted for the 40 mph cruise cycle on the subsequent testing for the animal and renewable feedstocks. Since logistics of replacing the engine back into the vehicle to generate the J1939 data for this specific engine were too impractical, an engine dynamometer test cycle version of this cycle that was developed for the ACES program was utilized (Clark et al., 2007). This cycle was developed from data collected through the E55/59 chassis dynamometer study of heavy-duty trucks.

2.4 Test Matrix

The test matrix was developed in conjunction with statisticians at CARB and the US EPA based on estimates of the magnitude of the impact biodiesel can have on NO_x emissions at a B20 level and estimates of test-to-test repeatability.

The test matrix is based on providing a randomized test matrix with long range replication. The initial test matrix provided replication of all test blends with replication of the base ULSD every 2 days. The initial test matrix also included randomization within the test day with different fuels being tested in the morning vs. the afternoon and with the cycles being conducted in a random order for each fuel sequence. For the GTL fuel, testing was only conducted on the FTP since this fuel was primarily being characterized for use as a NO_x mitigation strategy.

After the completion of the first round of testing on the soy-based biodiesel, it was decided to accelerate the rate of testing. The accelerated test matrix used for the remainder of the testing on the soy-based biodiesel utilized a test sequence similar to that used in the initial testing, but with essentially two days of the initial test matrix, or 12 tests, run in a single day.

Since the expected NO_x impact for the B5 level should be less than that of B20, and hence more difficult to statistically differentiate from the testing variability, the B5 blend was run outside the sequence. Initially, for the soy-based biodiesel, the B5 level was run only for the higher load cruise cycles since it was expected that larger impacts would be seen at higher loads. For the animal-based biodiesel, it was decided to test the B5 fuel on the FTP instead, since the testing repeatability was better for the FTP tests. The test matrices for the main portion of the engine testing are provided below.

Some additional tests were also run on the soy-based biodiesel since a number of tests were identified to be outliers, and because a new higher load cruise cycle was substituted into the test matrix. The nature of the outlier tests is discussed above. The number of additional test replicates conducted on a particular soy-based blend depended on the number of outliers in the initial round of testing. A full complement of tests on the 50 mph CARB HHDDT cycle was also conducted to allow for full comparability between the soy-based, animal-based, and renewable fuels.

A = Lght. UDDS B = FTP C1 = ARB 40 mph Cruise C = ARB 50 mph Cruise

Engine 1-2006 cummins ISM

Soy based biodiesel

Day 1

Fuel	Cycle
CARB	A
	C1
	B
B20	C1
	B
	A

Day 2

Fuel	Cycle
B20	B
	A
	C1
B50	B
	C1
	A

Day 3

Fuel	Cycle
B50	A
	B
	C1
CARB	C1
	A
	B

Day 4

Fuel	Cycle
CARB	C1
	A
	B
B100	A
	B
	C1

Day 5

Fuel	Cycle
B100	B
	C1
	A
B20	B
	A
	C1

Day 6

Fuel	Cycle
B20	C1
	B
	A
CARB	A
	C1
	B

Day 7

Fuel	Cycle
CARB	B
	A
	C1
B50	B
	A
	C1

Day 8

Fuel	Cycle
B50	A
	B
	C1
B100	C1
	A
	B

Day 9

Fuel	Cycle
B100	A
	C1
	B
CARB	B
	C1
	A

Day 10

Fuel	Cycle
CARB	A
	C1
	B
B20	A
	B
	C1

Day 11

Fuel	Cycle
B20	B
	A
	C1
B50	C1
	B
	A

Day 12

Fuel	Cycle
B50	A
	B
	C1
B100	B
	C1
	A

Day 13

Fuel	Cycle
B100	C1
	B
	C1
CARB	C1
	A
	B

Day 14

Fuel	Cycle
CARB	C1
	C1
	C1
B5	C1
	C1
	C1

Day 16

Fuel	Cycle
CARB	C
	A
	B
B20	A
	C
	B
B20	B
	A
	C
CARB	C
	B
	A

Day 17

Fuel	Cycle
CARB	A
	C
	B
B50	C
	A
	B
B50	C
	B
	A
CARB	A
	C
	B

Day 18

Fuel	Cycle
CARB	A
	B
	C
B100	B
	A
	C
B100	A
	C
	B
CARB	B
	C
	A

Day 19

Fuel	Cycle
CARB	C
	C
	C
B5	C
	C
	C
B5	C
	C
	C
CARB	C
	C
	C

Day 20

Fuel	Cycle
CARB	C
	C
	C
	C
B20	C
	C
	C
B50	C
	C
	C

Day 21

Fuel	Cycle
	A
	B
	A
	B
B100	C
	C
	C
CARB	C
	C
	C
	C

A = Lght. UDDS B = FTP C1 = ARB 40 mph Cruise C = ARB 50 mph Cruise

Engine 1-2006 cummins ISM

Animal based BDSL

	Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7		Day 8	
	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
	CARB	A	B50	A	B100	C	CARB	B	B100	A	B20	C	B100	B	B5	B
		C		B		B		C		C		A		C		B
		B		C		A		A		B		B		A		B
	B20	B	CARB	C	B20	B	B50	B	CARB	C	B50	A	CARB	B	CARB	B
		A		B		C		A		A		B		A		B
		C		A		A		C		B		C		C		B
	B20	C	CARB	B	B20	A	B50	B	CARB	A	B50	A	CARB	B		
		A		C		B		A		C		B		B		
		B		A		C		C		B		C		B		
	B50	A	B100	A	CARB	A	B100	C	B20	C	B100	B	B5	B		
		B		C		C		B		B		C		B		
		C		B		B		A		A		A		B		

Renewable Diesel

	Day 1		Day 2		Day 3		Day 4		Day 5		Day 6		Day 7	
	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
	CARB	A	R50	C	R100	C	CARB	B	R100	A		C	R100	B
		B		A		B		C		C		A		A
		C		B		A		A		B		B		C
	R20	C	CARB	B	R20	A	R50	C	CARB	B	R50	B	CARB	A
		A		A		B		A		A		C		C
		B		C		C		B		C		A		B
	R20	A	CARB	B	R20	A	R50	B	CARB	A	R50	C		
		C		C		B		A		B		B		
		B		A		C		C		C		A		
	R50	B	R100	C	CARB	A	R100	C	R20	A	R100	B		
		C		A		C		B		C		C		
		A		B		B		A		B		A		

GTL Diesel

	Day 1		Day 2		Day 3	
	Fuel	Cycle	Fuel	Cycle	Fuel	Cycle
		B	G50	B	G100	B
		B		B		B
		B		B		B
	G20	B	CARB	B	CARB	B
		B		B		B
		B		B		B
	G20	B	CARB	B		
		B		B		
		B		B		
	G50	B	G100	B		
		B		B		
		B		B		

9

2.5 Preliminary Testing

Prior to initiating the full testing on the test matrix, several preliminary tests were conducted on the first test engine. These preliminary tests included tests on both the baseline and a B20 animal blend. The objective of these preliminary tests was to verify that the experimental parameters such as test repeatability and the biodiesel NO_x differential were consistent with the estimates used in developing the test matrix. The results of this preliminary testing are provided below. The results show that the NO_x differential for this feedstock was similar to that expected based on EPA current estimates. Additionally, the coefficient of variation (COV) was on the order of 1%, similar to what was expected. The preliminary results showed that with these constraints, statistically significant differences in NO_x could be measured between the different test fuels at the 95%+ percent confidence level.

Table 2-3. Results of Preliminary Biodiesel Testing

	THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2 g/bhp-hr
CARB ULSD[*]					
ave.	0.289	0.757	2.108	0.078	632.492
st dev.	0.003	0.026	0.022	0.002	4.343
COV	1.1%	3.4%	1.0%	2.8%	0.7%
B20-Animal [*]					
ave.	0.250	0.692	2.146	0.061	637.065
st dev.	0.004	0.013	0.016	0.000	4.056
COV	1.8%	1.9%	0.7%	0.7%	0.6%
% difference (B20 – CARB)	-13.8%	-8.6%	1.8%	-21.2%	0.7%
T-Test	0.000	0.000	0.006	0.000	0.089

[*] Results based on 6 replicate FTP tests on each fuel

2.6 Emissions Testing

The engine emissions testing was performed at the University of California at Riverside's College of Engineering-Center for Environmental Research and Technology (CE-CERT) in CE-CERT's heavy-duty engine dynamometer laboratory. This engine dynamometer test laboratory is equipped with a 600 hp General Electric DC electric engine dynamometer and is a fully Code of Federal Regulations (CFR) compliant laboratory.

An engine map was conducted on the test fuel in the engine for the first test of the day. Given the random order of testing, this fuel was usually the fuel from the fuel change from the day before. A second engine map was also obtained for the second fuel tested each day. In order to provide a consistent basis for comparison of the emissions, all cycles were developed and run based on the initial engine map from operating the engine on the baseline CARB ULSD. This is consistent with the procedures used in the CARB procedures for certifying alternative diesel formulations.

Testing was conducted on an FTP, a light-UDDS, and combinations of the CARB HHDDT 40 mph and 50 mph cruise cycles. For all tests, standard emissions measurements of total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter (PM), and carbon dioxide (CO_2) were measured. The emissions measurements were made using the standard analyzers in CE-CERT's heavy-duty Mobile Emissions Laboratory (MEL) trailer. A brief description of the MEL is provided in Appendix C, with more details on the MEL provided in Cocker et al. (2004 a,b). No toxic testing will be conducted in conjunction with this portion of the testing.

2.7 Outlier Tests

Throughout the course of testing on the first engine some outliers were observed in the testing that appeared to be related to conditions set within the engine control module (ECM).

Prior to initiating the testing program, CE-CERT switched from an air-cooled to a water-cooled temperature control system for the turbocharged inlet air. This system operated well during the preliminary testing, but had some issues when the ambient temperature declined and the cooling water temperature dropped to levels below 68°F. Figure 2-1 shows real-time NO_x traces for four tests conducted over the UDDS cycle using the CARB ULSD. These traces clearly show significant differences in the emissions profiles between the tests. Figure 2-2 shows the corresponding intake air temperature (IAT) profiles for the same tests as recorded from the J1939 signal. As shown, tests with the cooler intake air temperature profiles, where the minimum temperature drops below 60°F, had considerably higher NO_x emissions compared to those with the higher intake air temperatures. These differences were seen both within the transient portion of the test and during the idle periods as well. These trends were also observed on the FTP and cruise cycles, but to a lesser extent since these cycles have higher loads and generally warmer operating conditions. In analyzing the first batch of testing rests, the real-time NO_x and IAT results were plotted for all tests to identify tests where this phenomenon was observed. For the subsequent analyses and subsequent plots in this report, all tests where the cooling water temperature to the intercooler was found to drop below 68°F were removed. A total of 45 of 159 tests were removed based on this criterion for the testing on the soy-based biodiesel feedstock. The water-based temperature control system was redesigned to provide full temperature control for the remainder of the tests and this phenomenon was not observed with the new system. Some additional tests were also performed to ensure there were sufficient replicates for subsequent statistical analysis for each of the different fuel blend/test cycle combinations for the soy-based biodiesel.
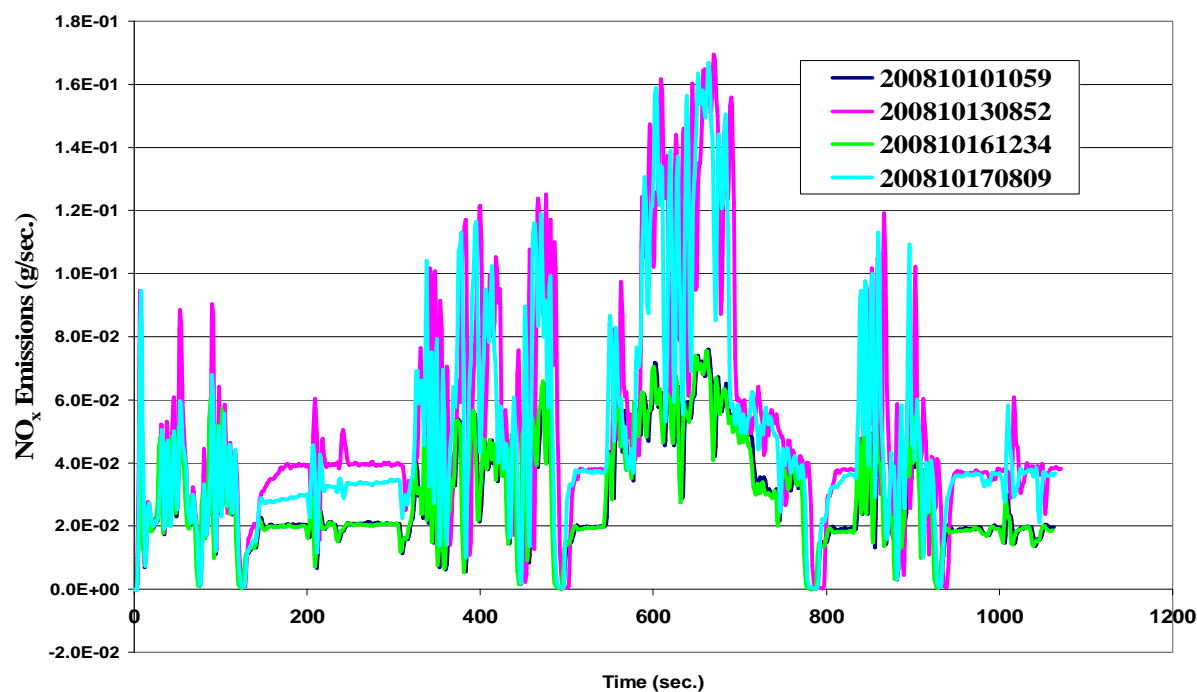
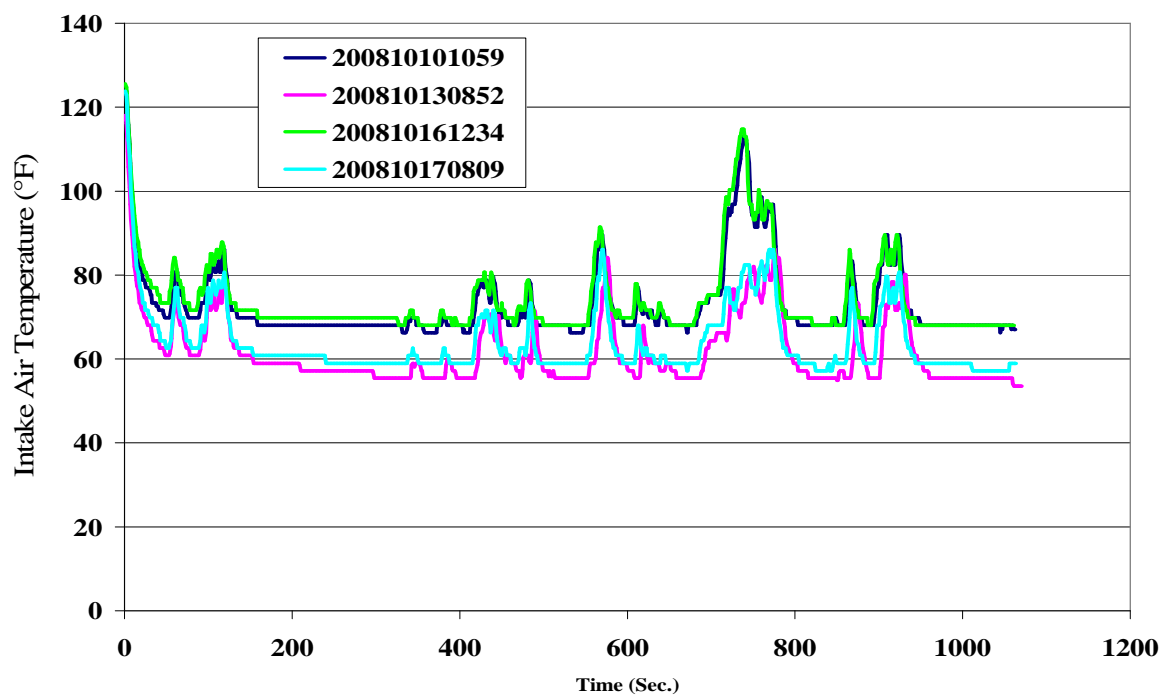**Figure 2-1. Real-Time NO$_x$ traces for four tests using CARB ULSD over the UDDS Cycle.**

Figure 2-2. Real-Time Intake Air Temperature traces for four tests using CARB ULSD over the UDDS Cycle.

A second condition was also observed where changes in engine operation were observed within the 50 mph CARB HHDDT cycle. For this test cycle, for a period of the test cycle from approximately 300 to 400 seconds, two distinct modes of operation were observed. This is shown in Figure 2-3, which shows all of the real-time NO_x traces for 50 mph CARB HHDDT cycle run on the animal-based biodiesel feedstock, as well as the associated CARB tests. The conditions associated with this engine operating condition and the statistics relating with this phenomena are described in greater detail in Appendix E. Of the ninety two 50 mph cruise cycles that were conducted on the first engine, approximately 2/3^{rds} of the tests showed emissions at the lower NO_x level and 1/3rd of the tests showed emissions at the higher NO_x level during this 300-400 second period. For the different fuels, CARB diesel showed a greater propensity of operating in the mode higher emission mode while the higher biodiesel blends showed a greater propensity for having low NO_x emissions during the 300-400 second time period. The primary impact in the regulated emissions was an increase in NO_x emissions, which ranged from 4.0 to 7.4% over the different test periods between the high and low mode operations. The operational conditions had the opposite impact on the other emissions, with emissions reductions ranging from 1-4.2% for THC, from 2.4 to 6.8% for CO, from 1.5 to 6.2% for PM, and from 0.7 to 1.9% for CO_2. As this operating condition could represent typical operation under these conditions, no tests were removed from the data sets and the associated analyses below. This complicated some of the statistical comparisons, especially at the 20% blend levels.
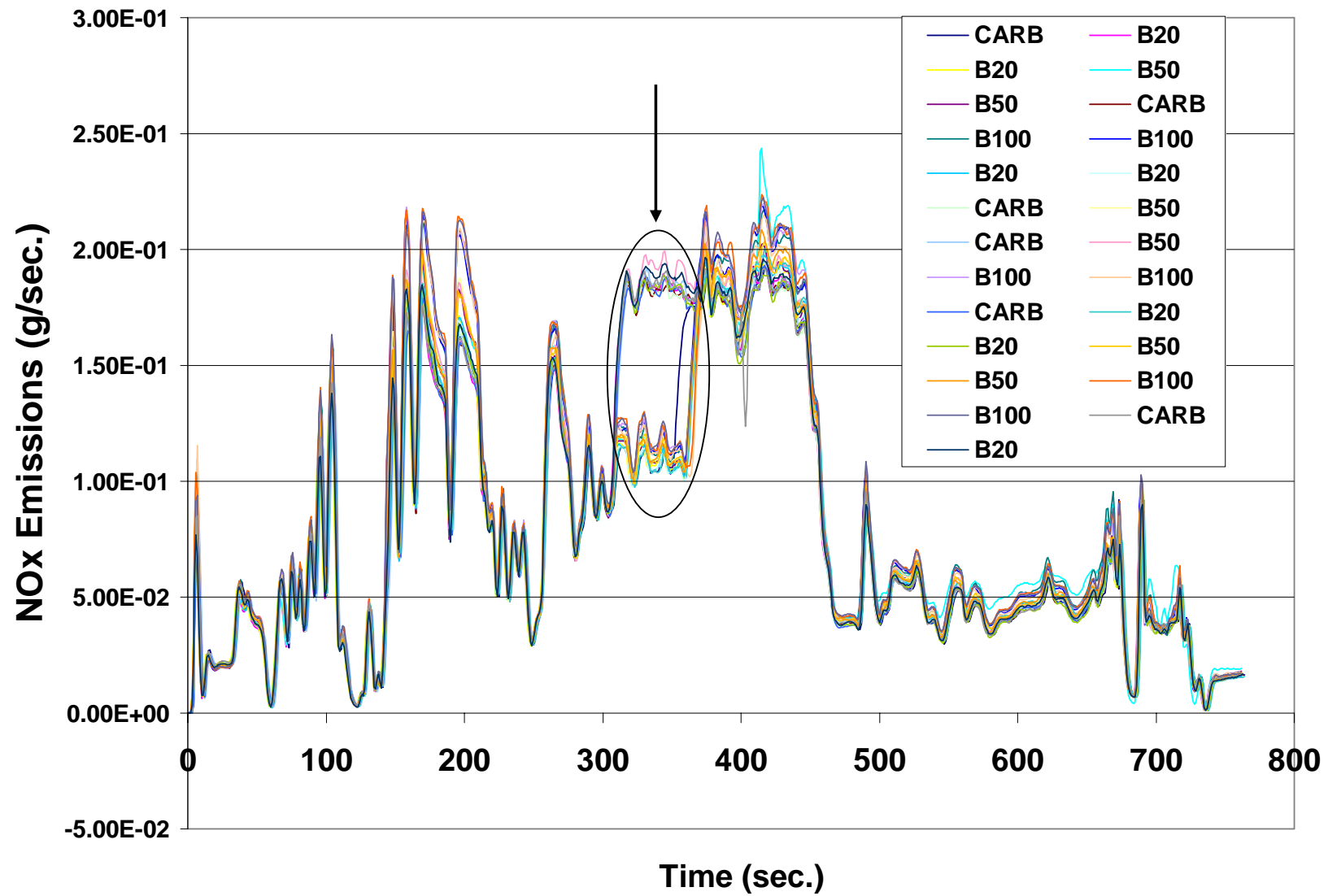
Figure 2-3. Real-Time NOₓ Emission Traces for the 50 MPH CARB Cruise Cycle for the Animal-Based Biodiesel Feedstock.

3.0 Biodiesel Results

3.1 NO_x Emissions

Understanding the impact of biodiesel on NO_x emissions is one of the more critical elements of this program. The NO_x emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock are presented in Figure 3-1 and Figure 3-2, respectively, on a gram per brake horsepower hour (g/bhp-hr) basis. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination. The error bars represent one standard deviation on the average value.
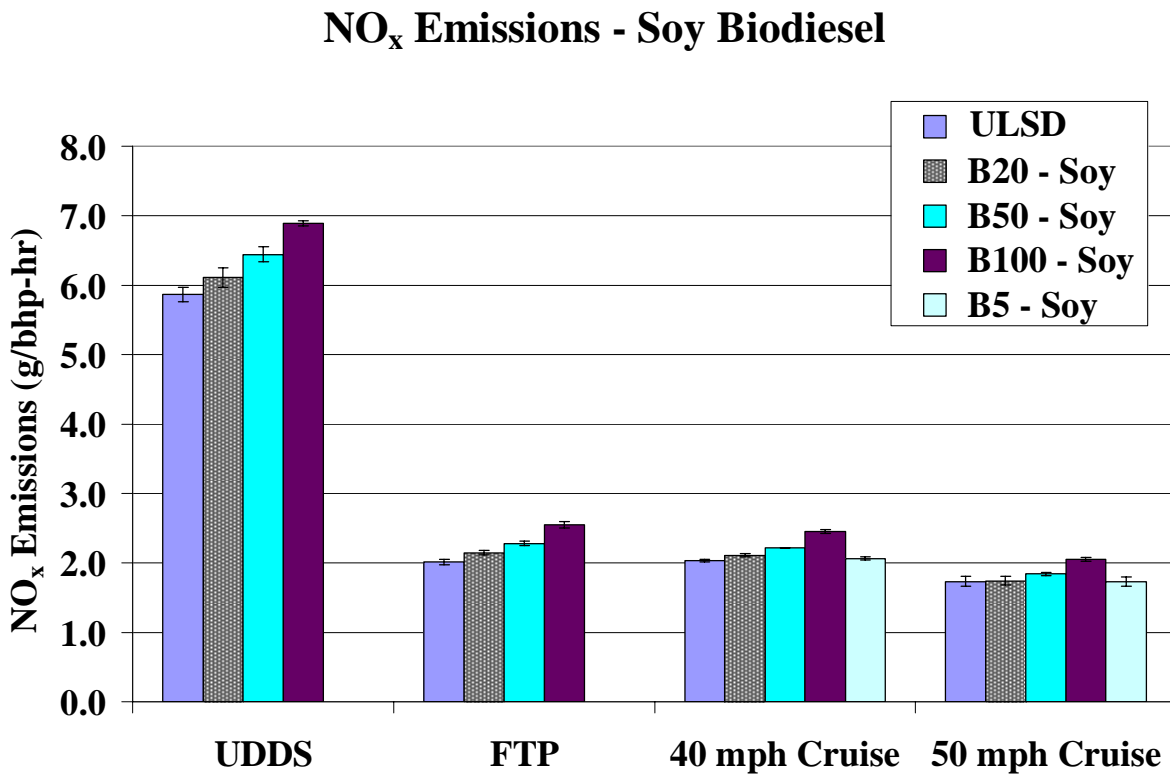

Figure 3-1. Average NO_x Emission Results for the Soy-Based Biodiesel Feedstock
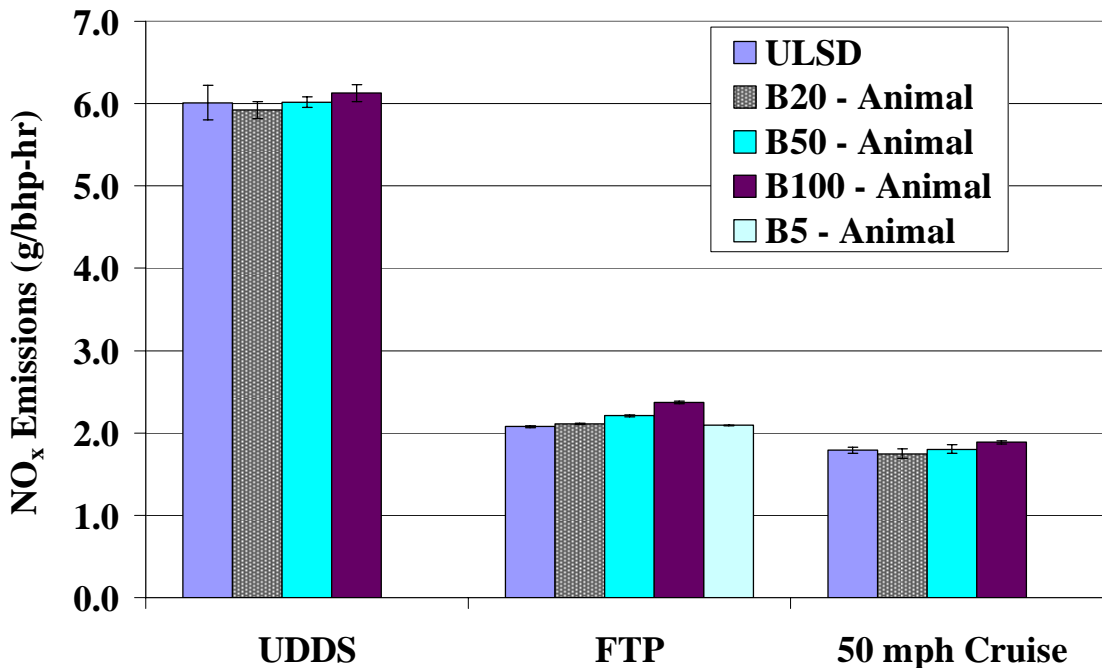
NO$_x$ Emissions - Animal Biodiesel

Figure 3-2. Average NO$_x$ Emission Results for the Animal-Based Biodiesel Feedstock

The average NO$_x$ emissions show trends of increasing NO$_x$ emissions with increasing biodiesel blend level, but the magnitude of the effects differ between the different feedstocks. Table 3-1 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a 2-tailed, 2 sample equal variance t-test. These statistical analyses provide information on the statistical significance of the different findings. For the discussion in this memorandum, results are considered to be statistically significant for p values ≤0.05. A more comprehensive statistical analysis is planned once the experimental testing on all of the test engines and vehicles is completed. The soy-based biodiesel blends showed a higher increase in NO$_x$ emissions for essentially all blend levels and test cycles. For the different cycles, the FTP seemed to show the strongest NO$_x$ increases for biodiesel for both soy-based and animal-based blends. For comparison, EPA base case estimates from their 2002 study showed increases in NO$_x$ of 2% at the B20 level, 5% at the B50 level, and 10% at the B100 level. The soy-based biodiesel blends showed increases that were higher than the EPA estimates for all of the test cycles. The NO$_x$ impacts found for the soy-based biodiesel are consistent, however, with the EPA estimates for the "clean base fuel" case, which show increases of 28% for a B100 fuel against a clean base fuel. For the animal-based biodiesel feedstock, the emission increases for the FTP cycle are consistent with the EPA base case estimates. For the UDDS cycle for the animal-based biodiesel feedstock, the emissions differences were not statistically significant for any of the blend levels. For the 50 mph Cruise cycle for the animal-based biodiesel, a statistically significant increase was only found for the B100 level that was approximately a 5% increase. It should be noted that

the percentage changes in emissions and the statistical significance of the changes in NO_x emissions for the 50 mph Cruise cycle were obscured by the different engine operation that was observed for that cycle, as discussed in section 2.7 and Appendix E.

		g/bhp-hr basis			
		Soy-based		Animal-based	
		%	P-	%	P-
	CARB vs.	Difference	values	Difference	values
UDDS	B20	4.1%	0.002	-1.5%	0.376
	B50	9.8%	0.000	0.1%	0.935
	B100	17.4%	0.000	1.9%	0.243
FTP	B5	2.2% (Mit)	0.000	0.3%	0.298
	B10	2.6% (Mit)	0.000		
	B20	6.6%	0.000	1.5%	0.000
	B50	13.2%	0.000	6.4%	0.000
	B100	26.6%	0.000	14.1%	0.000
40 mph Cruise	B5	1.7%	0.135		
	B20	3.9%	0.000		
	B50	9.1%	0.000		
	B100	20.9%	0.000		
50 mph Cruise	B5	-1.1%	0.588		
	B20	0.5%	0.800	-2.3%	0.151
	B50	6.3%	0.001	0.8%	0.588
	B100	18.3%	0.000	5.3%	0.000

Table 3-1. NO_x Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle.

It is also useful to look at the impacts of cycle power on NO_x emissions and the trends with biodiesel. In a recent study by the US EPA (Sze et al. 2007), it was found that NO_x emissions and the difference in NO_x emissions between a biodiesel blend and a base fuel or B0 blend both increased as the average power of the cycle increases. For this study, NO_x emissions did show a general increase in NO_x as the average cycle power increased. This is shown in Figure 3-3 for the soy-based biodiesel and in Figure 3-4 for the animal-based biodiesel. The differential between NO_x emissions for a biodiesel blend and the base fuel, however, did not increase as a function of average power as observed in the EPA study. This is shown in Figure 3-5 for the soy-based biodiesel and in Figure 3-6 for the animal-based biodiesel. Similar, the NO_x differential for biodiesel also did not increase as a function of fuel consumption, as shown in Figure 3-7 for the soy-based biodiesel and in Figure 3-8 for the animal-based biodiesel. Interestingly, the NO_x differential shows the highest values for the FTP or certification test for both the soy-based and animal-based biodiesel blends. It is not known why the current results differ from those found by EPA. For the present program, all testing was performed on the same engine map to maintain a consistent set of target performance points for each fuel over each cycle. It is possible that different engine mapping procedures were utilized in the EPA study. Additionally, the results in this study for the highest load cycle are obscured by the differences in engine operation that were observed for the 50 mph cruise cycle.

Average Cycle Power vs. NO$_x$ - Soy Biodiesel
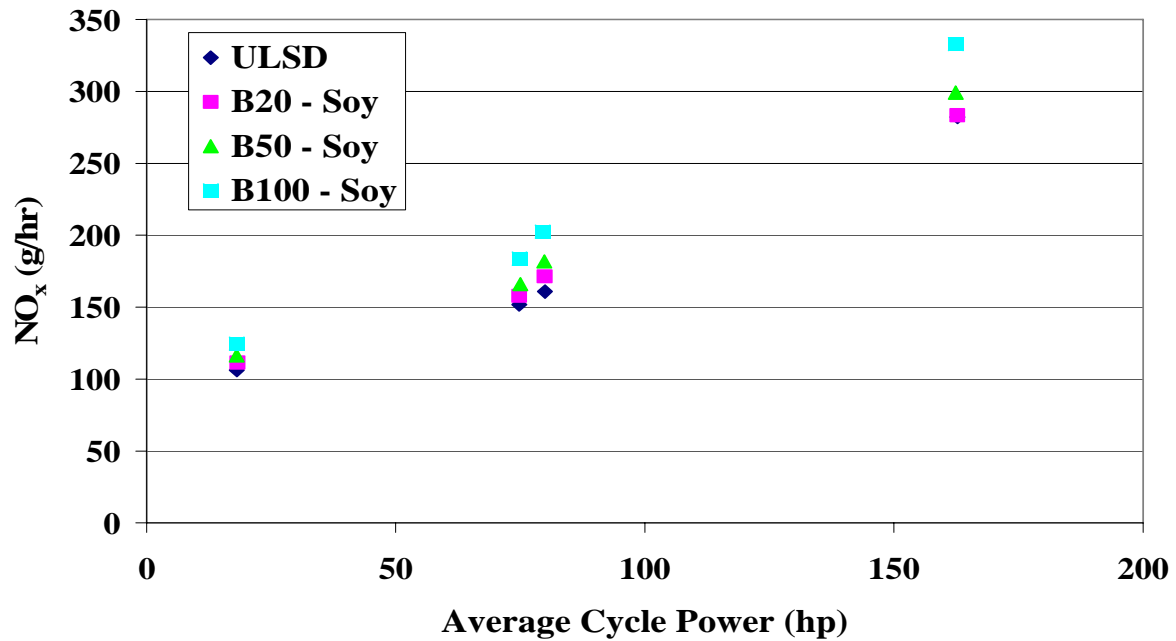

Figure 3-3. Average Cycle Power vs. NO$_x$ Emissions for Testing on Soy-Based Biodiesel Blends

Average Cycle Power vs. NO$_x$ - Animal Biodiesel
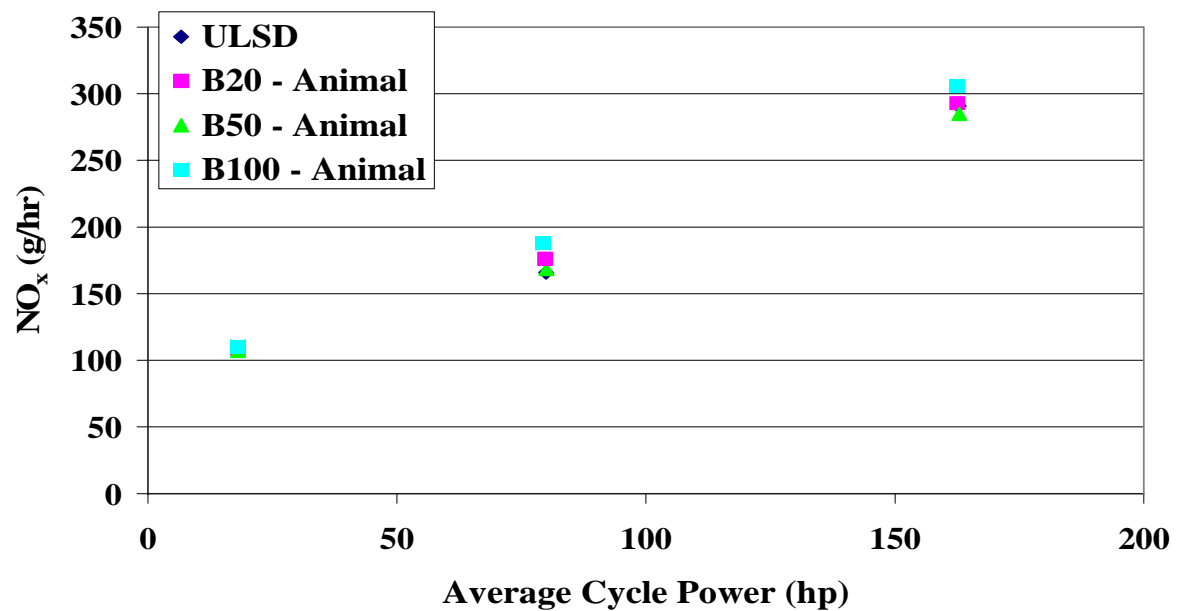
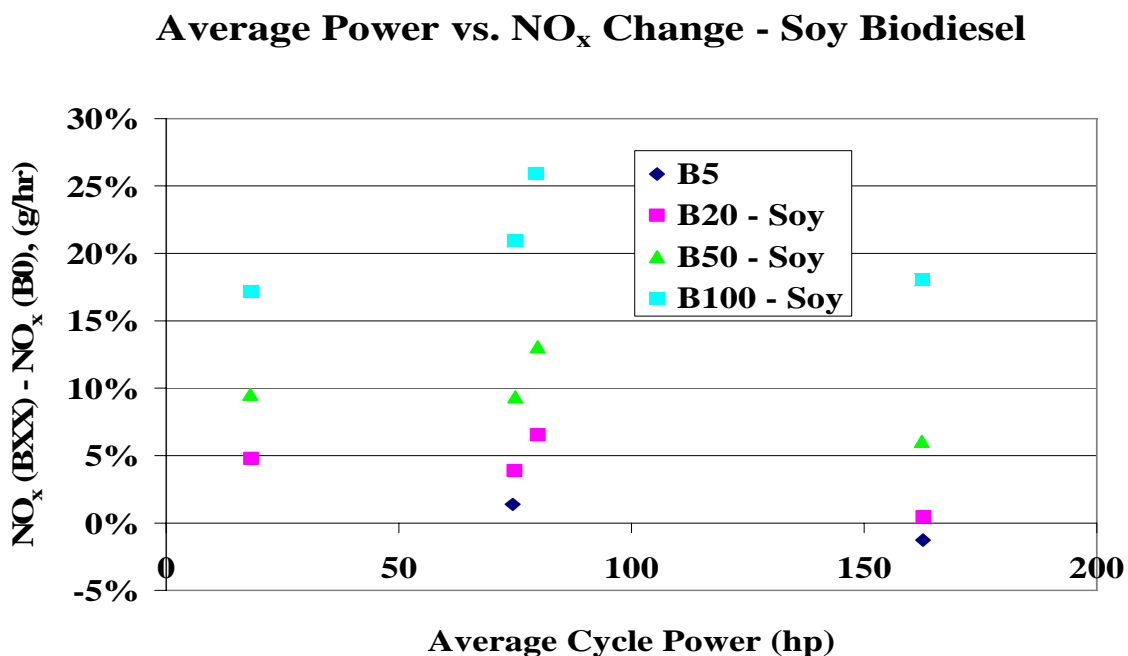**Figure 3-4. Average Cycle Power vs. NO_x Emissions for Testing on Animal-Based Biodiesel Blends**

Figure 3-5. Average Cycle Power vs. NO_x Emissions Change for Testing on Soy-Based Biodiesel Blends
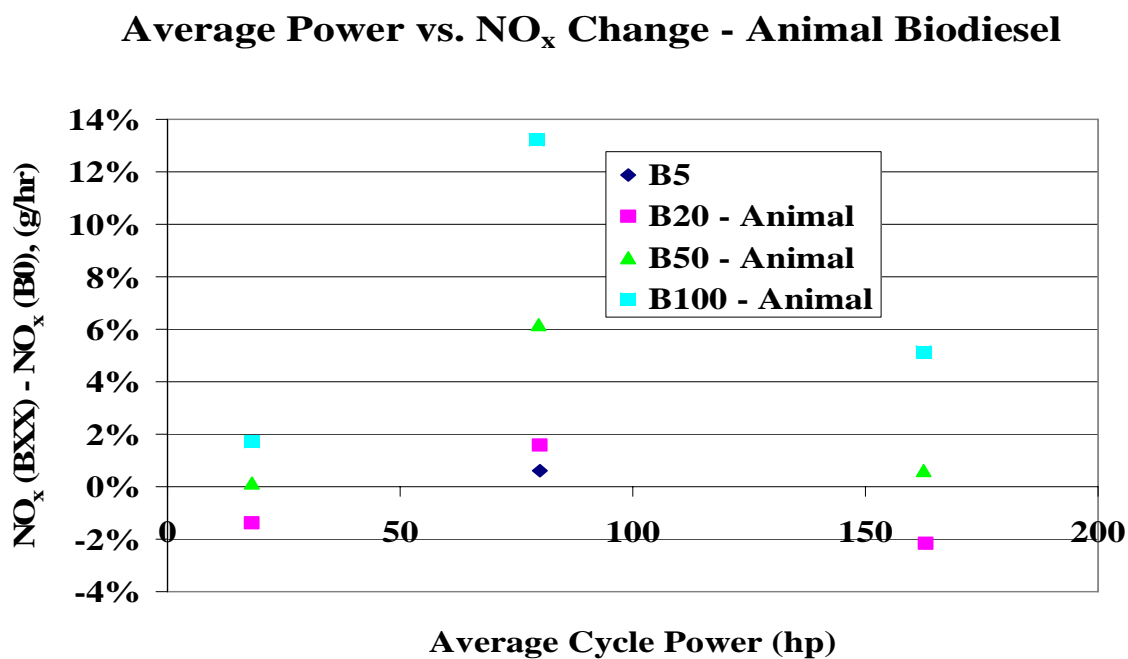
Fuels Use vs. NO$_x$ Emissions Change - Soy Biodiesel
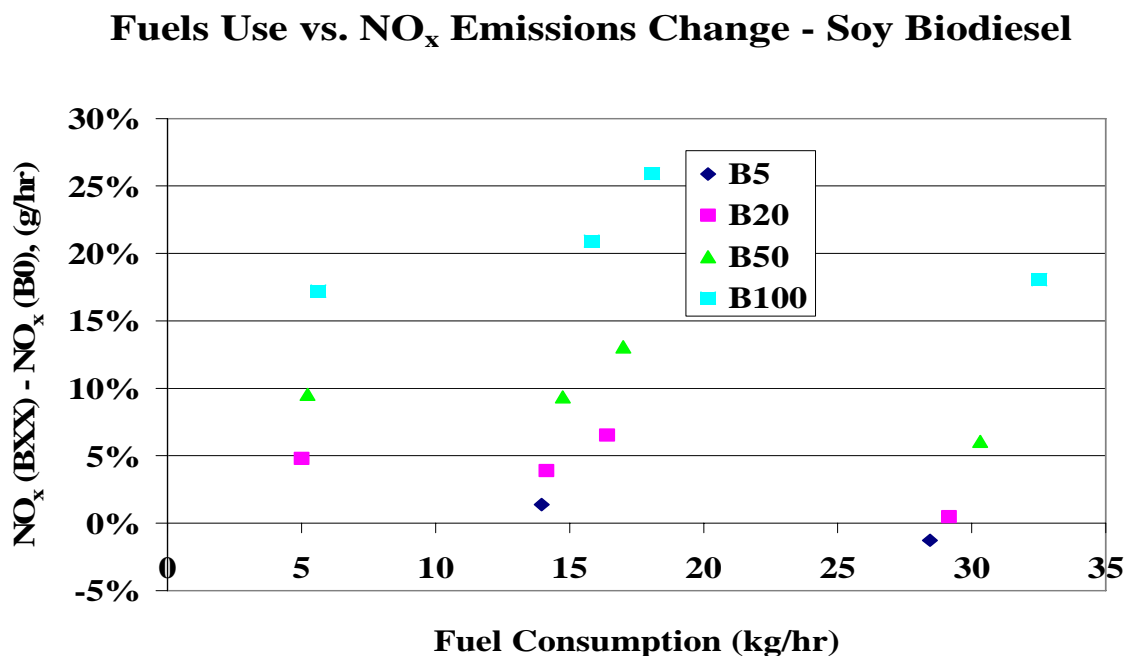
Figure 3-7. Fuel Consumption vs. NO$_x$ Emissions Change for Testing on Soy-Based Biodiesel Blends
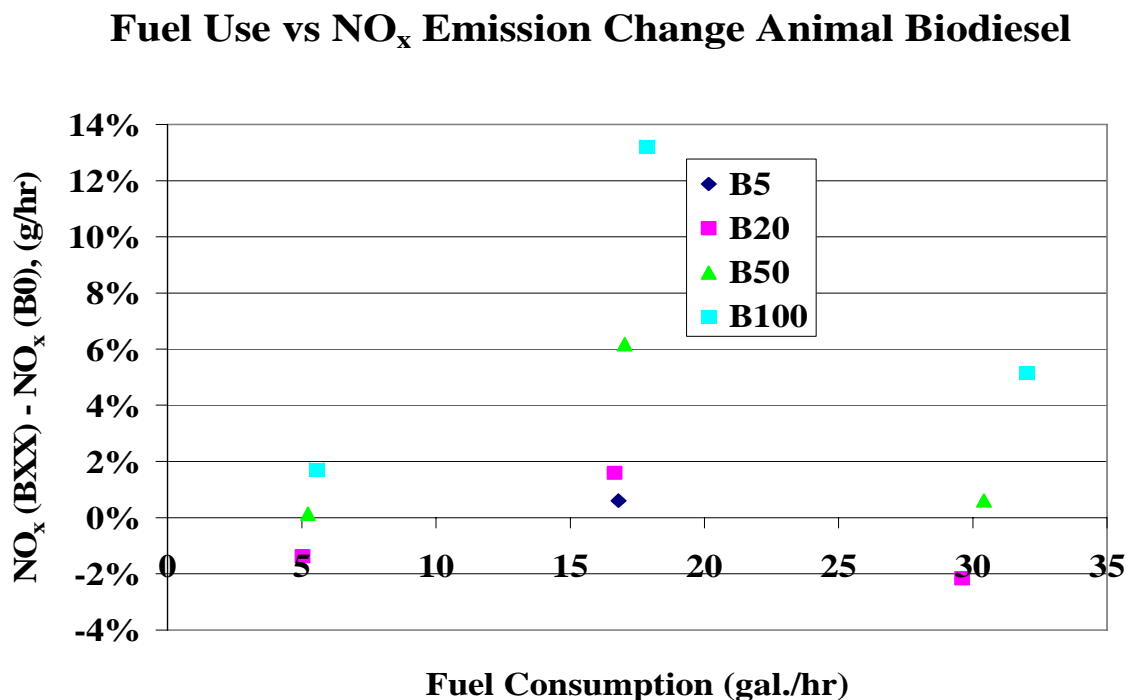
Fuel Use vs NO$_x$ Emission Change Animal Biodiesel

3.2 PM Emissions

The PM emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock are presented in Figure 3-9 and **Error! Reference source not found.**, respectively, on a g/bhp-hr basis. **Error! Reference source not found.** shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

PM Emissions - Soy Biodiesel

Figure 3-9. Average PM Emission Results for the Soy-Based Biodiesel Feedstock

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PM Emissions - Animal Biodiesel
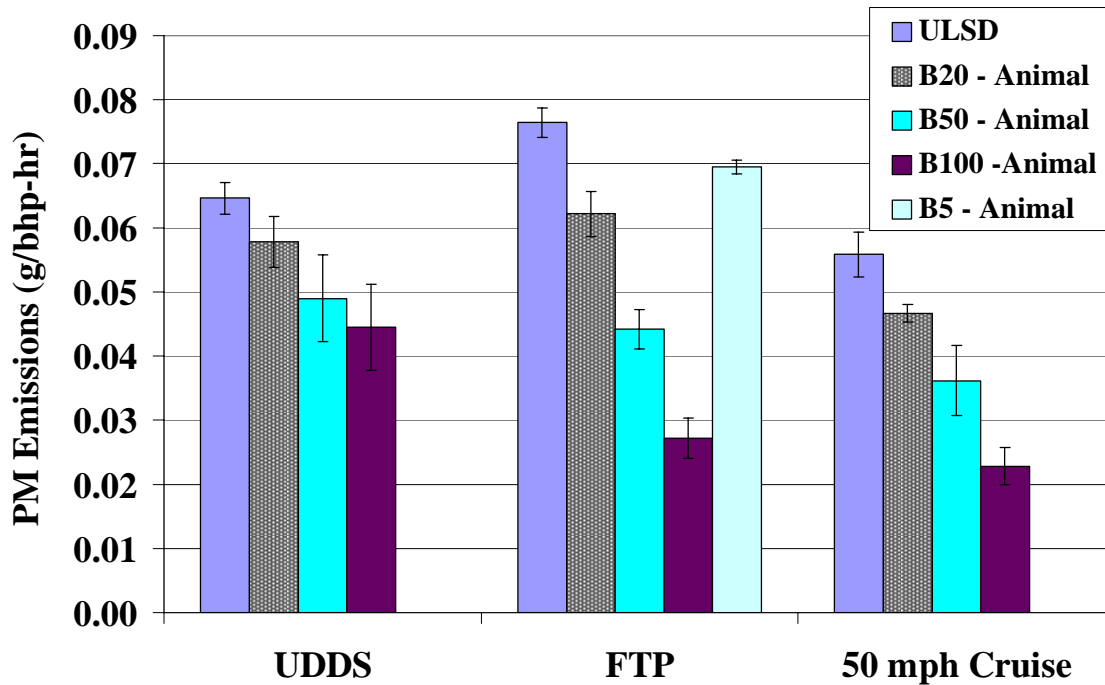
Figure 3-10. Average PM Emission Results for the Animal-Based Biodiesel Feedstock

PM emissions showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. This is consistent with a majority of the previous studies of emissions from biodiesel blends. For comparison, the EPA estimated reductions for the base case were 12% at a B20 level, 27% for a B50 level, and 47% at t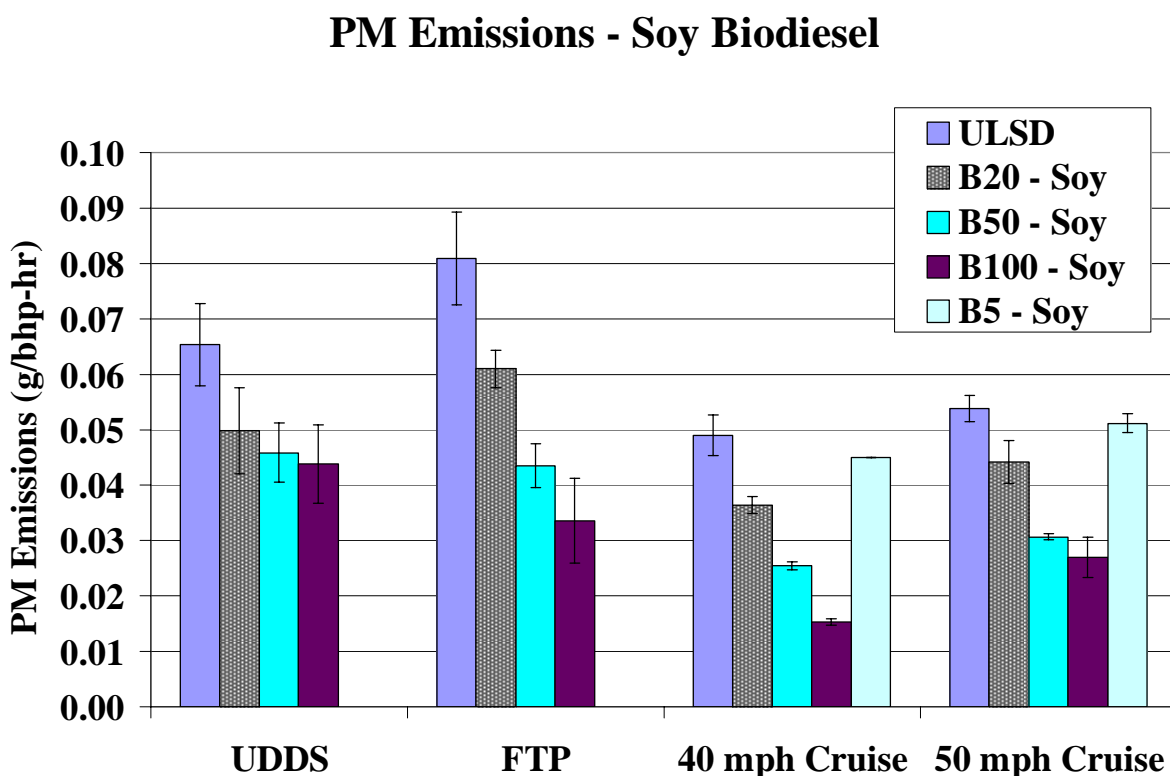he B100 level. EPA estimates for the PM reductions expected for a clean base fuel are smaller, with reductions of less than 10% for B20, ~20% for the B50 level, and ~35% for B100. The PM reductions for both the soy-based and animal-based biodiesel blends were generally larger than those found in the EPA study, and are closer to the estimates for an average base fuel than a clean base fuel. The smallest reductions were seen for the UDDS, or the lightest loaded cycle. The reductions for the FTP and the cruise cycles were comparable for both fuels. Although there were some differences in the percent reductions seen for the soy-based and animal-based biodiesel fuels, there were no consistent differences in the PM reductions for these two feedstocks over the range of blend levels and cycles tested here.

| | CARB vs. | Soy -based | | Animal - based | |
		% Difference	P-values	% Difference	P-values
UDDS	B20	-24%	0.002	-10%	0.009
	B50	-30%	0.000	-24%	0.001
	B100	-33%	0.000	-31%	0.000
FTP	B5	-6% (Mit)	0.000	-9%	0.000
	B10	-17% (Mit)	0.000		
	B20	-25%	0.000	-19%	0.000
	B50	-46%	0.000	-42%	0.000
	B100	-58%	0.000	-64%	0.000
40 mph Cruise	B5	-6%	0.101		
	B20	-26%	0.000		
	B50	-48%	0.000		
	B100	-69%	0.000		
50 mph Cruise	B5	-5%	0.036		
	B20	-18%	0.000	-16%	0.000
	B50	-43%	0.000	-35%	0.000
	B100	-50%	0.000	-59%	0.000

Table 3-2. PM Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle.

Similar to the NO_x emissions, PM emissions also showed a general trend of increasing emissions with increased average cycle power. This is shown in Figure 3-11 for the soy-based biodiesel and in Figure 3-12 for the animal-based biodiesel. This trend was not necessarily linear, however, as demonstrated by the differences in the emissions for the FTP and 40 mph cruise for the soy-based results. The differential between NO_x emissions for a biodiesel blend and the base fuel is shown as a function of power in Figure 3-13 for the soy-based biodiesel and in Figure 3-14 for the animal-based biodiesel, and as function of fuel consumption in Figure 3-15 for the soy-based biodiesel and in Figure 3-16 for the animal-based biodiesel. The data show a tendency for higher PM reductions for the FTP and 50 mph Cruise compared to the light-UDDS, but there is not a linear trend changes in emission reductions with either power or fuel use.

Average Cycle Power vs. PM - Soy Biodiesel
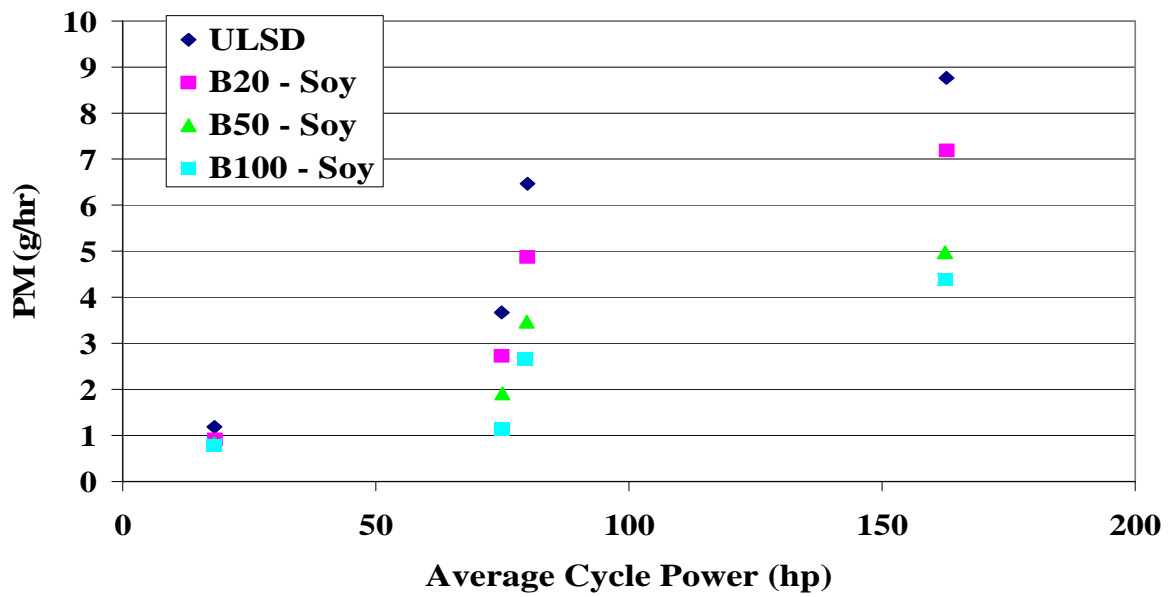
Figure 3-11. Average Cycle Power vs. PM Emissions for Testing on Soy-Based Biodiesel Blends

Average Cycle Power vs. PM - Animal Biodiesel
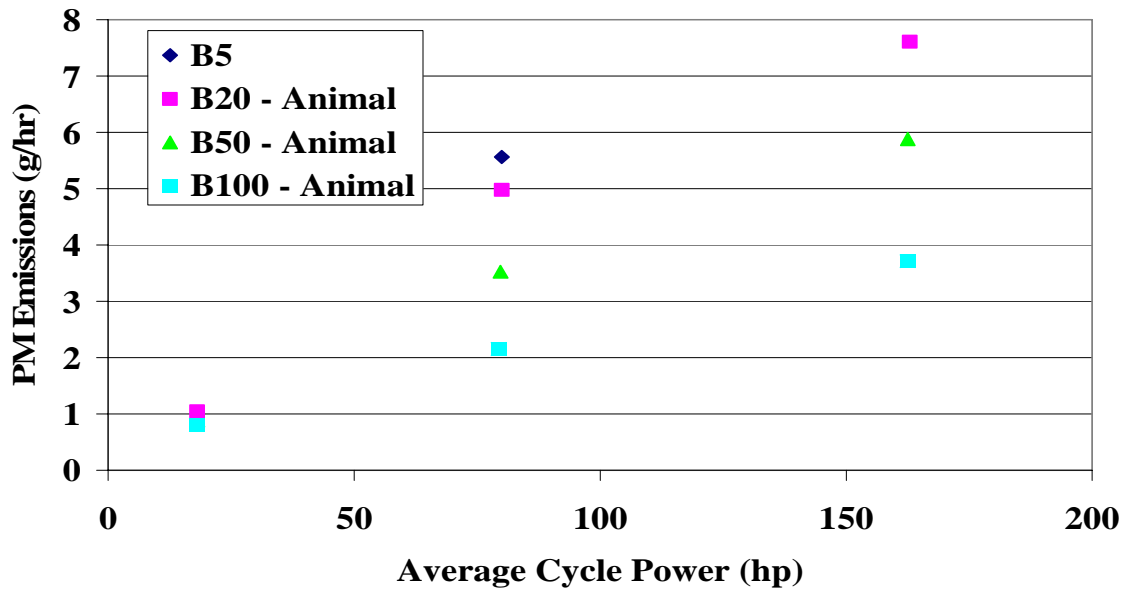
Figure 3-12. Average Cycle Power vs. PM Emissions for Testing on Animal-Based Biodiesel Blends

Average Power vs. PM Change - Soy Biodiesel
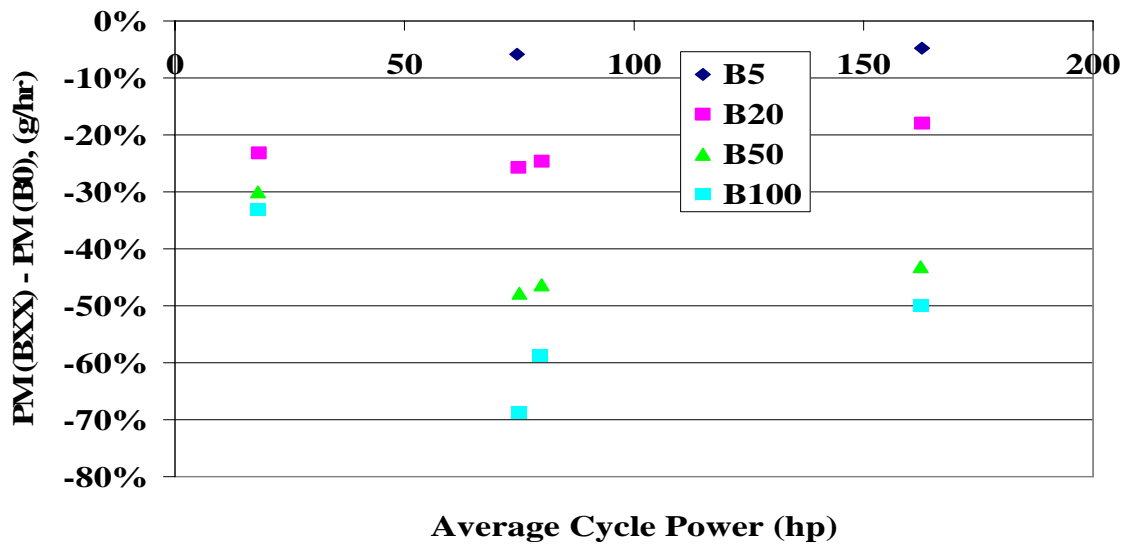
Figure 3-13. Average Cycle Power vs. PM Emissions Change for Testing on Soy-Based Biodiesel Blends

Average Power vs. PM Change - Animal Biodiesel
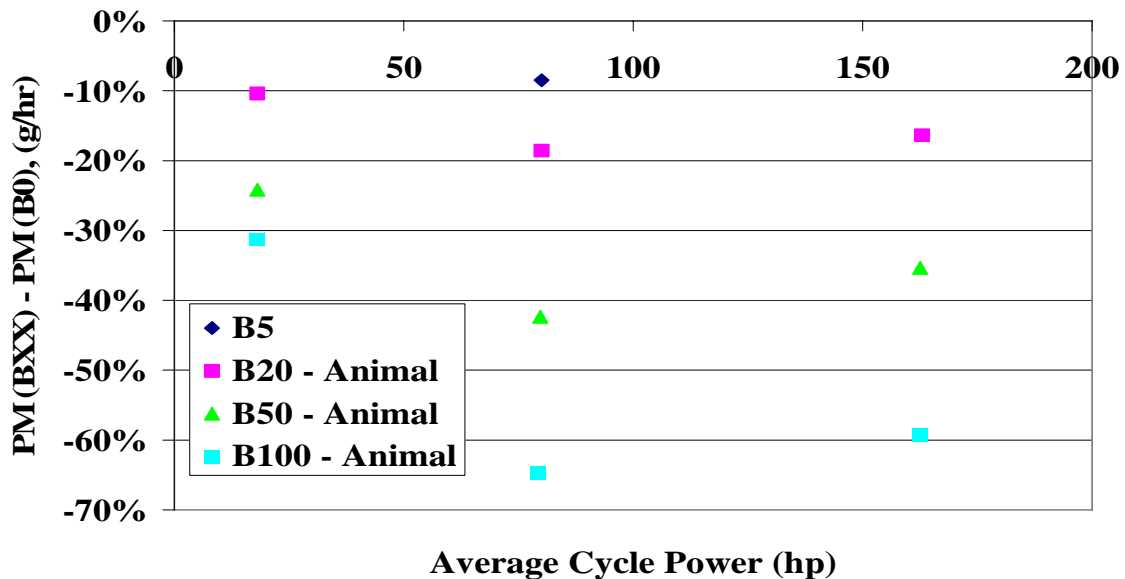
Figure 3-14. Average Cycle Power vs. PM Emissions Change for Testing on Animal-Based Biodiesel Blends

Fuels Use vs. PM Emissions Change - Soy Biodiesel
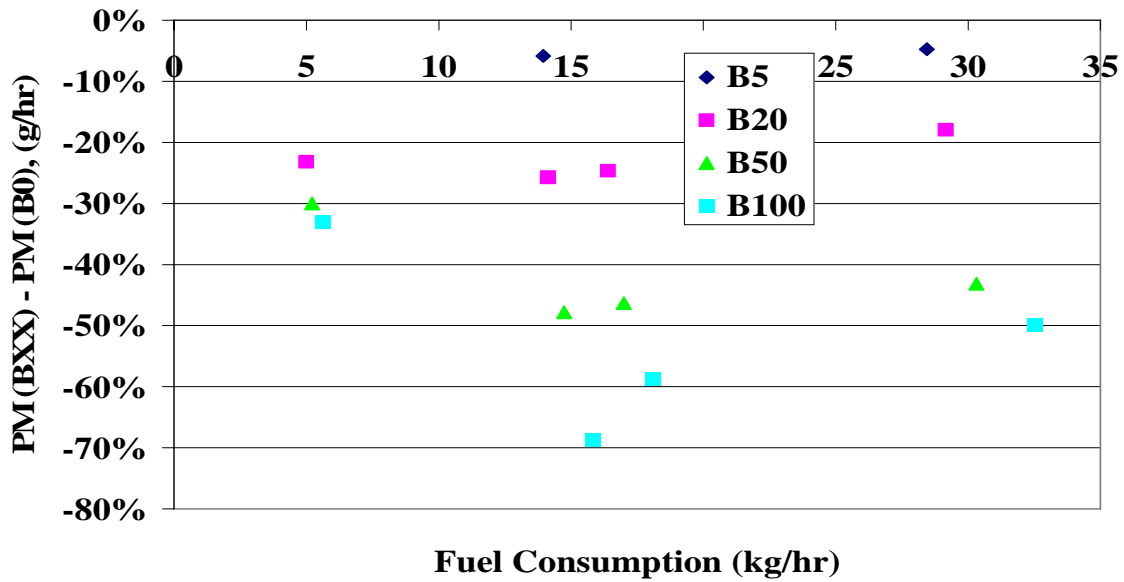
Figure 3-15. Fuel Consumption vs. PM Emissions Change for Testing on Soy-Based Biodiesel Blends

Fuel Use vs PM Emission Change Animal Biodiesel
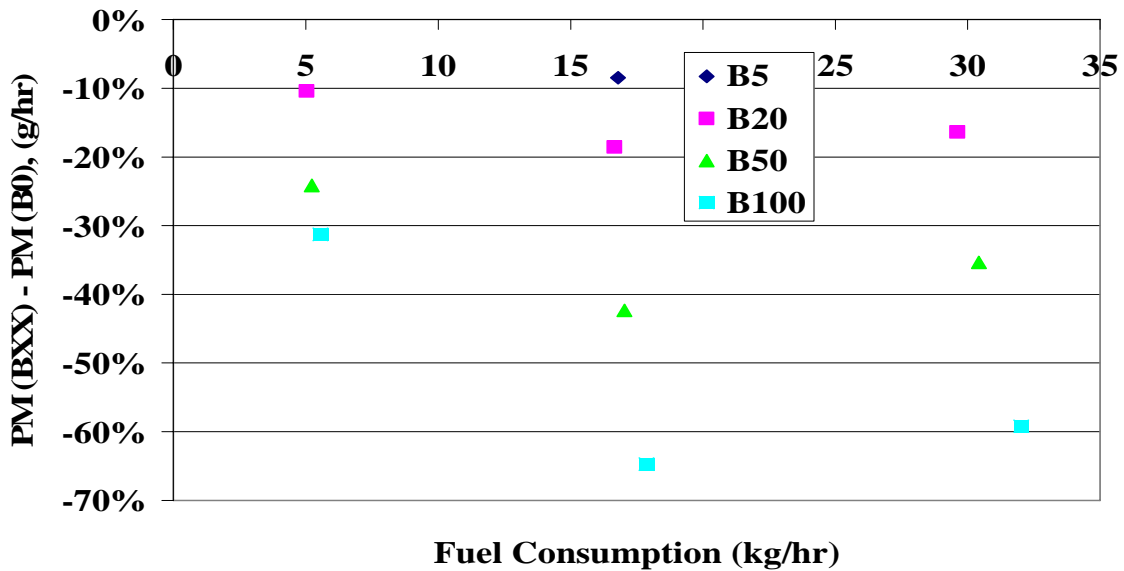
Figure 3-16. Fuel Consumption vs. PM Emissions Change for Testing on Animal-Based Biodiesel Blends

3.3 THC Emissions

The THC emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock are presented in Figure 3-17 and **Error! Reference source not found.**, respectively, on a g/bhp-hr basis. **Error! Reference source not found.** shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

THC Emissions - Soy Biodiesel
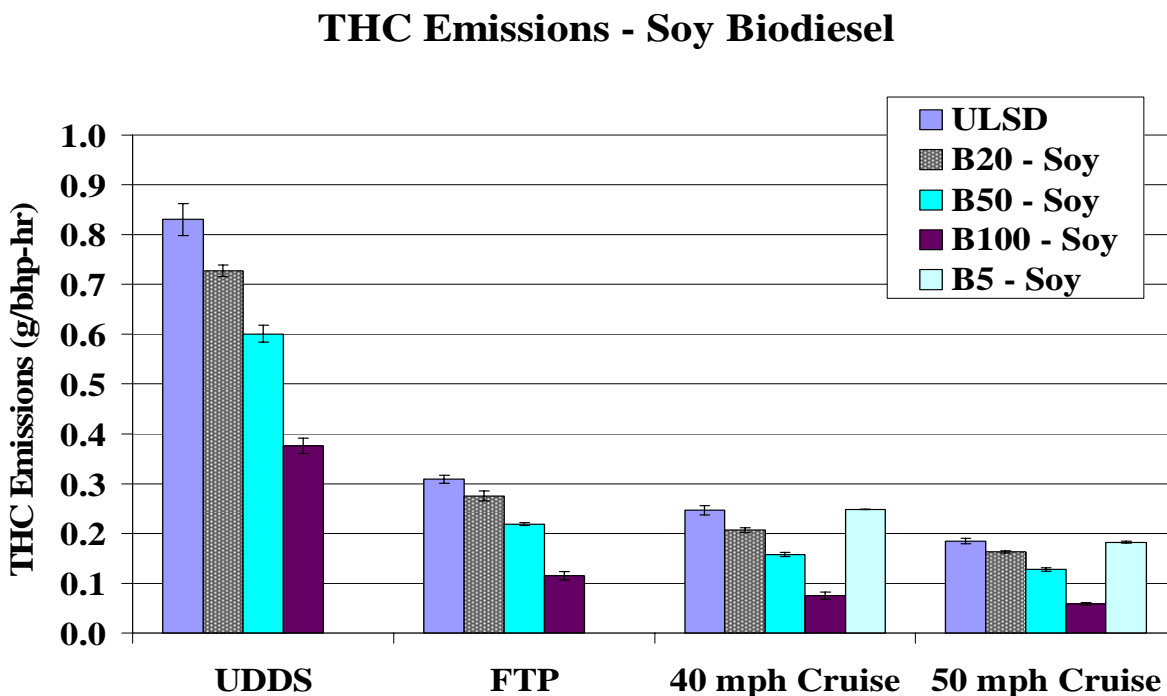
Figure 3-17. Average THC Emission Results for the Soy-Based Biodiesel Feedstock

THC Emissions - Animal Biodiesel
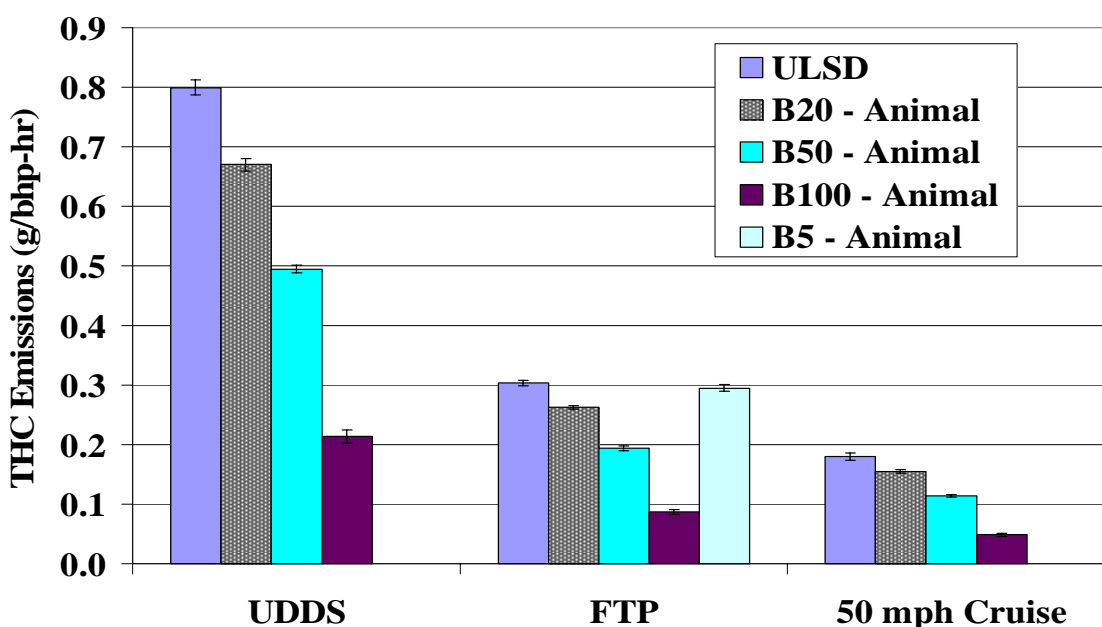
Figure 3-18. Average THC Emission Results for the Animal-Based Biodiesel Feedstock

THC emissions showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. This is again consistent with a majority of the previous studies of emissions from biodiesel blends. For comparison, the EPA base case estimated reductions were 20% at a B20 level, ~43% for a B50 level, and ~67% at the B100 level. EPA estimates for the THC reductions expected for a clean base fuel are smaller, with reductions of ~13% for B20, ~30% for the B50 level, and ~51% for B100. Overall, the THC reductions seen in this study are consistent with and similar to those found by EPA. The THC reductions for both the soy-based and animal-based biodiesel blends for B100 were closer to those found in the EPA study for the B100 level for the base case diesel fuel. The reductions for the B20 blend tended to be closer to those found for the clean diesel, while the reductions for the B50 blends were in between those estimated by EPA for the clean and average base fuels. For the soy-based biodiesel, the reductions are slightly less for the lower load UDDS, but for the animal-based biodiesel the THC reductions for all the test cycles were similar.

| | CARB vs. | Soy-based | | Animal-based | |
		% Difference	P-values	% Difference	P-values
UDDS	B20	-12%	0.000	-16%	0.000
	B50	-28%	0.000	-38%	0.000
	B100	-55%	0.000	-73%	0.000
FTP	B5	-1% (Mit)	0.136	-3%	0.011
	B10	-6% (Mit)	0.000		
	B20	-11%	0.000	-13%	0.000
	B50	-29%	0.000	-36%	0.000
	B100	-63%	0.000	-71%	0.000
40 mph Cruise	B5	-1%	0.573		
	B20	-16%	0.000		
	B50	-36%	0.000		
	B100	-70%	0.000		
50 mph Cruise	B5	-2%	0.222		
	B20	-12%	0.000	-14%	0.000
	B50	-31%	0.000	-37%	0.000
	B100	-68%	0.000	-73%	0.000

Table 3-3. THC Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle.

The THC emissions show a slight trend of increasing emissions with increased average cycle power, although this trend is not as strong as for NO_x or PM. This is shown in Figure 3-19 for the soy-based biodiesel and in Figure 3-20 for the animal-based biodiesel. The differential between THC emissions for a biodiesel blend and the base fuel is shown as a function of power in Figure 3-21 for the soy-based biodiesel and in Figure 3-22 for the animal-based biodiesel, and as function of fuel consumption in Figure 3-23 for the soy-based biodiesel and in Figure 3-24 for the animal-based biodiesel. The data generally show that there is not a strong trend in the THC differential for biodiesel as a function of either power or fuel consumption.

Average Cycle Power vs. THC - Soy Biodiesel
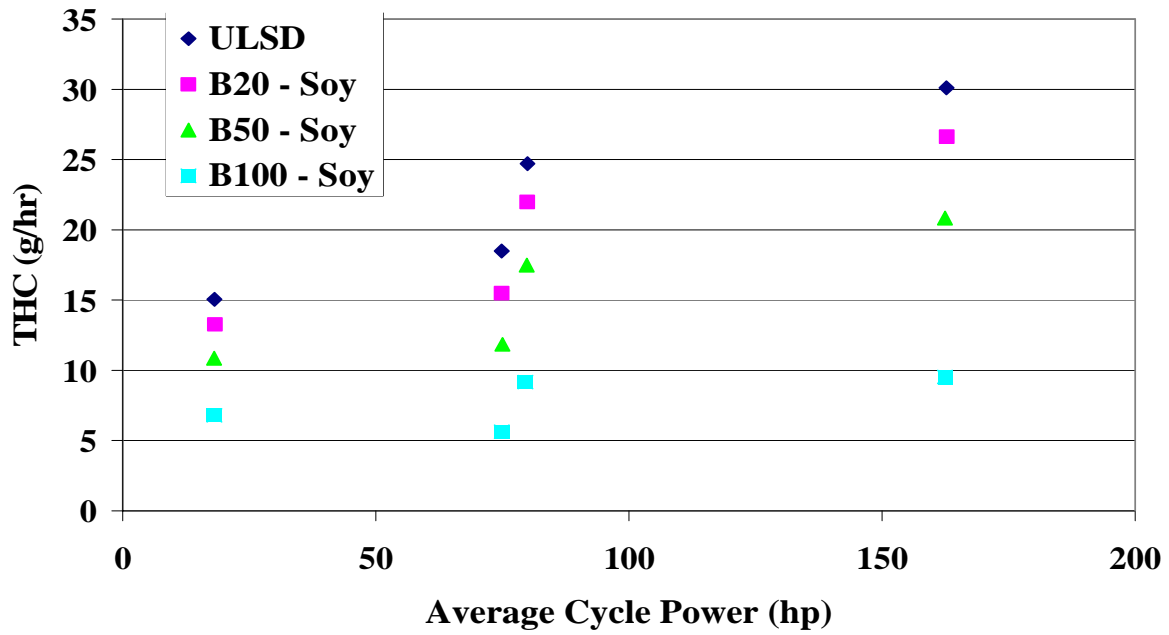
Figure 3-19. Average Cycle Power vs. THC Emissions for Testing on Soy-Based Biodiesel Blends

Average Cycle Power vs. THC - Animal Biodiesel
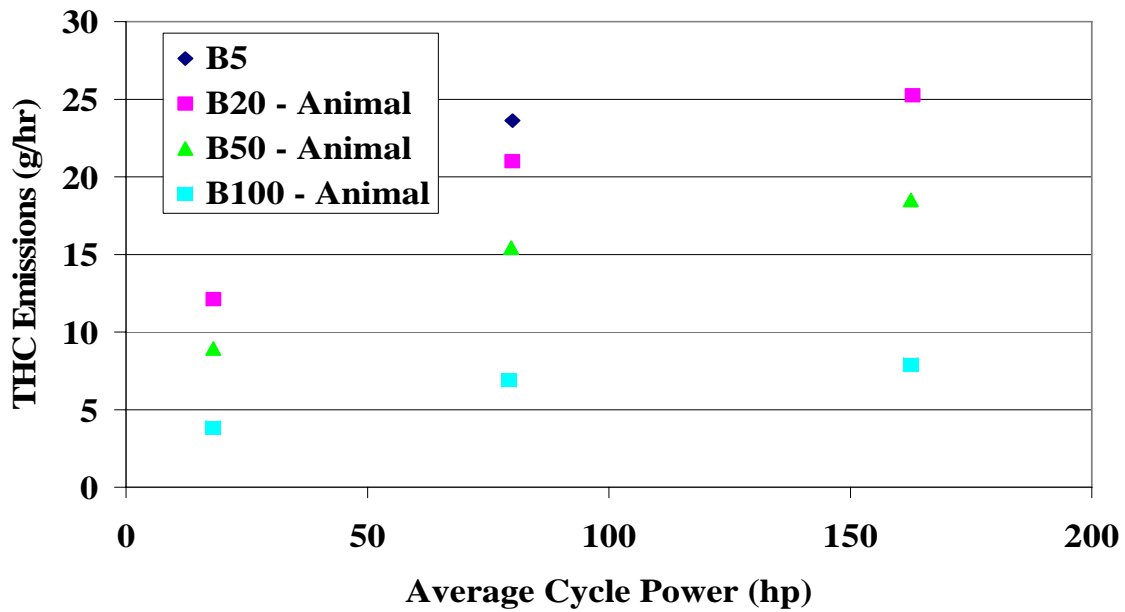
Figure 3-20. Average Cycle Power vs. THC Emissions for Testing on Animal-Based Biodiesel Blends

Average Power vs. THC Change - Soy Biodiesel
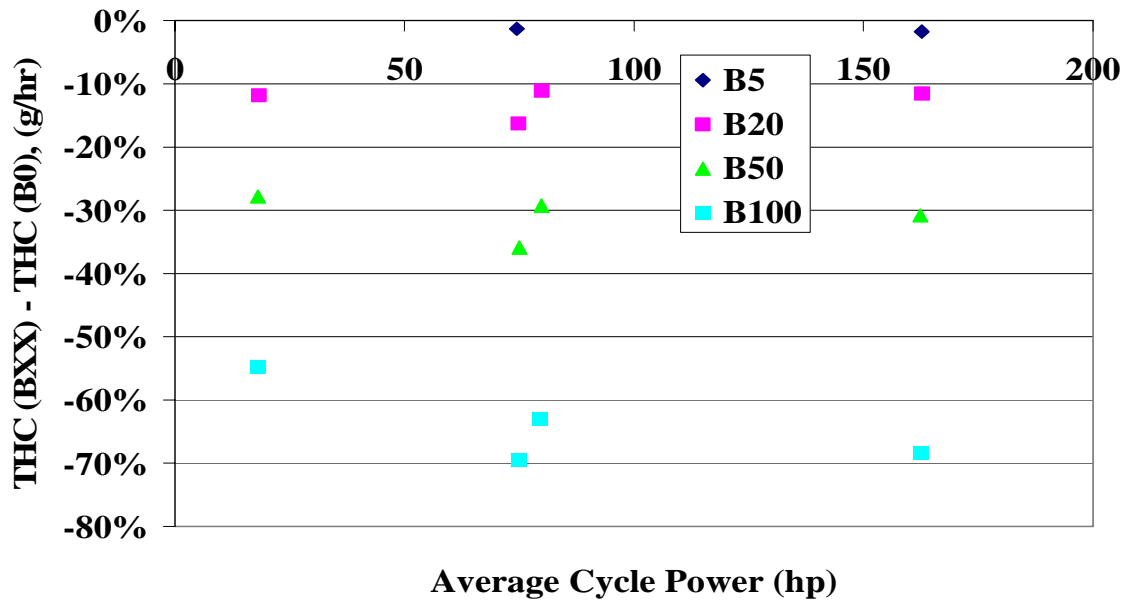
Figure 3-21. Average Cycle Power vs. THC Emissions Change for Testing on Soy-Based Biodiesel Blends

Average Power vs. THC Change - Animal Biodiesel
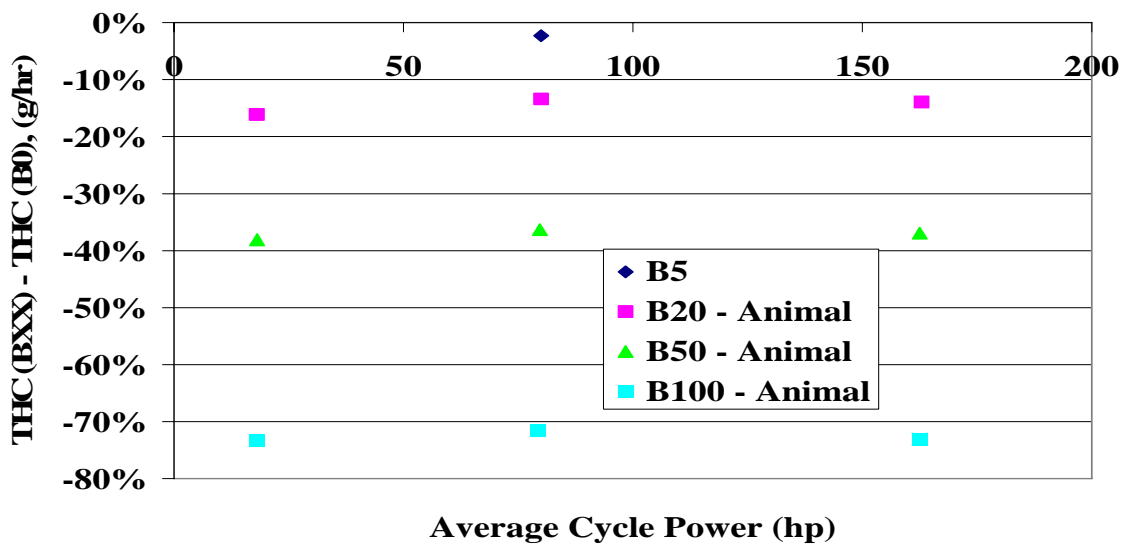
Figure 3-22. Average Cycle Power vs. THC Emissions Change for Testing on Animal-Based Biodiesel Blends

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Fuels Use vs. THC Change - Soy Biodiesel
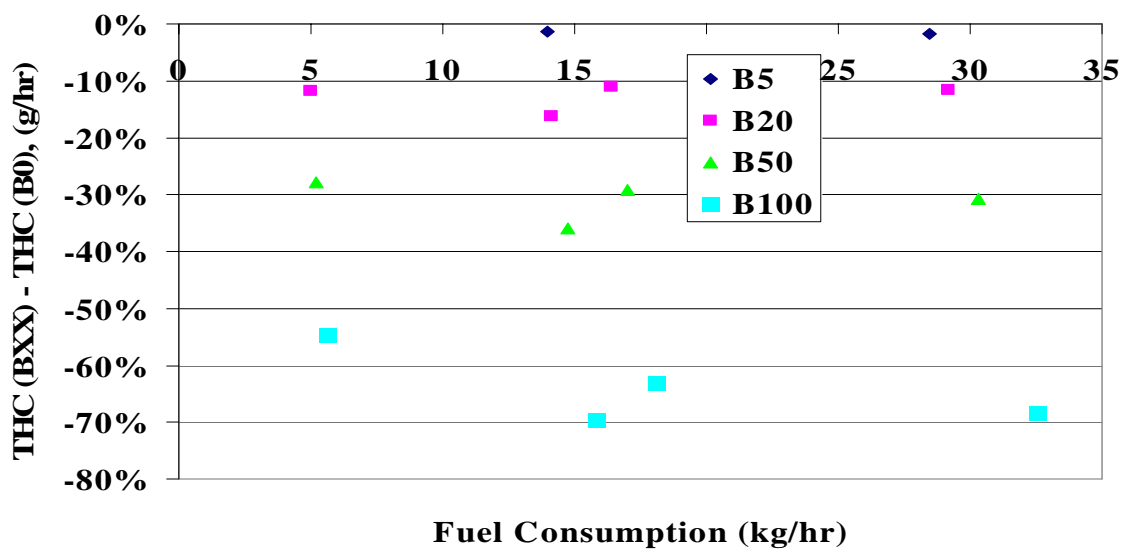
Figure 3-23. Fuel Consumption vs. THC Emissions Change for Testing on Soy-Based Biodiesel Blends

Fuel Use vs THC Change - Animal Biodiesel
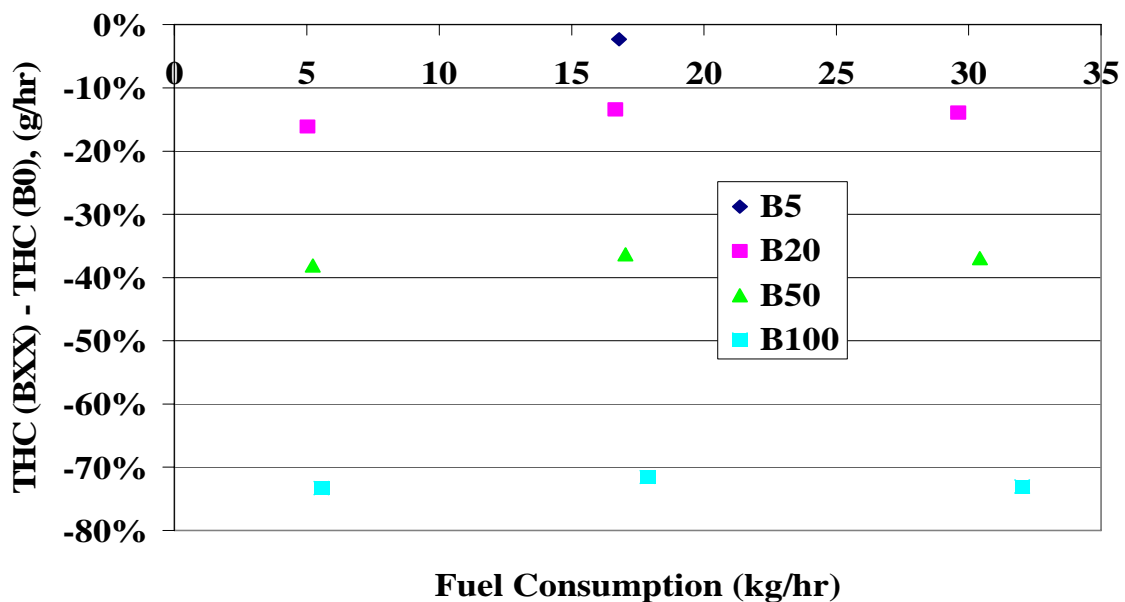
Figure 3-24. Fuel Consumption vs. THC Emissions Change for Testing on Animal-Based Biodiesel Blends

3.4 CO Emissions

The CO emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock are presented in Figure 3-25 and **Error! Reference source not found.**, respectively, on a g/bhp-hr basis. **Error! Reference source not found.** shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

CO Emissions - Soy Biodiesel
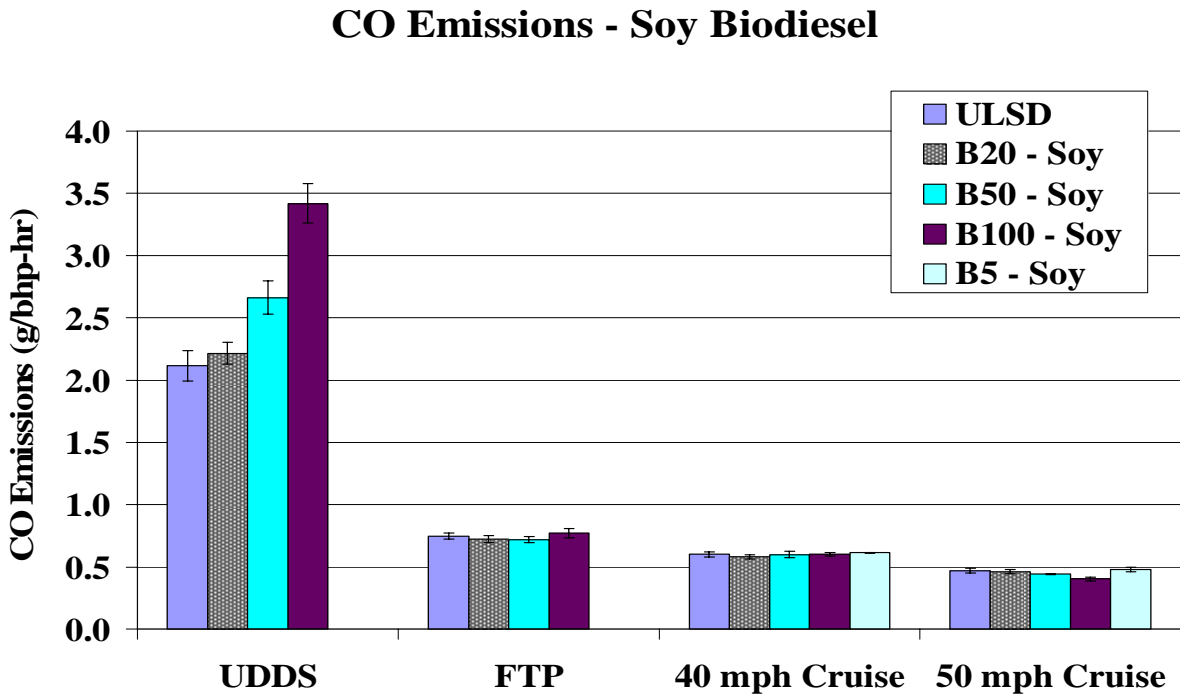
Figure 3-25. Average CO Emission Results for the Soy-Based Biodiesel Feedstock

CO Emissions - Animal Biodiesel
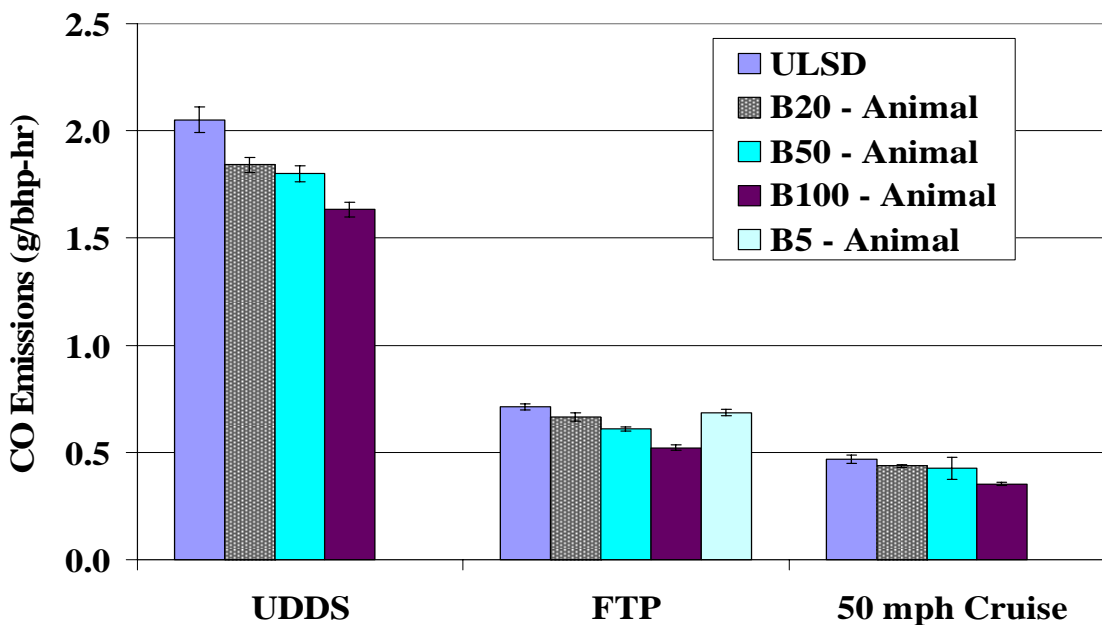
Figure 3-26. Average CO Emission Results for the Animal-Based Biodiesel Feedstock

For the animal-based CO emissions, consistent and statistically significant reductions were found for the biodiesel blends, consistent with previous studies. For comparison, the EPA base case estimated reductions were ~12% at a B20 level, ~28% for a B50 level, and ~48% at the B100 level. EPA estimates for the CO reductions expected for a clean base fuel are smaller, with reductions of less than 10% for B20, ~20% for the B50 level, and ~37% for B100. The CO reductions seen for the animal-based biodiesel are comparable to the EPA estimates for the B20 blend, but are lower than the EPA estimates for the B50 and B100 blends.

The CO trends for the soy-based biodiesel were less consistent. The CO emissions for the soy-based biodiesel did show consistent reductions with increasing biodiesel blend levels for the highest load, 50 mph cruise cycle. It should be noted that the percentage differences for the both the soy-based and animal-based biodiesel were also impacted by the engine operation differences seen for the 50 mph cruise, as discussed in Section 2.7 and Appendix E. For the FTP and Cruise-1 cycles, the biodiesel blends did not show any strong trends relative to the CARB ULSD and a number of differences were not statistically significant. Interestingly, the CO emissions for the lowest load UDDS cycle showed higher emissions for the Soy biodiesel blends, with the largest increases seen for the highest blend level. The increases for the UDDS cycle were all statistically significant. Additional testing would likely be needed to better understand the nature of these results, which are opposite the trends seen in most previous studies.

	CARB vs.	Soy -based		Animal - based	
		% Difference	P-values	% Difference	P-values
UDDS	B20	5%	0.115	-10%	0.000
	B50	26%	0.000	-12%	0.000
	B100	62%	0.000	-20%	0.000
FTP	B5	-1% (Mit)	0.405	-4%	0.008
	B10	-2% (Mit)	0.151		
	B20	-3%	0.078	-7%	0.000
	B50	-4%	0.038	-14%	0.000
	B100	3%	0.163	-27%	0.000
40 mph Cruise	B5	2%	0.427		
	B20	-3%	0.160		
	B50	0%	0.986		
	B100	0%	0.868		
50 mph Cruise	B5	1%	0.649		
	B20	-2%	0.330	-7%	0.003
	B50	-6%	0.002	-9%	0.066
	B100	-14%	0.000	-25%	0.000

Table 3-4. CO Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle.

CO emissions show a trend of increasing emissions with increased average cycle power for the animal-based biodiesel for all blends and for the soy-based biodiesel for the ULSD and the B20 blends. This is shown in Figure 3-27 for the soy-based biodiesel and in Figure 3-28 for the animal-based biodiesel. For the B50 and B100 blends for the soy-based biodiesel, the data did not show an increase with increasing power. This can be attributed in part to the increase in CO emissions for these blends on the UDDS cycle. The differential between CO emissions for a biodiesel blend and the base fuel is shown as a function of power in Figure 3-29 for the soy-based biodiesel and in Figure 3-30 for the animal-based biodiesel, and as function of fuel consumption in Figure 3-31 for the soy-based biodiesel and in Figure 3-32 for the animal-based biodiesel. For the soy-based biodiesel, the CO differentials show a reverse trend, with the highest increases seen at the lowest power/fuel use level on the UDDS. The CO differentials for the animal-based biodiesel did not show any strong trends as a function of average cycle power or fuel consumption. In fact, the highest differentials for the animal-based biodiesel were for the FTP certification test that had the middle power rating.

Average Cycle Power vs. CO - Soy Biodiesel
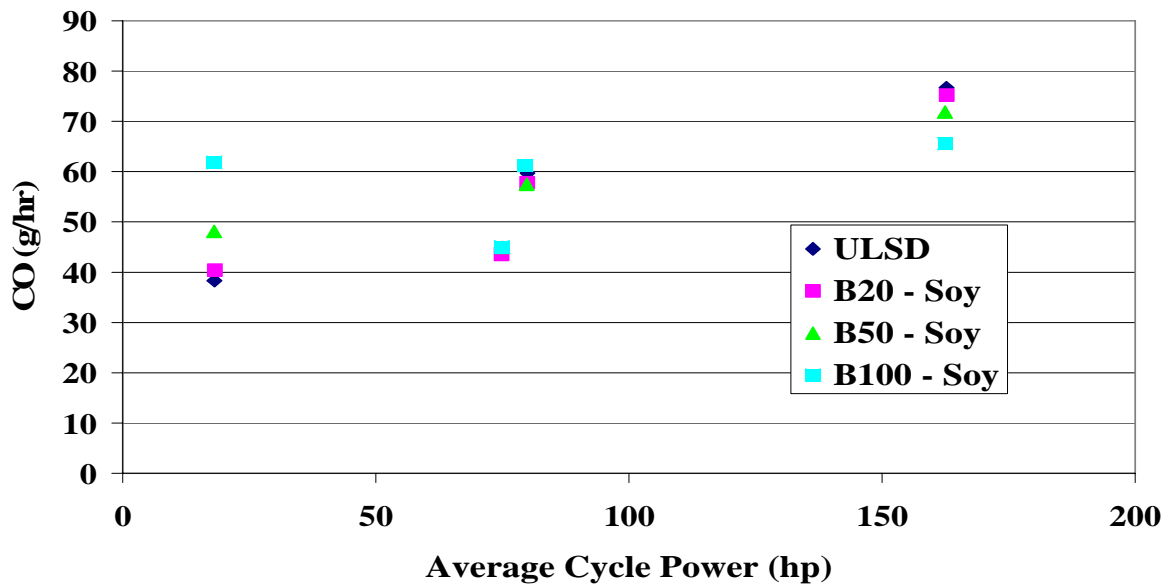
Figure 3-27. Average Cycle Power vs. CO Emissions for Testing on Soy-Based Biodiesel Blends

Average Cycle Power vs. CO - Animal Biodiesel
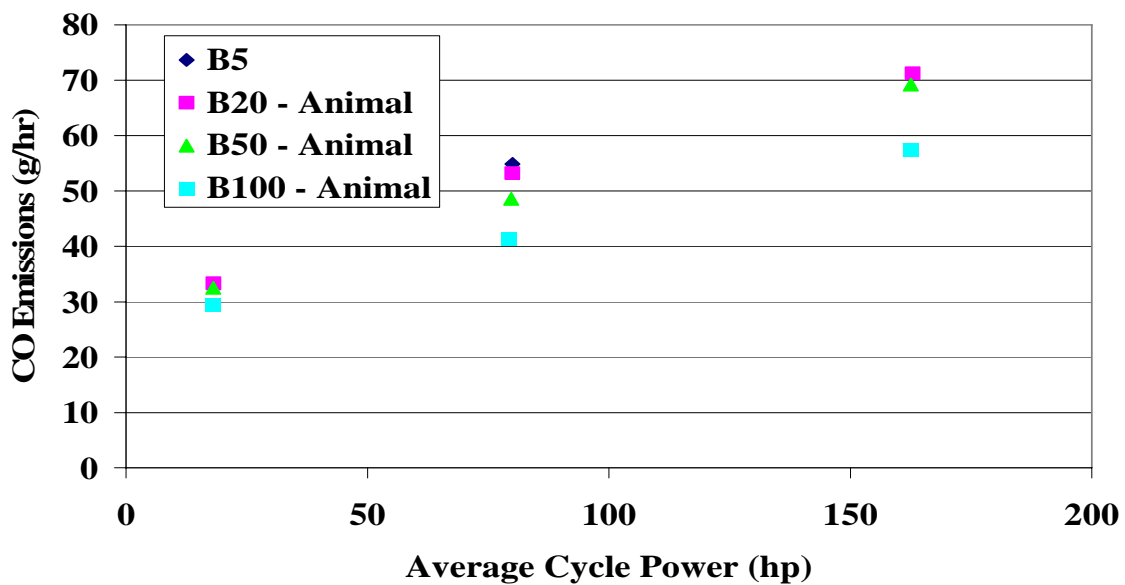
Figure 3-28. Average Cycle Power vs. CO Emissions for Testing on Animal-Based Biodiesel Blends

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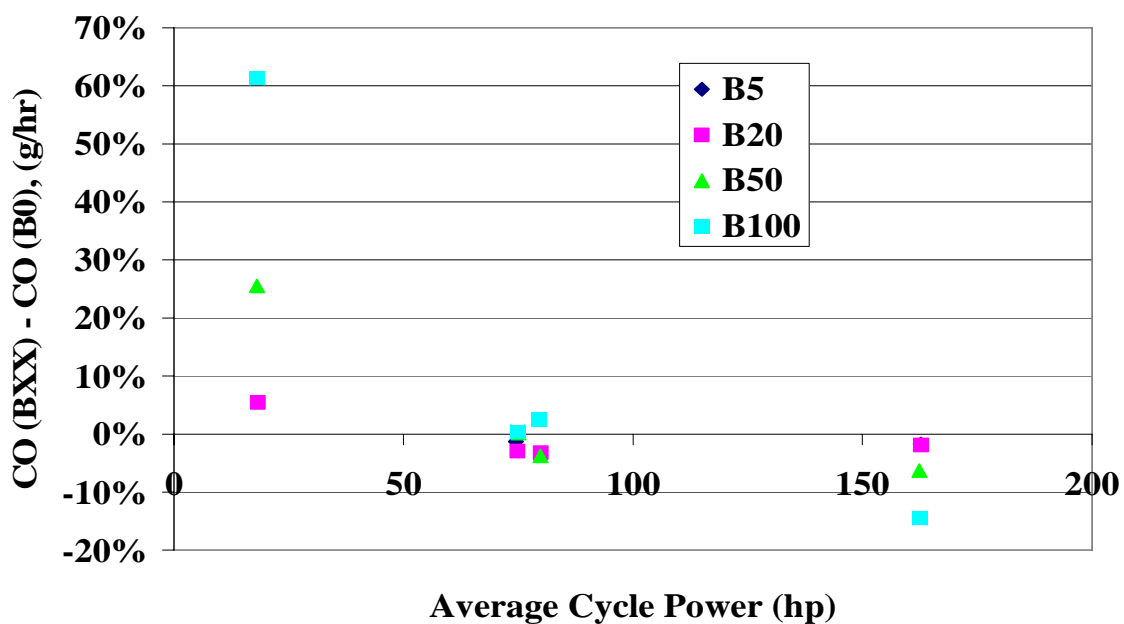
Figure 3-29. Average Cycle Power vs. CO Emissions Change for Testing on Soy-Based Biodiesel Blends

Figure 3-30. Average Cycle Power vs. CO Emissions Change for Testing on Animal-Based Biodiesel Blends

Fuels Use vs. CO Change - Soy Biodiesel
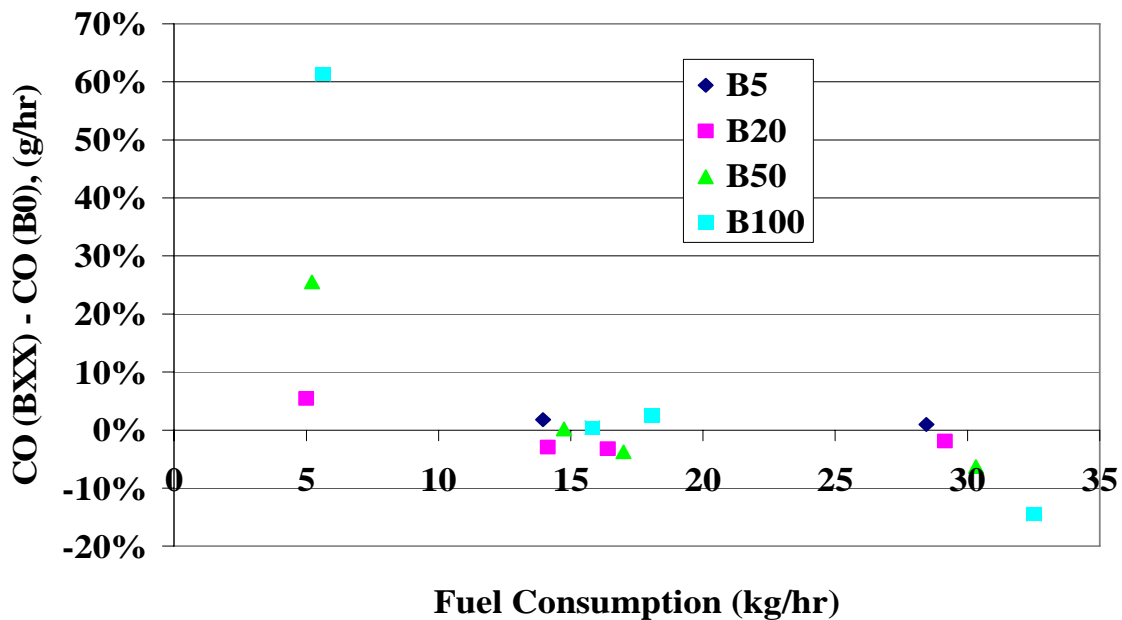
Figure 3-31. Fuel Consumption vs. CO Emissions Change for Testing on Soy-Based Biodiesel Blends

Fuel Use vs CO Change - Animal Biodiesel
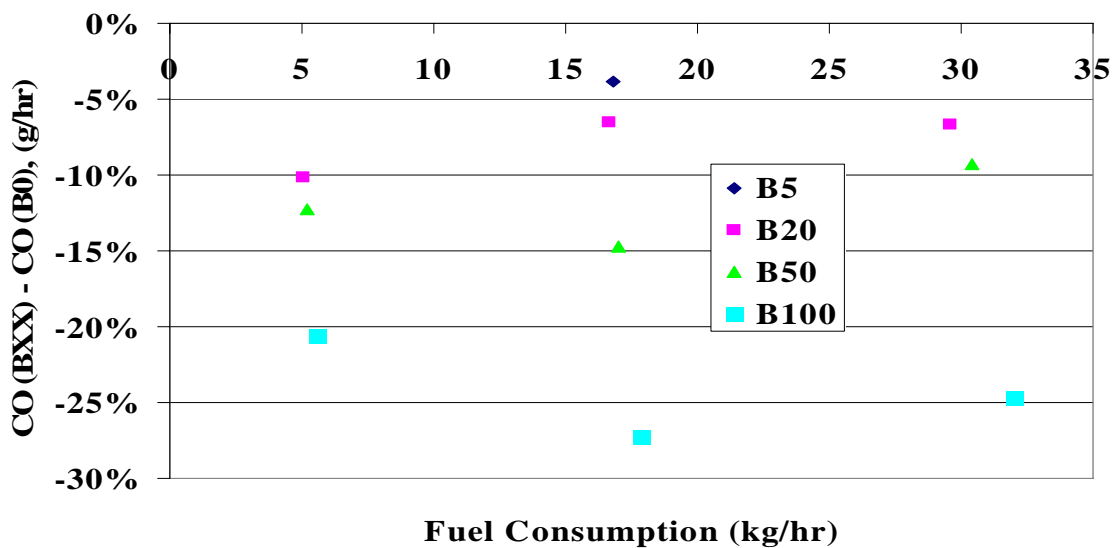
Figure 3-32. Fuel Consumption vs. CO Emissions Change for Testing on Animal-Based Biodiesel Blends

3.5 CO_2 Emissions

The CO_2 emission results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock are presented in Figure 3-33 and **Error! Reference source not found.**, respectively, on a g/bhp-hr basis. Table 3-5 shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

CO_2 Emissions - Soy Biodiesel
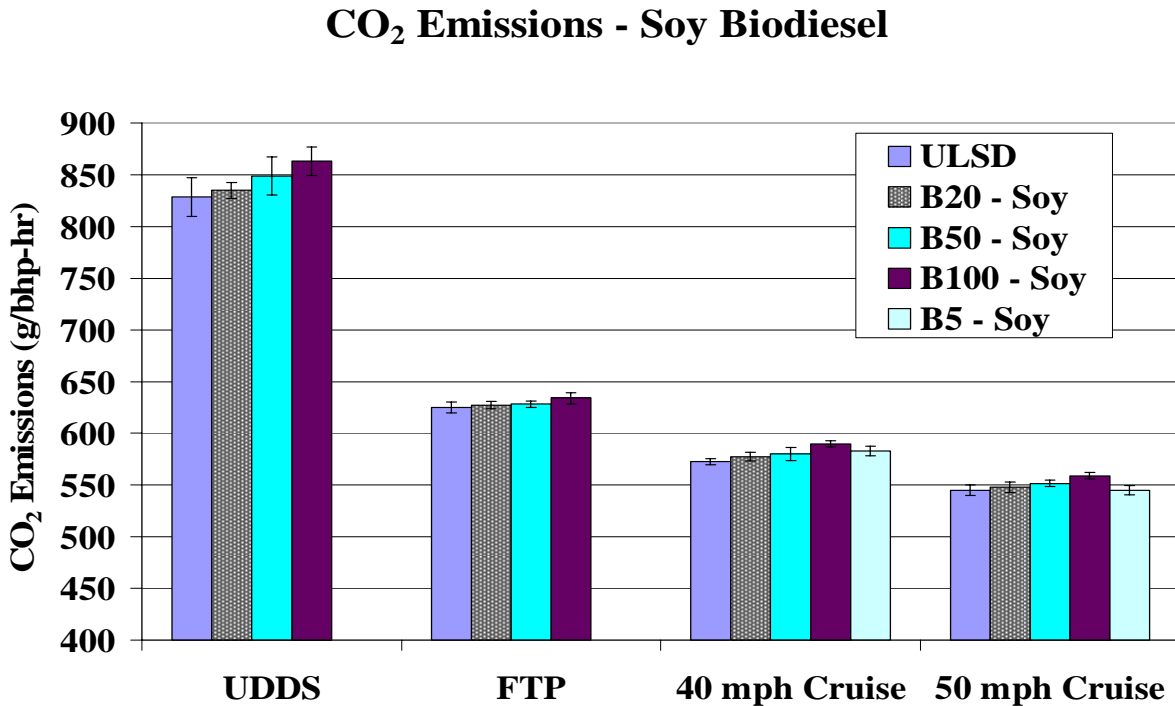
Figure 3-33. Average CO_2 Emission Results for the Soy-Based Biodiesel Feedstock

CO$_2$ Emissions - Animal Biodiesel
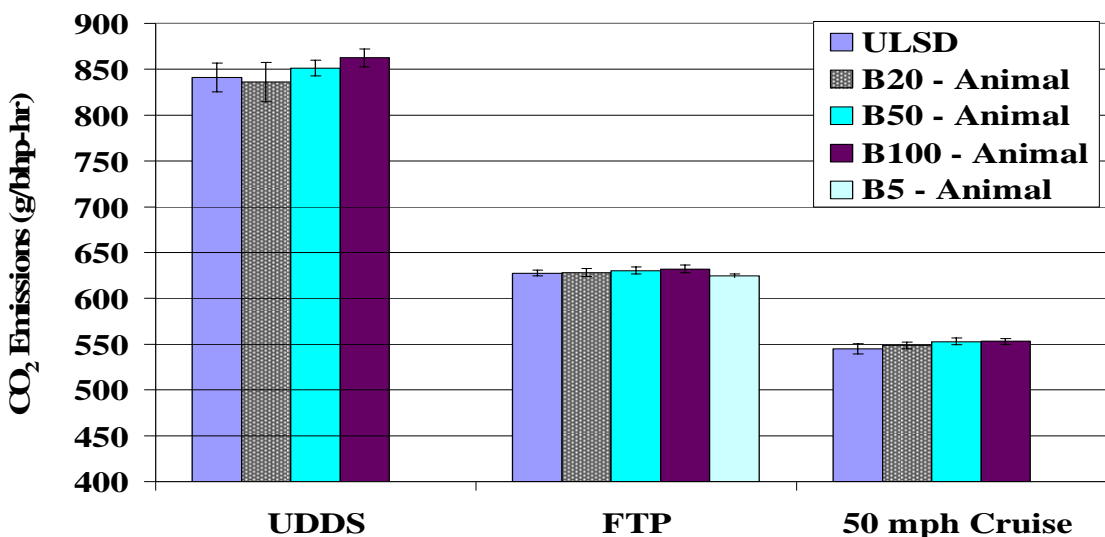
Figure 3-34. Average CO$_2$ Emission Results for the Animal-Based Biodiesel Feedstock

The test results overall showed a slight increase in CO$_2$ emissions for the higher biodiesel blends. This increase ranged from about 1-4% with the increases being statistically significant for the B100 fuels for all of the tests, and for the B50 fuel for the cruise cycles and some other cycles.

	CARB vs.	Soy -based		Animal - based	
		% Difference	P-values	% Difference	P-values
UDDS	B20	0.8%	0.448	-0.6%	0.640
	B50	2.5%	0.055	1.2%	0.201
	B100	4.2%	0.003	2.5%	0.016
FTP	B5	0.1% (Mit)	0.816	-0.3%	0.191
	B10	-0.1% (Mit)	0.569		
	B20	0.4%	0.309	0.1%	0.733
	B50	0.5%	0.159	0.4%	0.117
	B100	1.5%	0.007	0.7%	0.018
40 mph Cruise	B5	1.7%	0.085		
	B20	0.8%	0.056		
	B50	1.3%	0.053		
	B100	3.0%	0.000		
50 mph Cruise	B5	0.0%	0.959		
	B20	0.6%	0.227	0.7%	0.170
	B50	1.2%	0.008	1.5%	0.014
	B100	2.6%	0.000	1.6%	0.008

Table 3-5. CO$_2$ Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle.

3.6 Brake Specific Fuel Consumption

The brake specific fuel consumption results for the testing with the soy-based biodiesel feedstock and the animal-based biodiesel feedstock are presented in Figure 3-35 and **Error! Reference source not found.**, respectively, on a gallons per brake horsepower hour (gal./bhp-hr) basis. **Error! Reference source not found.** shows the percentage differences for the different biodiesel feedstocks and blend levels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.
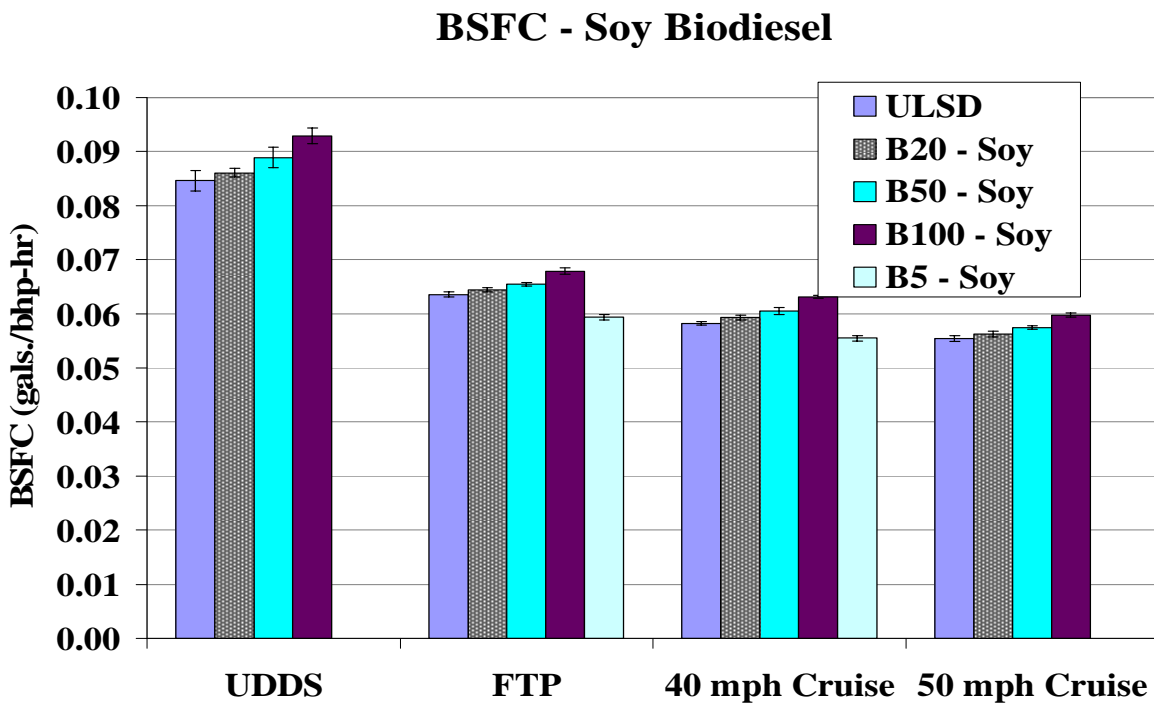
Figure 3-35. Average Brake Specific Fuel Consumption Results for the Soy-Based Biodiesel Feedstock

BSFC - Animal Biodiesel
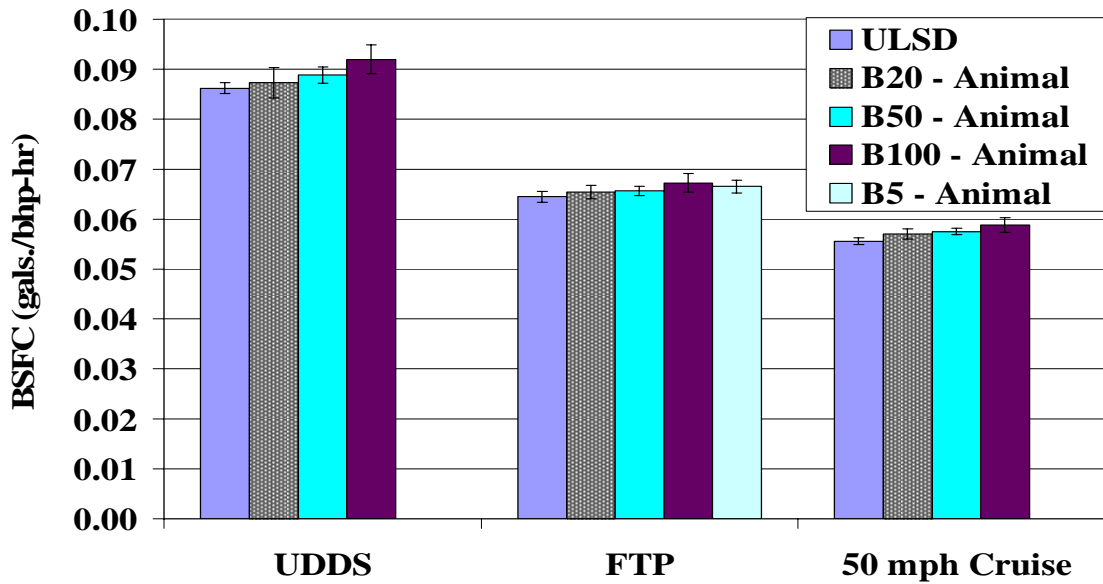
Figure 3-36. Average Brake Specific Fuel Consumption Results for the Animal-Based Biodiesel Feedstock

The biodiesel blends showed an increase in fuel consumption with increasing levels of biodiesel. This is consistent with expectations based on the lower energy density of the biodiesel. The fuel consumption differences were generally greater for the soy-based biodiesel in comparison with the animal-based biodiesel. The changes in fuel consumption for the soy-based biodiesel blends range from 1.4 to 1.8% for the B20 to 6.8 to 9.8% for the B100. The changes in fuel consumption for the animal-based biodiesel blends range from no statistical difference to 2.6% for the B20 to 4.4 to 6.7% for the B100.

| | CARB vs. | Soy -based | | Animal - based | |
		% Difference	P-values	% Difference	P-values
UDDS	B20	1.8%	0.093	1.2%	0.404
	B50	5.1%	0.001	3.1%	0.005
	B100	9.8%	0.000	6.7%	0.000
FTP	B5	2.2% (Mit)	0.095	2.9%	0.031
	B10	-2.4% (Mit)	0.018		
	B20	1.4%	0.001	1.4%	0.145
	B50	3.1%	0.000	1.8%	0.038
	B100	6.8%	0.000	4.4%	0.001
40 mph Cruise	B5	1.9%	0.065		
	B20	1.8%	0.001		
	B50	3.8%	0.000		
	B100	8.4%	0.000		
50 mph Cruise	B5	0.3%	0.690		
	B20	1.6%	0.002	2.6%	0.010
	B50	3.8%	0.000	3.5%	0.000
	B100	8.0%	0.000	5.9%	0.000

Table 3-6. Brake Specific Fuel Consumption Percentage Differences Between the Biodiesel Blends and the CARB ULSD base fuel for each Cycle.

4.0 Renewable Diesel and GTL Results

4.1 NO$_x$ Emissions

Renewable and GTL diesel fuels are considered to be one potential strategy for meeting the low carbon fuel standard requirements as well as mitigating any NO$_x$ increases seen with increasing levels of biodiesel. NO$_x$ emissions for the different blends and different test cycles for the renewable diesel fuel and the GTL diesel fuel are shown in Figure 4-1 and Figure 4-2, respectively, on a g/bhp-hr basis. For the GTL diesel, only FTP testing was done, since this fuel was tested primarily for inclusion in the NO$_x$ mitigation testing discussed below and, as such, it was not characterized over the full range of cycles used to characterize the other fuels. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination. The error bars represent one standard deviation on the average value.

NO$_x$ Emissions - Renewable Blends
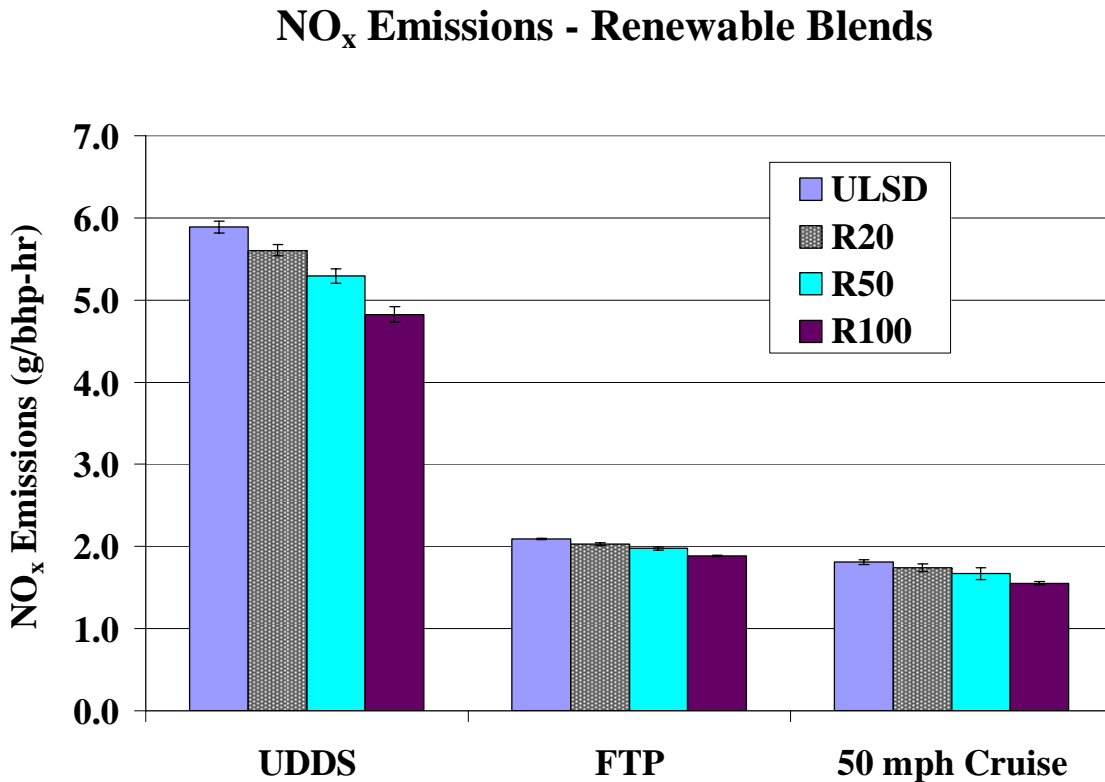
Figure 4-1. Average NO$_x$ Emission Results for the Renewable Blends

NO$_x$ Emissions - GTL Blends
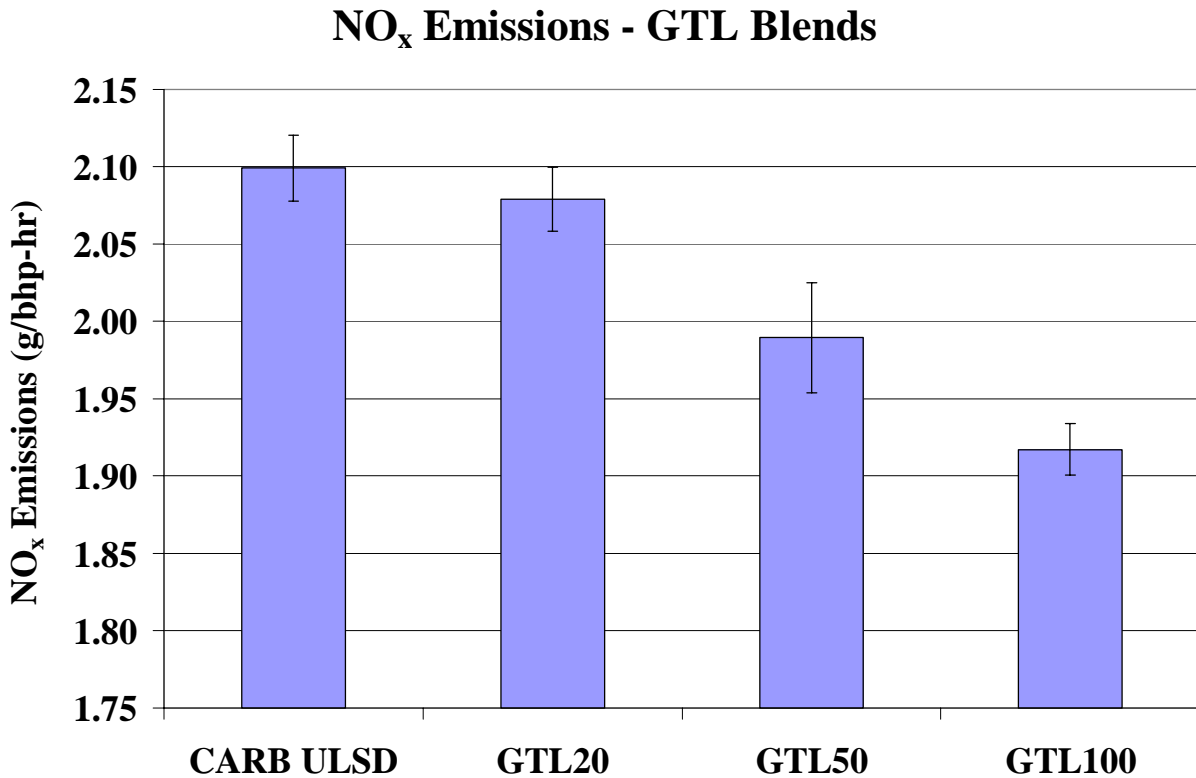
Figure 4-2. Average NO$_x$ Emission Results for the GTL Blends

NO$_x$ emissions showed a trend of decreasing emissions with increasing levels of the renewable and GTL diesel fuels. Table 4-1 shows the percentage differences for the different renewable blends for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

	CARB vs.	Renewable % Difference	P-values	GTL % Difference	P-values
UDDS	20% blend	-4.9%	0.000		
	50% blend	-10.2%	0.000		
	100% blend	-18.1%	0.000		
FTP	20% blend	-2.9%	0.000	-0.9%	0.053
	50% blend	-5.4%	0.000	-5.2%	0.000
	100% blend	-9.9%	0.000	-8.7%	0.000
50 mph Cruise	20% blend	-3.8%	0.007		
	50% blend	-7.8%	0.000		
	100% blend	-14.2%	0.000		

Table 4-1. NO$_x$ Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

For the renewable and GTL diesel fuels, the results show a steady decrease in NO_x emissions with increasingly higher levels of renewable diesel fuel. Over the FTP cycle, the NO_x reductions for the renewable and GTL diesel were comparable for each of the blend levels. Larger emissions reductions were found over the UDDS and Cruise cycles, where only the renewable diesel fuel was tested. It should be noted that the magnitude of the impact of NO_x reductions over the 50 mph cruise cycle was somewhat impacted by the differing engine operation conditions discussed in Section 2.7.

The reductions in NO_x for the renewable diesel fuel are comparable to those found in previous studies of heavy-duty engines (Rothe et al. 2005; Kleinschek 2005; Aatola et al. 2008) and busses (Kuronen et al. 2007; Erikkila and Nylund) on a 100% renewable blend. The reduction of 5.4% for the R50 blend on the FTP is similar to the 5% reduction seen by Rothe et al. (2005) for a 50% blend on a heavy-duty engine. The NO_x reductions for the renewable diesel are also consistent with model predictions based on the EPA's Unified Model (Hodge, 2009). In previous studies, statistically significant NO_x reductions for the renewable diesel were not found for all testing configurations, however, including some lower blend levels (Aatola et al. 2008; Erkkila and Nylund) and for light-duty vehicles (Rantanen et al. 2005).

In comparison with the biodiesel feedstocks, the levels of reduction are less than the corresponding increases in NO_x seen for the soy-base biodiesel, but are more comparable to the increases seen for the animal-based biodiesel blends. With respect to NO_x mitigation, this suggests that the renewable and GTL diesel fuel levels will need to be slightly greater than the corresponding biodiesel level in order to mitigate the associated NO_x increase, as discussed in further detail below. This is especially true for the soy-based biodiesel blends.

The renewable diesel fuel was characterized over the different cycles with different power levels, while the GTL fuel was not. NO_x emissions are plotted against cycle average power for the renewable blends in Figure 4-3. These data show that NO_x emissions increase with average cycle power, as with the results in section 3.1. The NO_x differential between the CARB ULSD and the different blends was not a function of either average cycle power or fuel consumption, as shown in Figure 4-4 and in Figure 4-5, respectively. These Figures show that the lowest reductions in NO_x with the renewable fuel blend were found for the FTP certification cycle, which was in the middle of the power range examined.

Average Cycle Power vs. NO$_x$ - Renewable Blends

Figure 4-3. Average Cycle Power vs. NO$_x$ Emissions for Testing on the Renewable Blends

Average Power vs. NO$_x$ Change - Renewable Blends

Figure 4-4. Average Cycle Power vs. NO$_x$ Emissions Change for Testing on the Renewable Blends

Fuel Use vs. NO$_x$ Change - Renewable Blends

Figure 4-5. Fuel Consumption vs. NO$_x$ Emissions Change for Testing on the Renewable Blends

4.2 PM Emissions

The PM emission results for the testing with the renewable and GTL diesel are presented in Figure 4-6 and **Error! Reference source not found.**, respectively, on a g/bhp-hr basis. **Error! Reference source not found.** shows the percentage differences for the renewable and GTL diesel for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

PM Emissions - Renewable Blends

Figure 4-6. Average PM Emission Results for the Renewable Blends

PM Emissions - GTL Blends

Figure 4-7. Average PM Emission Results for the GTL Blends

PM emissions showed consistent and significant reductions for the renewable and GTL blends, with the magnitude of the reductions increasing with blend level. The reductions for the renewable diesel were statistically significant for the higher blends and ranged from 12-15% for the R50 and from 24-34% for the R100. A statistically significant 4% reduction was also found for the R20 over the FTP. The GTL fuel showed a statistically significant reduction over the FTP, with reductions ranging from 8% for the 20% blend to 29% for the 100% blend. Similar reductions are found for the UDDS, FTP, and Cruise cycles for the renewable diesel indicating that cycle load does not have a significant impact on the PM reductions. The PM reductions for the renewable diesel are consistent with model predictions based on the EPA's Unified Model (Hodge, 2009).

	CARB vs.	Renewable % Difference	Renewable P-values	GTL % Difference	GTL P-values
UDDS	20% blend	-5%	0.401		
	50% blend	-12%	0.044		
	100% blend	-28%	0.000		
FTP	20% blend	-4%	0.023	-8%	0.000
	50% blend	-15%	0.000	-12%	0.000
	100% blend	-34%	0.000	-29%	0.000
50 mph Cruise	20% blend	-3%	0.220		
	50% blend	-14%	0.000		
	100% blend	-24%	0.000		

Table 4-2. PM Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

PM emissions showed a trend of increasing emissions as a function of average cycle power for the various renewable blends, as presented in Figure 4-8. The PM differential between the CARB ULSD and the different blends was not a function of either average cycle power or fuel consumption, as shown in Figure 4-9 and in Figure 4-10, respectively. These Figures show that the largest reductions in PM with the renewable fuel blends were found for the FTP certification cycle, which was in the middle of the power range examined. Note that the PM reductions were largest for the FTP while the corresponding NO_x reductions were the smallest for the FTP consistent with a classical tradeoff between NO_x and PM emissions.

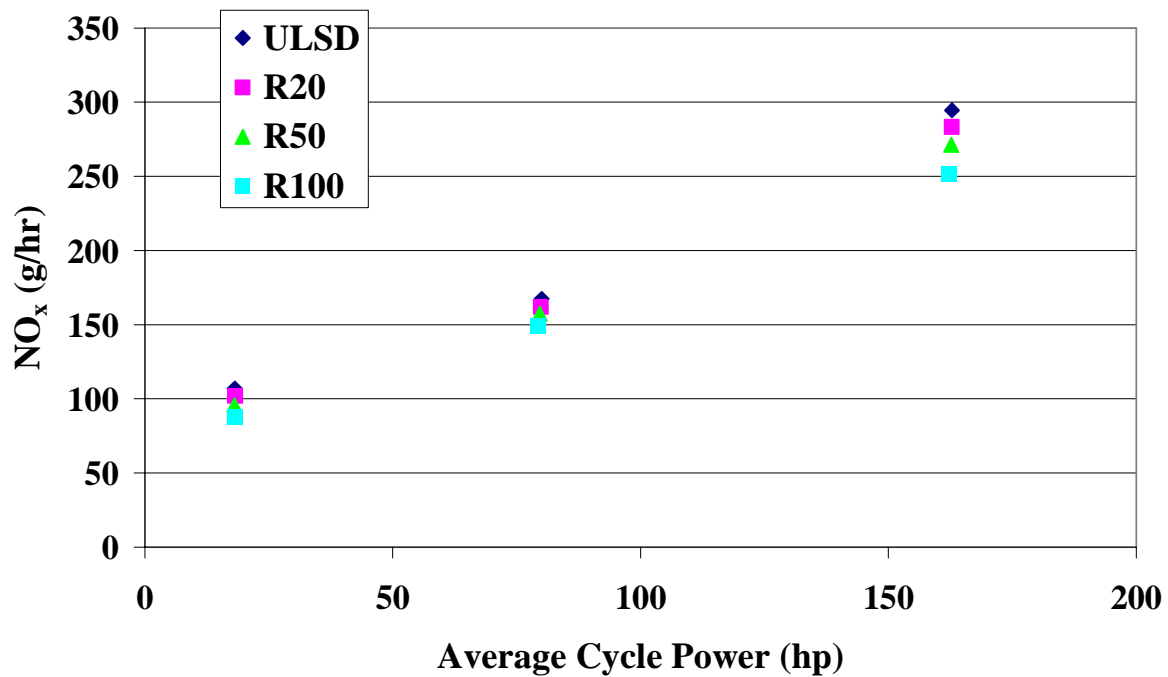# Average Cycle Power vs. PM - Renewable Blends

Figure 4-8. Average Cycle Power vs. PM Emissions for Testing on the Renewable Blends

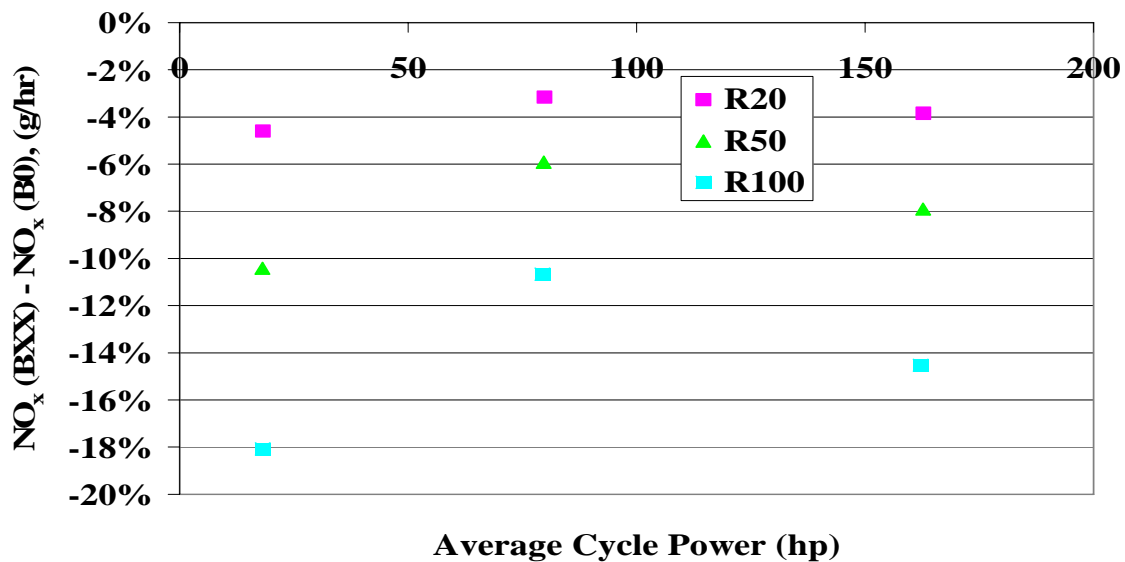# Average Power vs. PM Change - Renewable Blends

Figure 4-9. Average Cycle Power vs. PM Emissions Change for Testing on the Renewable Blends
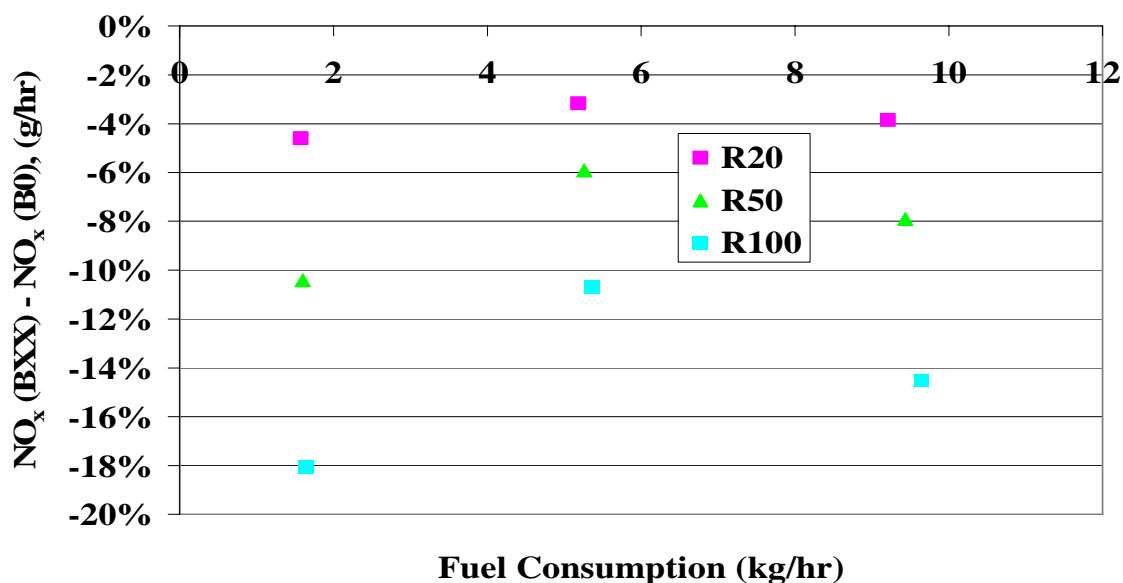
Fuel Use vs. PM Change - Renewable Blends

Figure 4-10. Fuel Consumption vs. PM Emissions Change for Testing on the Renewable Blends

4.3 THC Emissions

The THC emission results for the testing with the renewable and GTL diesels are presented in Figure 4-11 and **Error! Reference source not found.**, respectively, on a g/bhp-hr basis. **Error! Reference source not found.** shows the percentage differences for the renewable and GTL diesels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.
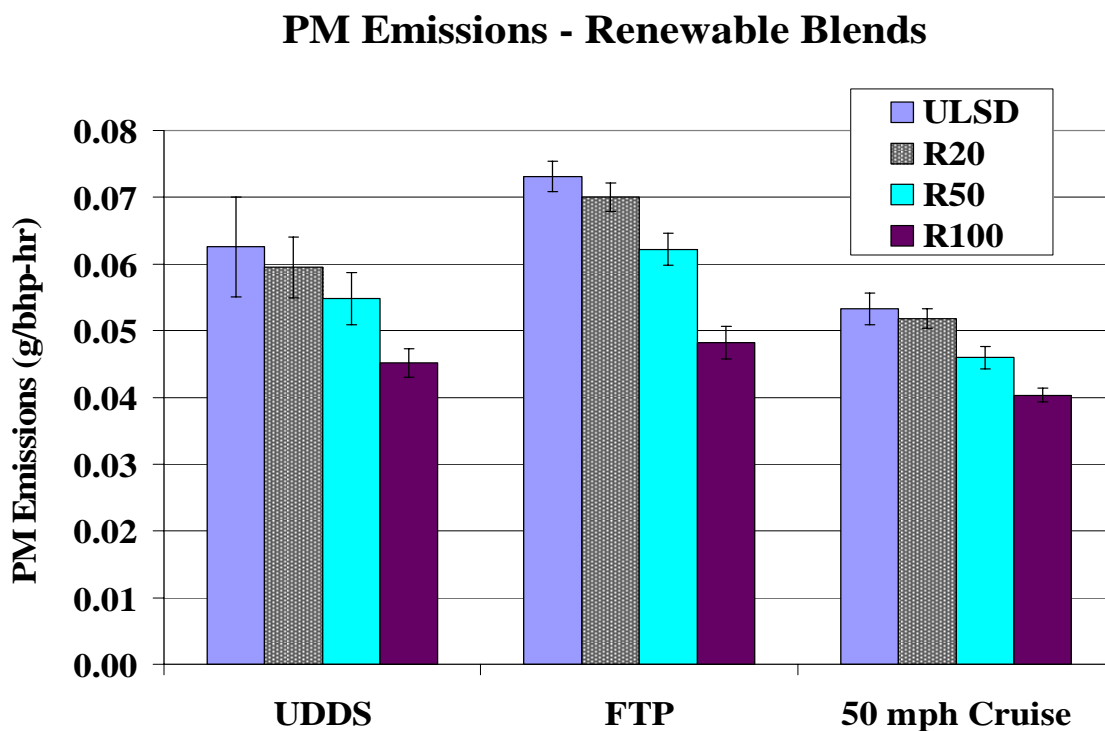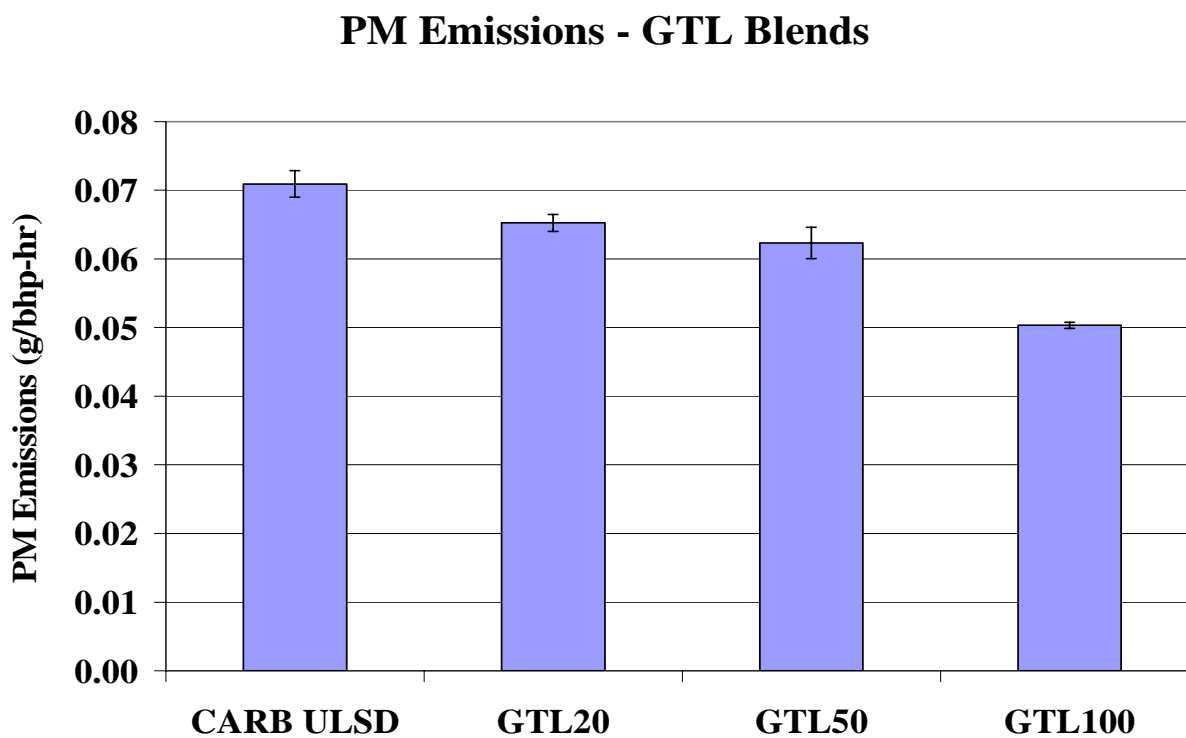
THC Emissions - Renewable Blends

Figure 4-11. Average THC Emission Results for the Renewable Blends

THC Emissions - GTL Blends

Figure 4-12. Average THC Emission Results for the GTL Blends

For the THC emissions, the GTL fuel showed statistically significant reductions over the FTP that increased with increasing blend level. These reductions ranged from 5% for the 20% blend to 28% for the 100% blend. The renewable diesel did not show consistent trends for THC emissions over the different test cycles. Statistically significant THC reductions were found for the renewable diesel fuel for the lowest load UDDS cycle, with the THC reductions increasing with increasing levels of the renewable diesel fuel. For the other cycles/blend levels, statistically significant reductions were only found for the R100 blend over the FTP. In several previous studies of the renewable diesel fuel, more consistent and robust reductions in THC as a function of increasing blend level have been found (Rothe et al. 2005; Kleinschek 2005; Aatola et al. 2008; Rantanen et al. 2008). These differences from the current study could be related to differences in the distillation properties of the fuels used in the different studies. In the European studies with the NExBTL fuel, a summer grade was used while a winter grade NExBTL was used in the current study. The summer grade NExBTL had higher T10 and T50 distillation temperatures, which are important parameters with respect to hydrocarbon emissions in the EPA's Unified Model. In fact, predictions with the EPA's Unified Model show that there should not be any significant differences between the THC emissions for the CARB fuel in comparison with the NExBTL winter blend used in the study, whereas the model predicts more significant and measureable reductions between the European base diesel fuel and the NExBTL summer blends used in the previous studies (Hodge, 2009). It should also be noted that in some cases in earlier studies, statistically significant reductions were not identified due to low THC emission levels from the engine or for lower blend levels (Kuronen et al. 2007; Erikkila and Nylund).

| | CARB vs. | Renewable | | GTL | |
		% Difference	P-values	% Difference	P-values
UDDS	20% blend	-3%	0.018		
	50% blend	-6%	0.002		
	100% blend	-12%	0.000		
FTP	20% blend	0%	0.719	-5%	0.000
	50% blend	0%	0.777	-16%	0.000
	100% blend	-4%	0.057	-28%	0.000
50 mph Cruise	20% blend	2%	0.207		
	50% blend	2%	0.230		
	100% blend	-1%	0.510		

Table 4-3. THC Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

THC emissions showed a trend of increasing emissions as a function of average cycle power for the various renewable blends, as presented in Figure 4-13. The THC differential between the CARB ULSD and the different blends showed a trend of smaller reductions for cycles with higher average power levels and greater fuel consumption, as shown in Figure 4-14 and in Figure 4-15, respectively. It should be noted, however, that the reductions in THC emissions for the FTP and 50 mph Cruise were only statistically significant for the R100 fuel over the FTP. Thus, any trends are primarily driven by the larger emissions reductions for the lightly loaded UDDS

cycle.
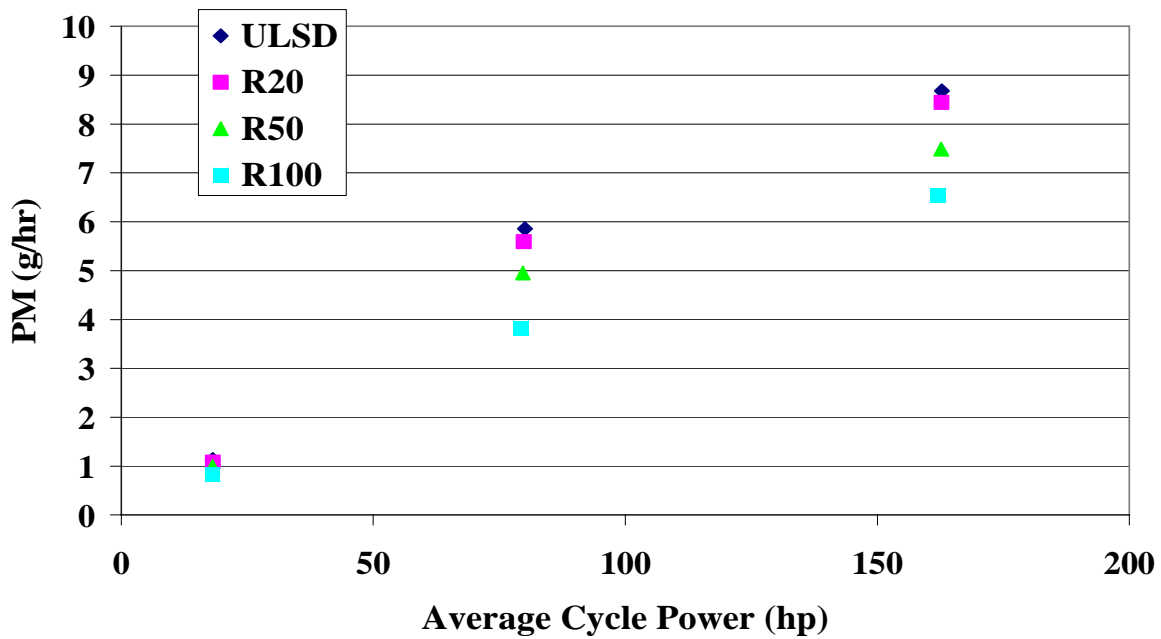
Average Cycle Power vs. THC - Renewable Blends
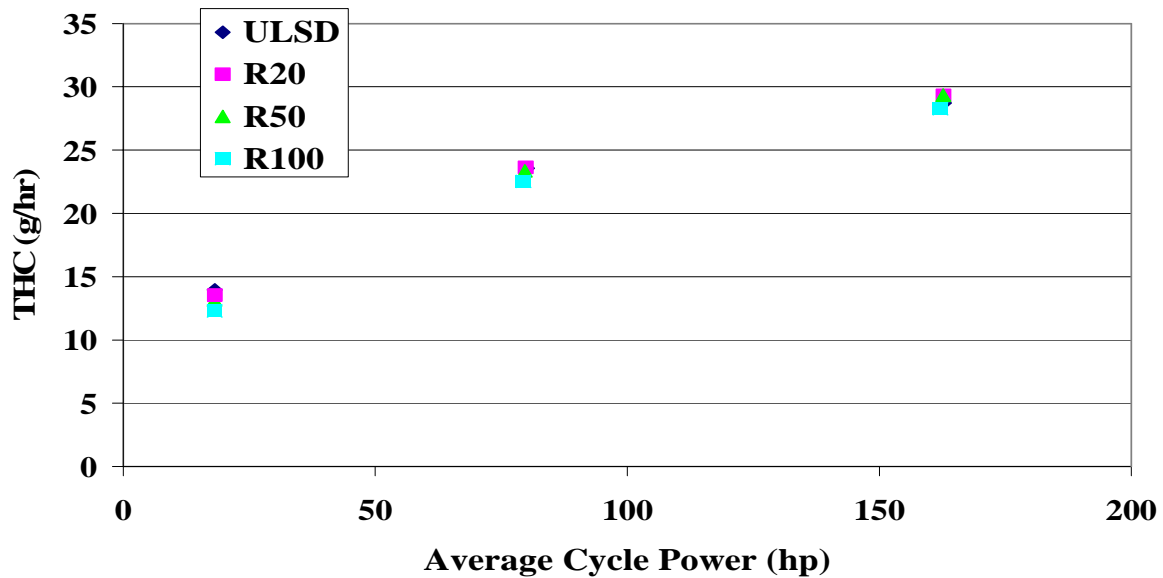
Figure 4-13. Average Cycle Power vs. THC Emissions for Testing on the Renewable Blends

Average Power vs THC Change -Renewable Blends
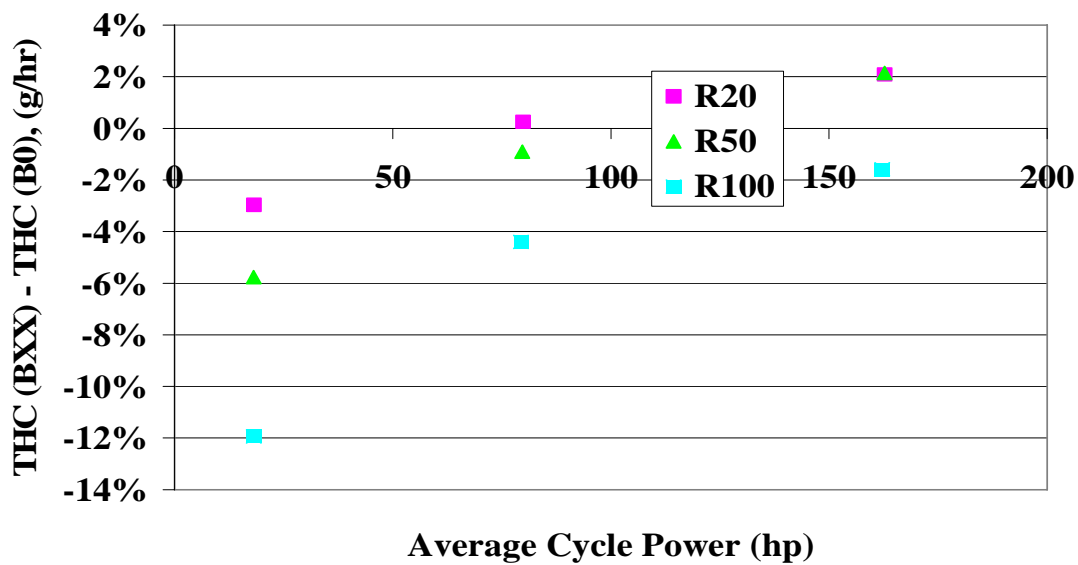
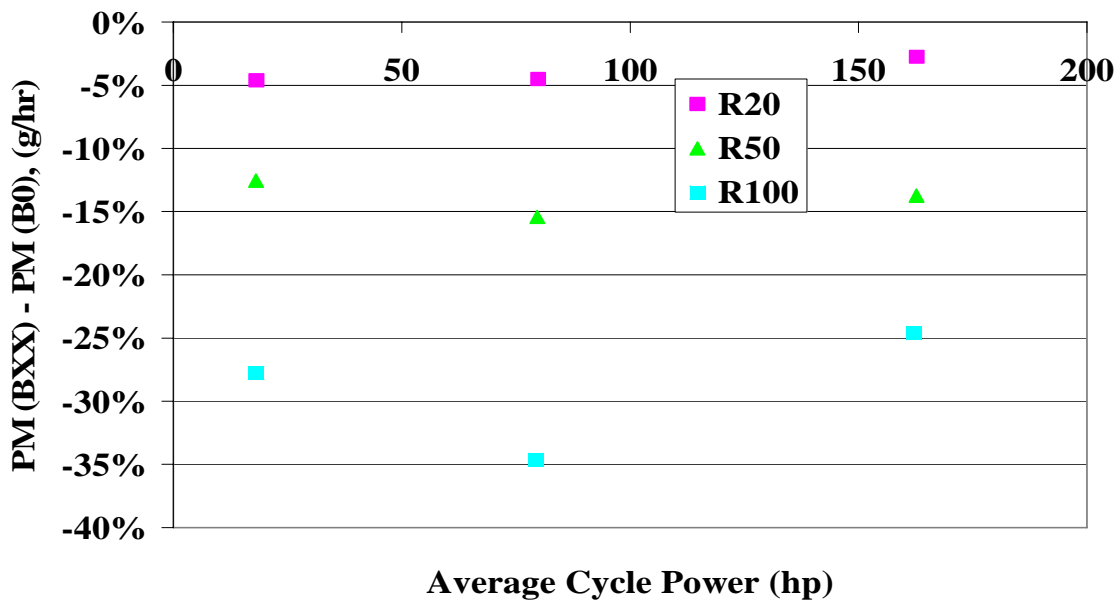**Figure 4-14. Average Cycle Power vs. THC Emissions Change for Testing on the Renewable Blends**

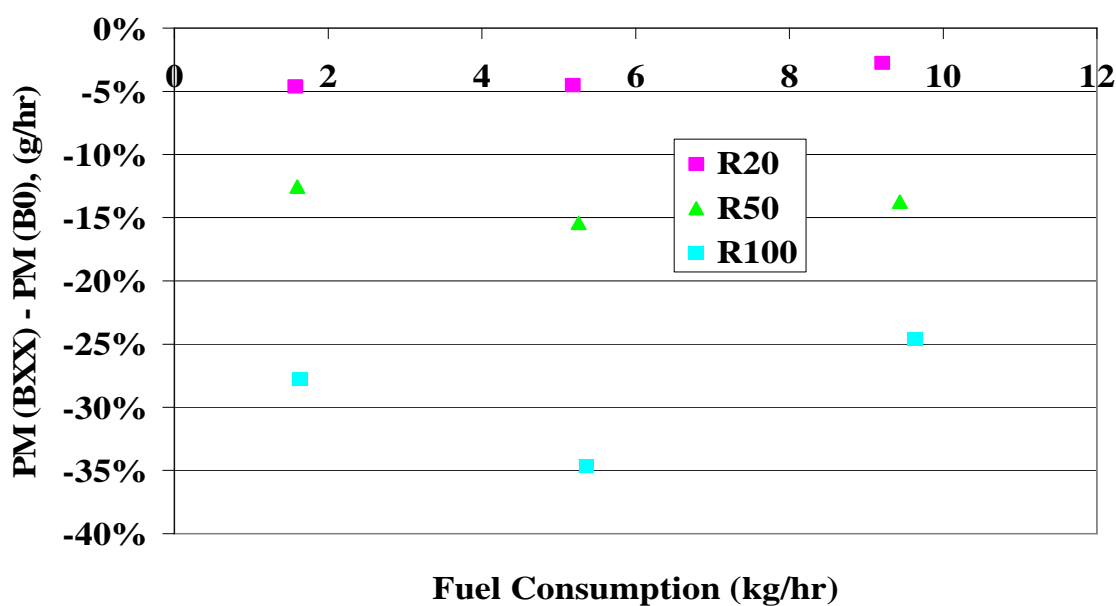# Fuel Use vs. THC Change - Renewable Blends
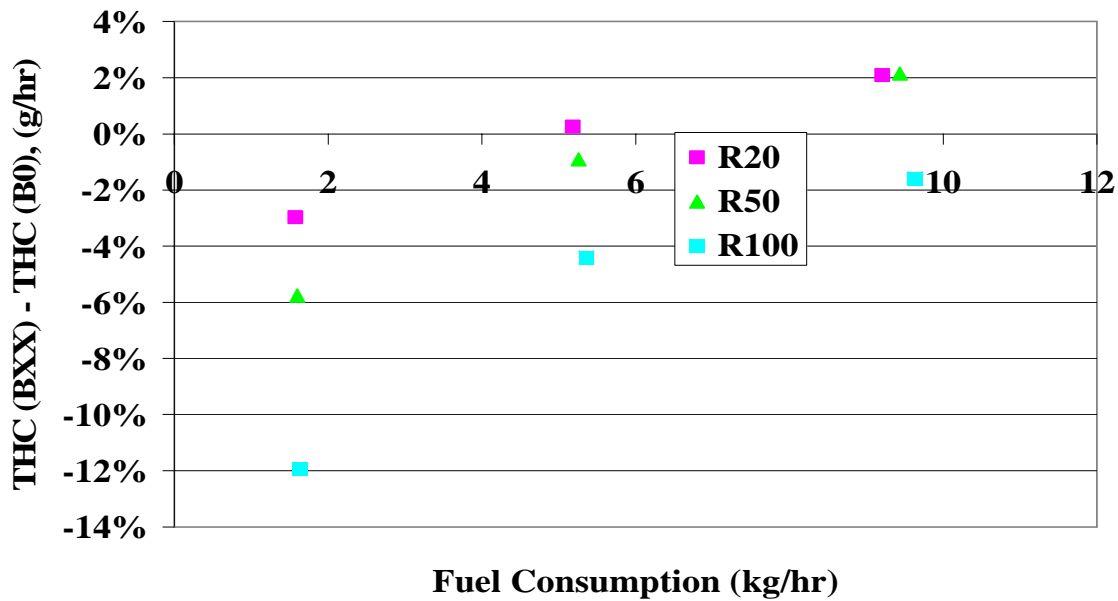
Figure 4-15. Fuel Consumption vs. THC Emissions Change for Testing on the Renewable Blends

4.4 CO Emissions

The CO emission results for the testing with the renewable and GTL diesels are presented in Figure 4-16 and **Error! Reference source not found.**, respectively, on a g/bhp-hr basis. **Error! Reference source not found.** shows the percentage differences for the renewable and GTL diesels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test, along with the associated p-values for statistical comparisons using a t-test.

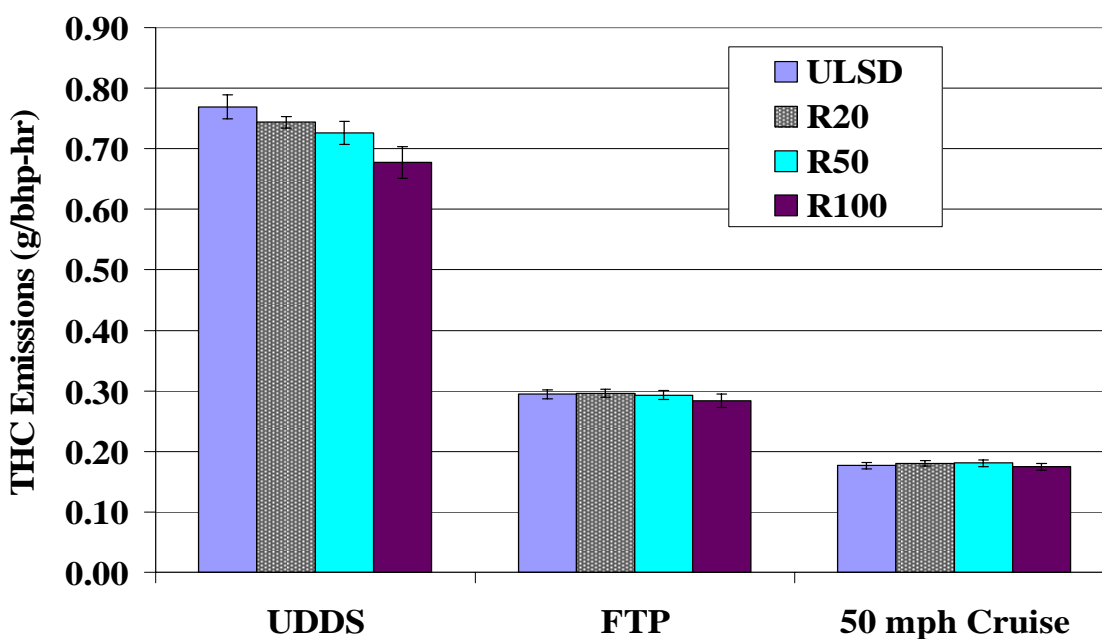# CO Emissions - Renewable Blends
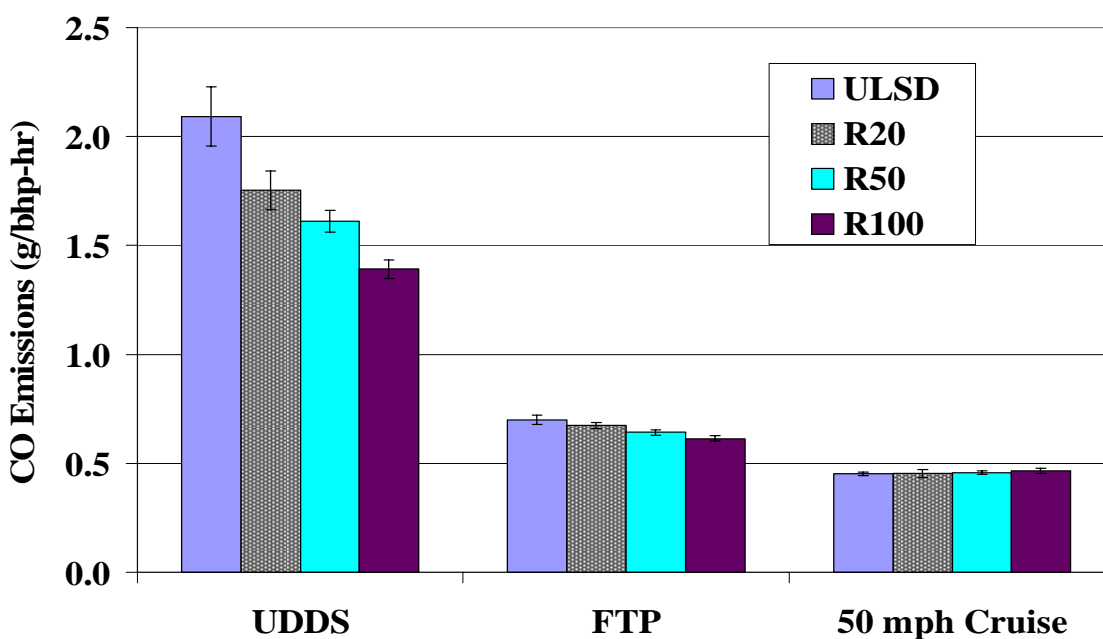
Figure 4-16. Average CO Emission Results for the Renewable Blends
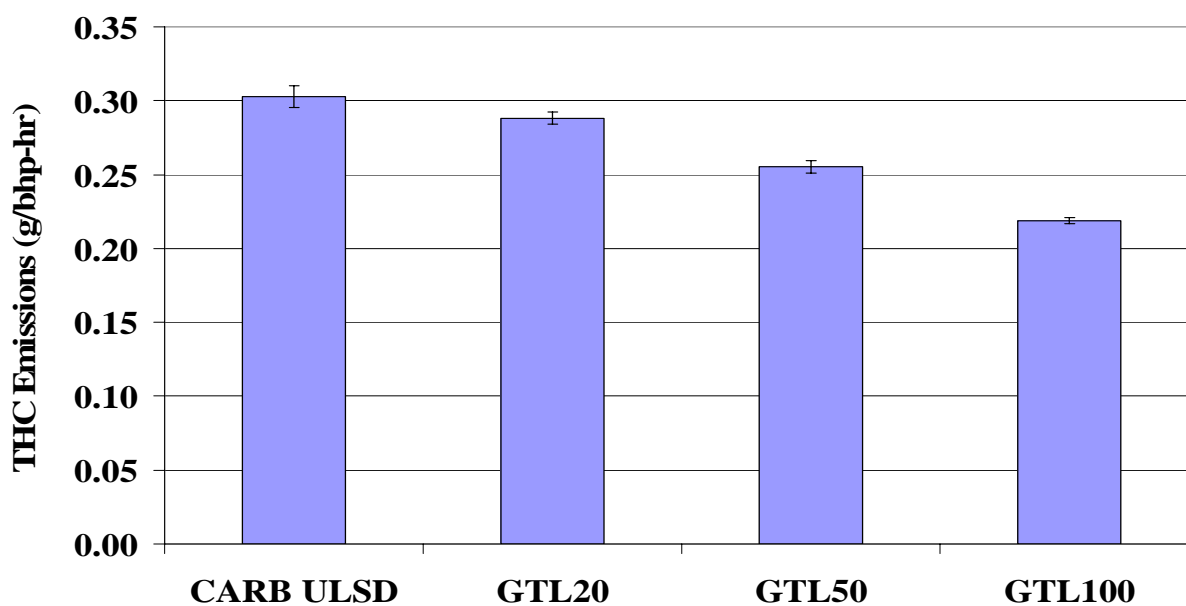
CO Emissions - GTL Blends
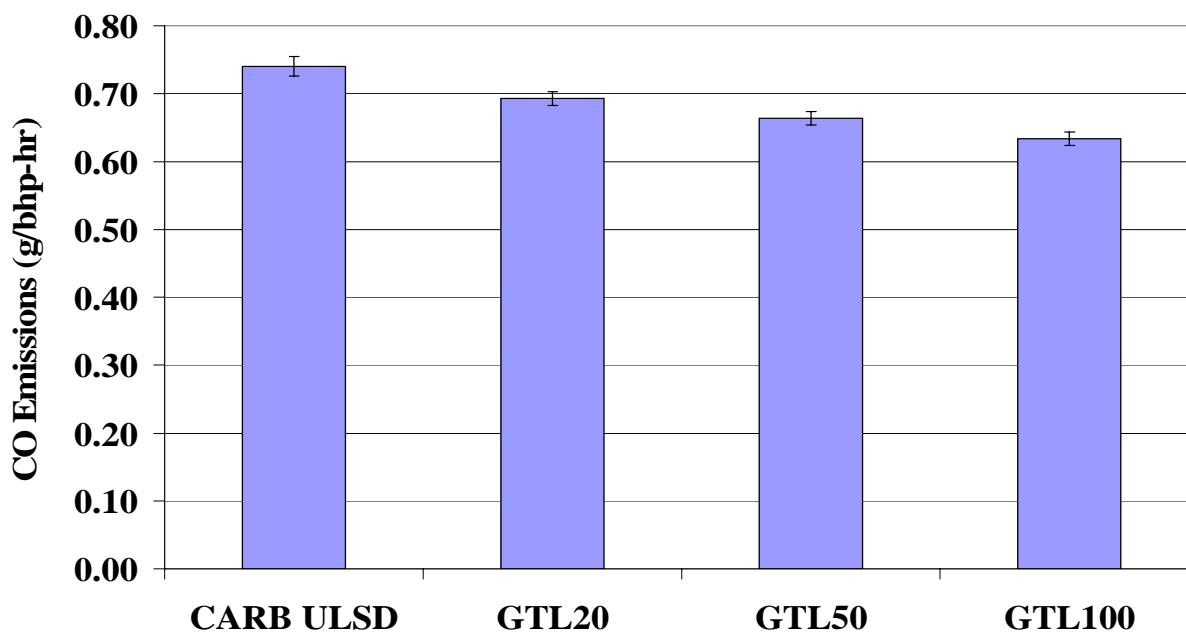
Figure 4-17. Average CO Emission Results for the GTL Blends

Reductions in CO emissions with the renewable diesel fuel were found for the UDDS and FTP cycles, but not for the cruise cycle. Over these cycles, the percentage reductions increased with increasing renewable diesel fuel blend. The GTL fuel also showed similar reductions over the FTP. The comparisons of CO emissions over the 50 mph cruise may have been complicated by the changes in engine operation that were seen for that cycle. The reductions in CO emissions as a function of renewable blend level for the UDDS and the FTP are within the range seen in previous studies of renewable blends in engine and chassis dynamometer tests (Rothe et al. 2005; Kleinschek 2005; Aatola et al. 2008; Rantanen et al. 2008; Kuronen et al. 2007; Erikkila and Nylund). The cruise cycle did not show consistent trends due to the variability of engine operation, as explained under section 2.7.

		Renewable		GTL	
	CARB vs.	% Difference	P-values	% Difference	P-values
UDDS	20% blend	-16%	0.000		
	50% blend	-23%	0.000		
	100% blend	-33%	0.000		
FTP	20% blend	-4%	0.022	-6%	0.000
	50% blend	-8%	0.000	-10%	0.000
	100% blend	-12%	0.000	-14%	0.000
50 mph Cruise	20% blend	0%	0.831		
	50% blend	1%	0.234		
	100% blend	3%	0.022		

Table 4-4. CO Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

CO emissions showed a trend of increasing emissions as a function of average cycle power for the various renewable blends, as presented in Figure 4-18. The CO differential between the CARB ULSD and the different blends showed a trend of smaller reductions for cycles with higher average power levels and greater fuel consumption, as shown in Figure 4-19 and in Figure 4-20, respectively. These trends are similar to those seen for the THC emissions for the renewable blends. The trend is slightly more robust for the CO emissions since the emissions reductions for both the UDDS and FTP are statistically significant, as well as the reductions for the R100 blend for the 50 mph cruise. Again, however, the comparisons for CO emissions over the 50 mph cruise may have been complicated by the changes in engine operation that were seen for that cycle.
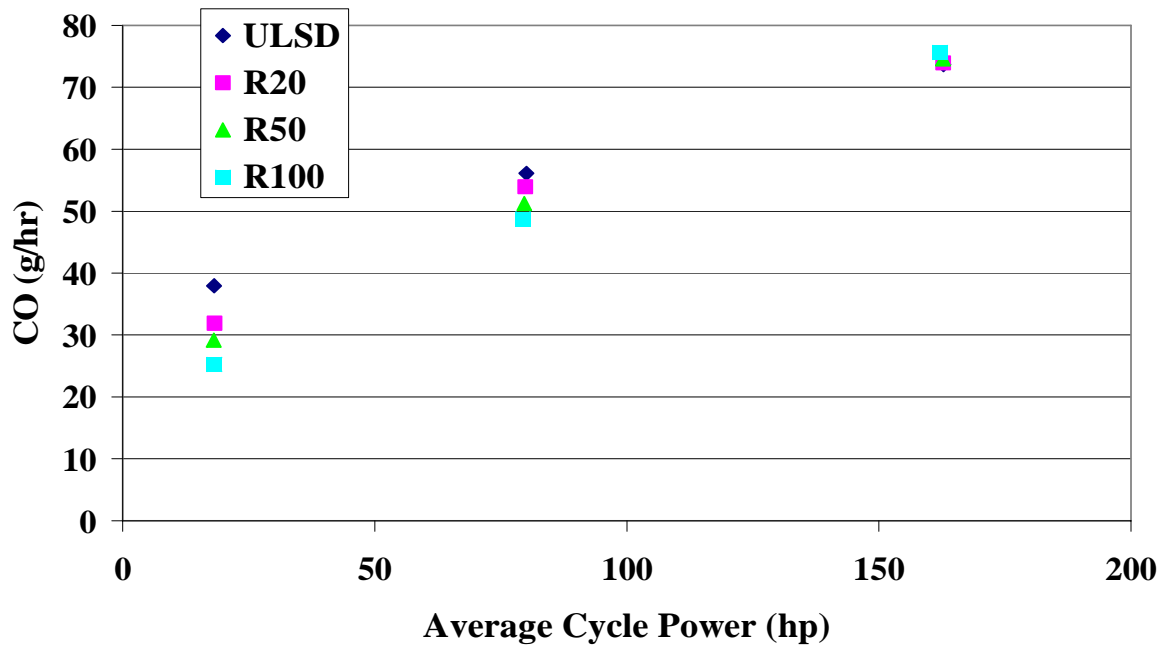
Figure 4-18. Average Cycle Power vs. CO Emissions for Testing on the Renewable Blends
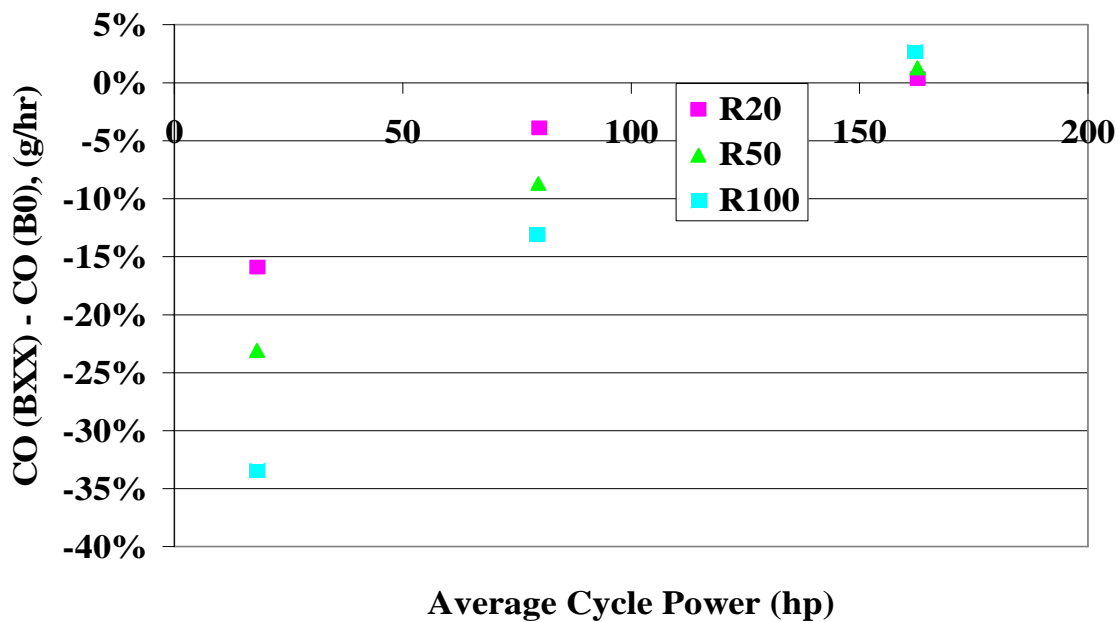
Figure 4-19. Average Cycle Power vs. CO Emissions Change for Testing on the Renewable Blends

Fuel Use vs. CO Change - Renewable Blend
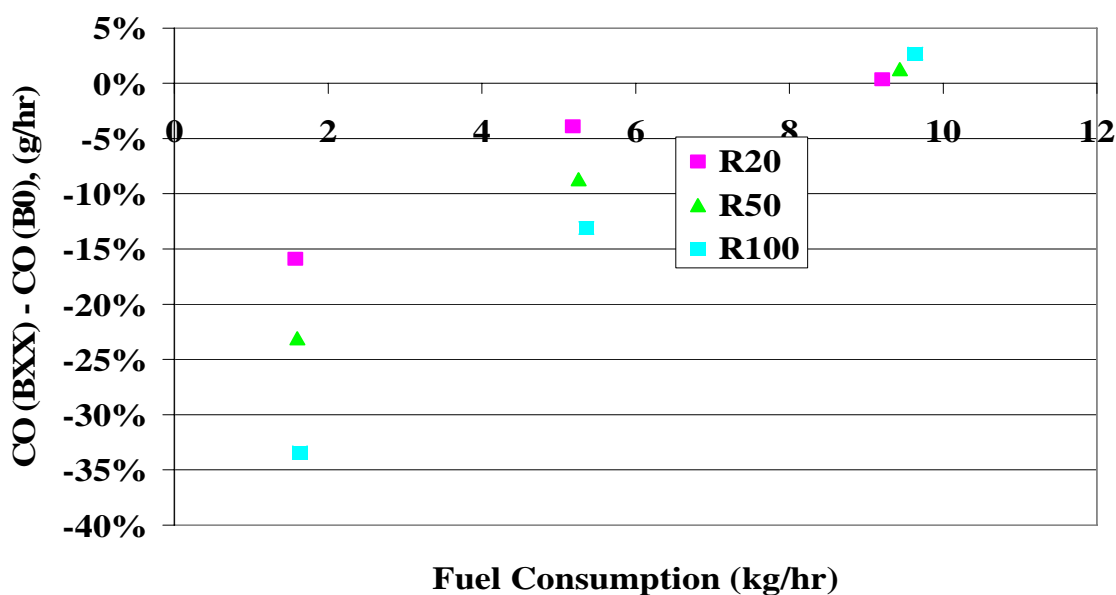
Figure 4-20. Fuel Consumption vs. CO Emissions Change for Testing on the Renewable Blends

4.5 CO_2 Emissions

The CO_2 emission results for the testing with the renewable and GTL diesels are presented in Figure 4-21 and Figure 4-22, respectively, on a g/bhp-hr basis. Table 4-5 shows the percentage differences for the renewable and GTL diesels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

CO$_2$ Emissions - Renewable Blends
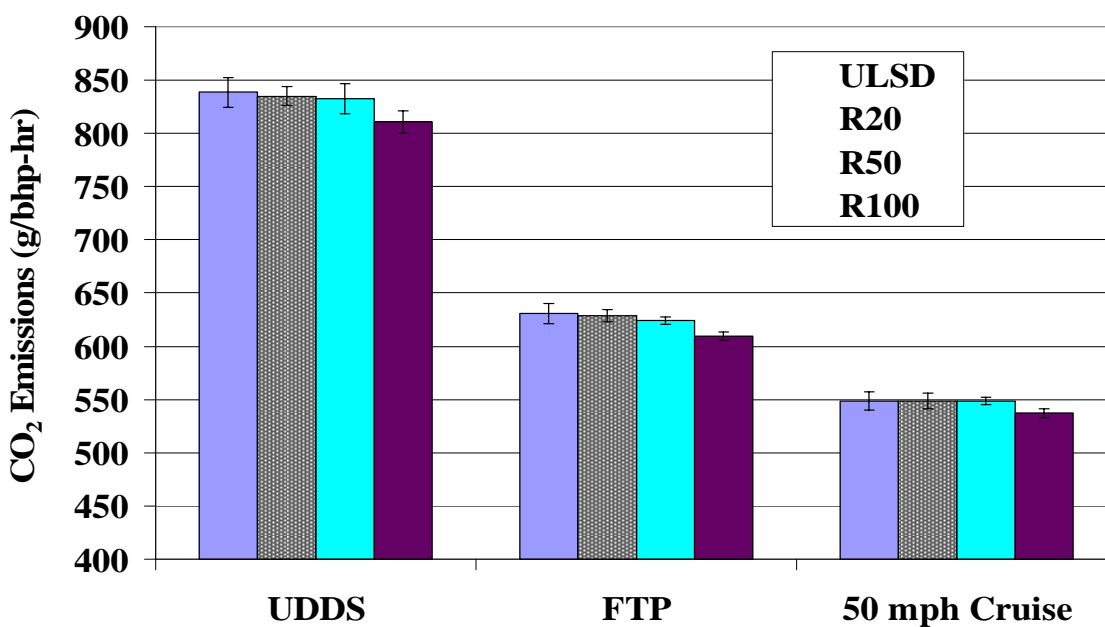
Figure 4-21. Average CO$_2$ Emission Results for the Renewable Blends

CO$_2$ Emissions - GTL Blends
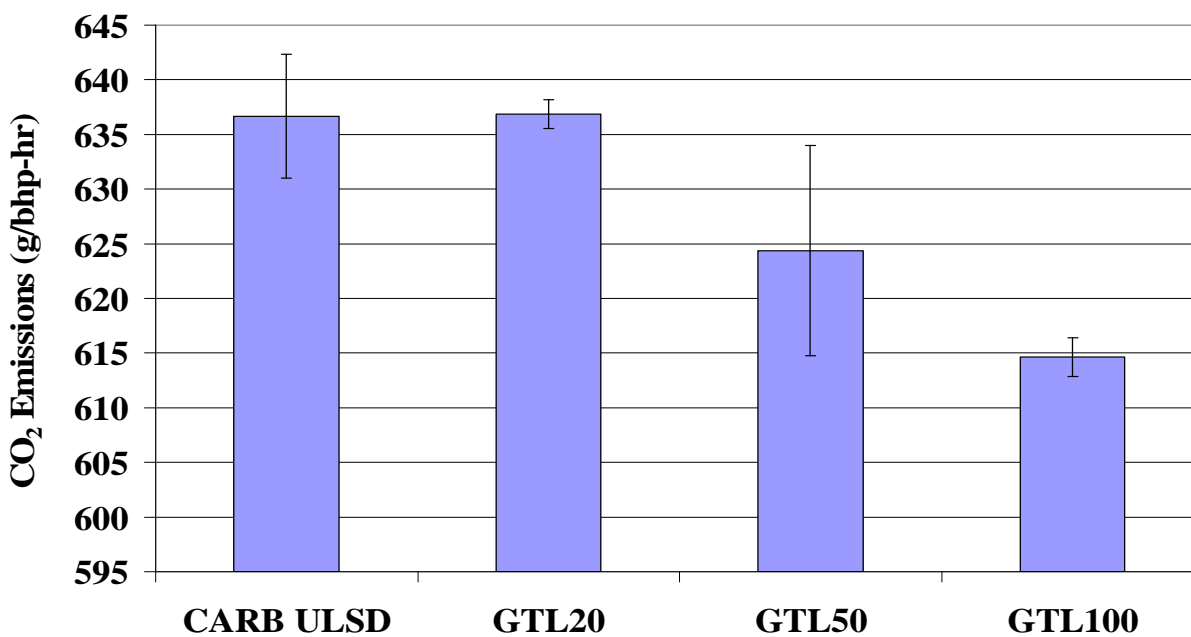
Figure 4-22. Average CO$_2$ Emission Results for the GTL Blends

The CO_2 emissions for the neat or 100% blend of renewable diesel and the 50% and 100% blends of the GTL fuels were lower than those for the CARB ULSD for each of the test cycles. This slight reduction in CO_2 emissions is consistent and comparable to previous studies of the renewable diesel fuel (Kleinschek 2005; Rantanen et al. 2005, Kuronen et al. 2007). There were no statistically significant CO_2 differences between the CARB ULSD and the 20% blend of the renewable or GTL fuels or the 50% blend of the renewable blend.

		Renewable		GTL	
	CARB vs.	% Difference	P-values	% Difference	P-values
UDDS	20% blend	-0.4%	0.595		
	50% blend	-0.7%	0.448		
	100% blend	-3.3%	0.002		
FTP	20% blend	-0.3%	0.652	0.0%	0.933
	50% blend	-1.0%	0.124	-1.9%	0.001
	100% blend	-3.4%	0.000	-3.5%	0.000
50 mph Cruise	20% blend	0.0%	0.972		
	50% blend	0.0%	0.996		
	100% blend	-2.1%	0.011		

Table 4-5. CO_2 Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

4.6 Brake Specific Fuel Consumption

The brake specific fuel consumption emission results for the testing with the renewable and GTL diesels are presented in Figure 4-23 and **Error! Reference source not found.**, respectively, on a gal./bhp-hr basis. **Error! Reference source not found.** shows the percentage differences for the renewable and GTL diesels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

BSFC - Renewable Blends
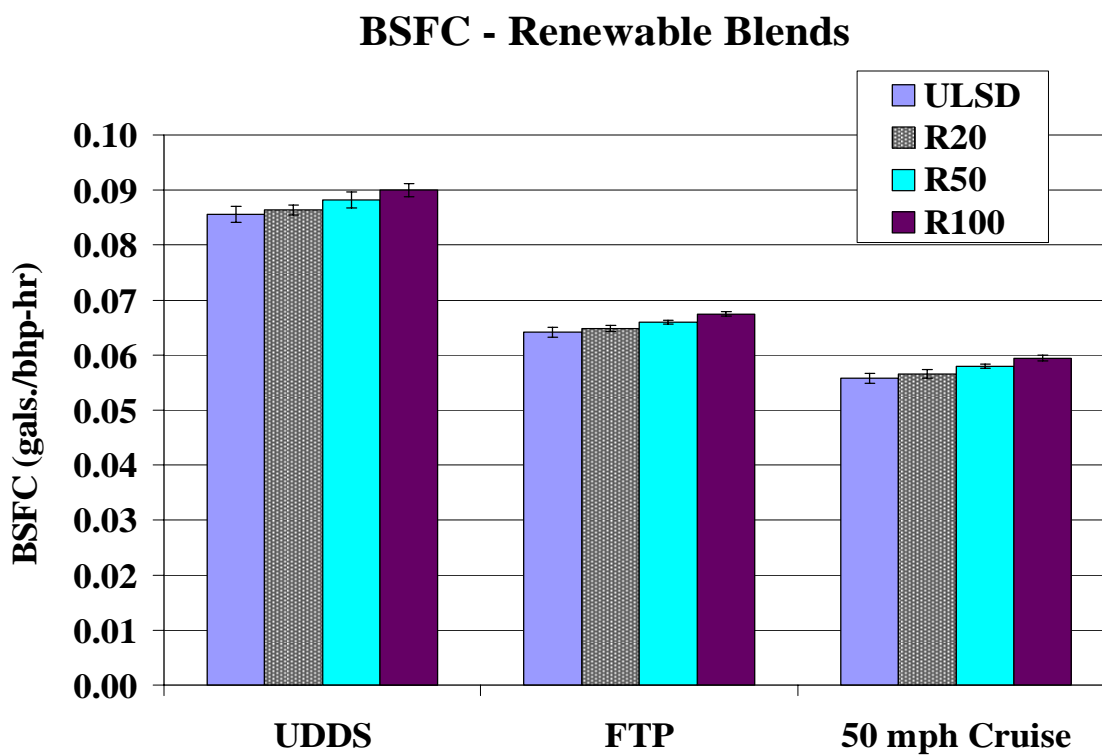
Figure 4-23. Average Brake Specific Fuel Consumption Results for the Renewable Blends
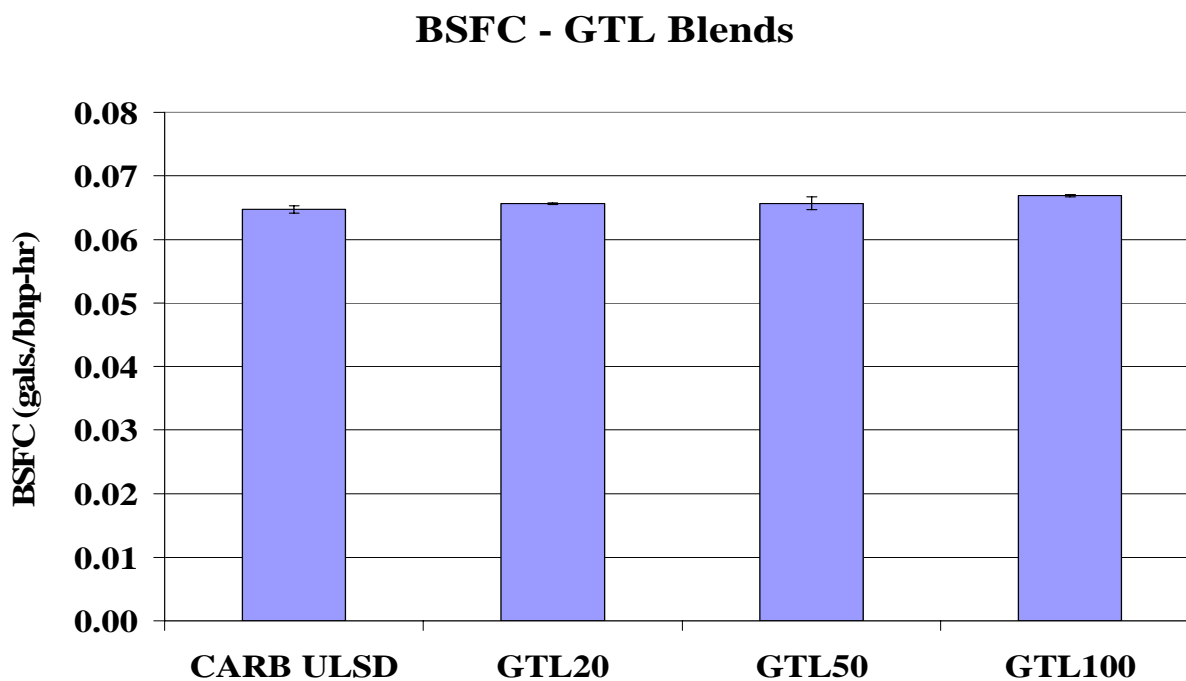
BSFC - GTL Blends

Figure 4-24. Average Brake Specific Fuel Consumption for the GTL Blends

The brake specific fuel consumption data showed increasing fuel consumption with increasing levels of renewable and GTL diesel fuel. The increases in fuel consumption range from 1.0-1.4% for the R20 and 5.1 to 6.6% for the R100. The increases in fuel consumption with blend level are slightly higher for the cruise cycle compared to the lower load UDDS and FTP. The fuel consumption differences are consistent with the results from previous studies (Rothe et al. 2005; Kleinschek 2005; Aatola et al. 2008; Rantanen et al. 2008; Kuronen et al. 2007; Erikkila and Nylund), and can be attributed to the lower density or energy density of the renewable fuel compared to the CARB baseline fuel. The brake specific fuel consumption increases for the GTL ranged from 1.3% for the 20% blend to 3.3% for the 100% blend.

		Renewable		GTL	
	CARB vs.	% Difference	P-values	% Difference	P-values
UDDS	20% blend	1.0%	0.255		
	50% blend	3.1%	0.007		
	100% blend	5.1%	0.000		
FTP	20% blend	1.1%	0.117	1.3%	0.001
	50% blend	2.9%	0.001	1.4%	0.008
	100% blend	5.2%	0.000	3.3%	0.000
50 mph Cruise	20% blend	1.4%	0.107		
	50% blend	4.0%	0.000		
	100% blend	6.6%	0.000		

Table 4-6. Brake Specific Fuel Consumption Percentage Differences Between the Renewable and GTL Blends and the CARB ULSD base fuel for each Cycle.

5.0 NO$_x$ Mitigation Results

5.1 NO$_x$ Emissions

The mitigation of the NO$_x$ emissions is one of the most critical elements of this program. For this program, a variety of strategies examined. These included formulations with additives and renewable and diesel fuels. The NO$_x$ emission results for the various mitigation strategies are presented in Figure 5-1 on a gram per brake horsepower hour basis. The results for each test cycle/blend level combination represent the average of all test runs done on that particular combination within a particular test period. The NO$_x$ mitigation testing was conducted over three separate test periods, the results of which are separated by the vertical lines in the figure. All comparisons with the CARB diesel are based on the CARB diesel results from that specific test period, so that the impacts of drift between different test periods was minimized. The error bars represent one standard deviation on the average value.
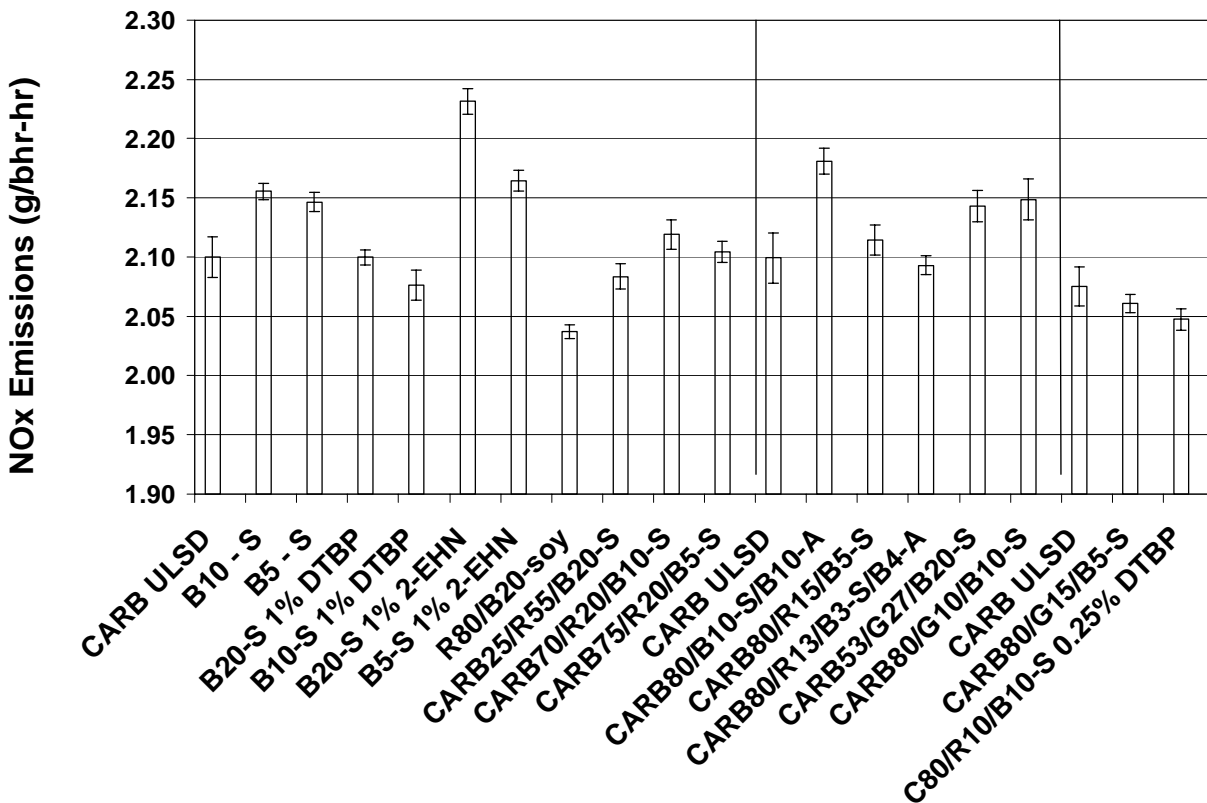
Figure 5-1. Average NO$_x$ Emission Results for the NO$_x$ Mitigation Formulations

Table 5-1 shows the percentage differences for the different mitigation formulations along with the associated p-values for statistical comparisons using a t-test. Again note that all comparisons with the CARB diesel are based on the CARB diesel results from that specific test period. The results show that several of the formulations were either NO$_x$ neutral or showed reductions in NO$_x$ in comparison with the based CARB fuel. These formulations are shaded in the Table.

Several lower level blends were tested in this portion of the program. This included a B10-soy and a B5-soy. The results from the B20-soy from the primary testing on the soy-based biodiesel feedstock are also included for comparison. These B5-soy and B10-soy blends both also showed increases in NO_x in comparison with the CARB fuel, although the increases were approximately 1/3 of the increases seen for the B20-soy blend. Additionally, a blend composed of 10% soy-biodiesel and 10% animal-based biodiesel with 80% CARB ULSD was tested. This blend showed an increase of approximately 3.9%, which is approximately the same value as the average of the increases for the B20-soy (+6.6%) and the B20-animal (+1.5%). This indicates that the NO_x impact for a particular biodiesel feedstock can be mitigated in part by blending with another biodiesel feedstock with a lower tendency for increasing NO_x.

CARB vs.	% Difference	P-values
B5 - S	2.2%	0.000
B10 - S	2.6%	0.000
B20 – S*	6.6%	0.000
B20-S 1% DTBP	0.0%	0.959
B10-S 1% DTBP	-1.1%	0.002
B20-S 1% 2-EHN	6.3%	0.000
B5-S 1% 2-EHN	3.1%	0.000
R80/B20-soy	-3.0%	0.000
CARB25/R55/B20-S	-0.8%	0.029
CARB70/R20/B10-S	0.9%	0.014
CARB75/R20/B5-S	0.2%	0.674
CARB80/B10-S/B10-A	3.9%	0.000
CARB80/R15/B5-S	0.7%	0.117
CARB80/R13/B3-S/B4-A	-0.3%	0.501
CARB53/G27/B20-S	2.1%	0.000
CARB80/G10/B10-S	2.4%	0.000
CARB80/G15/B5-S	-0.7%	0.068
CARB80/R10/B10-S 0.25% DTBP	-1.3%	0.002

* From testing with soy-biodiesel feedstock

Table 5-1. NO_x Percentage Differences Between the Blends used for the NO_x Mitigation and the CARB ULSD base fuel.

Two additives were tested in this test phase, 2-ethylhexyl nitrate (2-EHN) and di tertiary butyl peroxide (DTBP). Of these two additives, the DTBP was the most effective in this testing configuration. A 1% DTBP additive blend was found to fully mitigate the NO_x impacts for a B20 soy biodiesel. Tests at a lower B10-soy biodiesel level with a 1% DTBP additive were additionally found to reduce NO_x emissions below those of the CARB fuel. The 2-EHN was tested at 1% level in both a B20-soy and B5-soy blend. This additive did not show any significant NO_x reductions from the pure blends for this engine.

A number of renewable and GTL blends with biodiesel were also tested. At higher levels of the renewable diesel fuel, the blends showed NO_x emissions below those of the baseline CARB ULSD. This included a R80/B20-soy and a CARB25/R55/B20-soy blend. At lower levels, more

comparable to those that could potentially be used to meet the low carbon fuel standard, several blends showed NO_x neutrality including a CARB75/R20/B5-soy, a CARB80/R13/B3-soy/B4-animal, and a CARB80/R15/B5-soy. A CARB80/GTL15/B5-soy blend was also found to achieve NO_x neutrality. Overall, the renewable and GTL diesels provide comparable levels of reductions for NO_x neutrality at the 15% blend level with a B5-soy. As discussed above, the level of renewable or GTL diesel fuels can be reduced if a biodiesel fuel with more favorable NO_x characteristics is used. This is demonstrated by the success of the CARB80/R13/B3-S/B4-A blend that combined both the soy and animal-based biodiesel. The use of an additive in conjunction with lower levels of renewable diesel and GTL can also be used to provide NO_x neutrality, as shown by the CARB80/R10/B10-S 0.25% DTBP blend.

5.2 PM Emissions

The PM emission results for the various mitigation strategies are presented in Figure 5-2 on a g/bhp-hr basis. **Error! Reference source not found.** shows the percentage differences for the various mitigation strategies for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

Figure 5-2. Average PM Emission Results for the NO_x Mitigation Formulations

The PM emissions for all of the NO_x mitigation formulations all showed reductions in PM for both the additive blends and the renewable blends. The largest reductions were found for the formulations with higher percentages of both biodiesel (B20) and the renewable diesel (55%-

67

80%). Most of the other blends provided PM reductions that are slightly greater than those found for the corresponding B20 or lower soy biodiesel blends.

CARB vs.	% Difference	P-values
B5 - S	-6%	0.000
B10 - S	-17%	0.000
B20 – S*	-25%	0.000
B20-S 1% DTBP	-16%	0.000
B10-S 1% DTBP	-6%	0.000
B20-S 1% 2-EHN	-17%	0.000
B5-S 1% 2-EHN	-4%	0.007
R80/B20-S	-47%	0.000
CARB25/R55/B20-S	-40%	0.000
CARB70/R20/B10-S	-17%	0.000
CARB75/R20/B5-S	-11%	0.000
CARB80/B10-S/B10-A	-26%	0.000
CARB80/R15/B5-S	-11%	0.000
CARB80/R13/B3-S/B4-A	-9%	0.000
CARB53/G27/B20-S	-32%	0.000
CARB80/G10/B10-S	-18%	0.000
CARB80/G15/B5-S	-9%	0.000
C80/R10/B10-S 0.25% DTBP	-11%	0.000

* From testing with soy-biodiesel feedstock

Table 5-2. PM Percentage Differences Between the Blends used for the NO$_x$ Mitigation and the CARB ULSD base fuel.

5.3 THC Emissions

The THC emission results for the various mitigation strategies are presented in Figure 5-3 on a g/bhp-hr basis. **Error! Reference source not found.** shows the percentage differences for the various mitigation strategies for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.
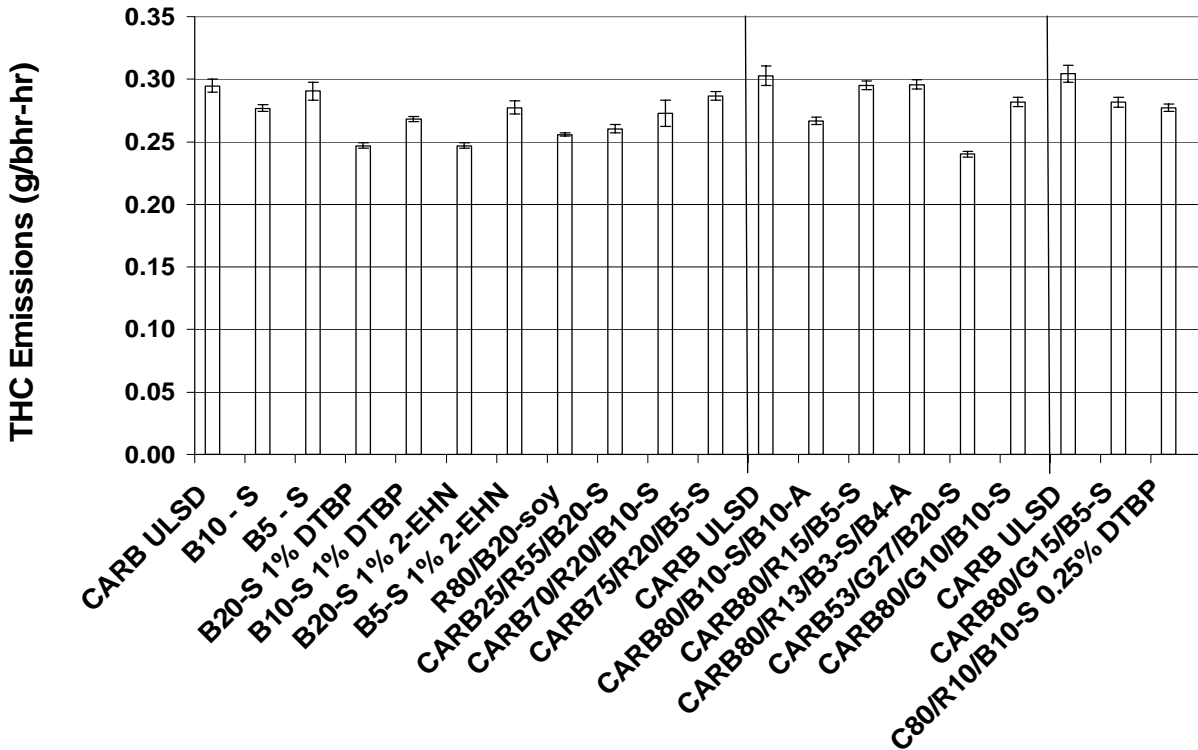
Figure 5-3. Average THC Emission Results for the NO$_x$ Mitigation Formulations

THC emissions showed consistent reductions for the NO$_x$ mitigation blends ranging from 3 to 21%. These reductions were highest for the blends with the B20 blend level. Generally, the blends of biodiesel with either a renewable diesel, a GTL diesel, or an additive showed THC reductions that were either higher than or equivalent to the levels found for the biodiesel by itself at a particular blend level.

CARB vs.	% Difference	P-values
B5 – S	-1%	0.087
B10 - S	-6%	0.000
B20 - S	-11%	0.000
B20-S 1% DTBP	-16%	0.000
B10-S 1% DTBP	-9%	0.000
B20-S 1% 2-EHN	-16%	0.000
B5-S 1% 2-EHN	-6%	0.000
R80/B20-soy	-13%	0.000
CARB25/R55/B20-S	-12%	0.000
CARB70/R20/B10-S	-8%	0.000
CARB75/R20/B5-S	-3%	0.014
CARB80/B10-S/B10-A	-12%	0.000
CARB80/R15/B5-S	-3%	0.024
CARB80/R13/B3-S/B4-A	-2%	0.039
CARB53/G27/B20-S	-21%	0.000
CARB80/G10/B10-S	-7%	0.000
CARB80/G15/B5-S	-7%	0.000
CARB80/R10/B10-S 0.25% DTBP	-9%	0.000

* From testing with soy-biodiesel feedstock

Table 5-3. THC Percentage Differences Between the Blends used for the NO$_x$ Mitigation and the CARB ULSD base fuel.

5.4 CO Emissions

The CO emission results for the various mitigation strategies are presented in Figure 5-4 on a g/bhp-hr basis. **Error! Reference source not found.** shows the percentage differences for the various mitigation strategies for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.
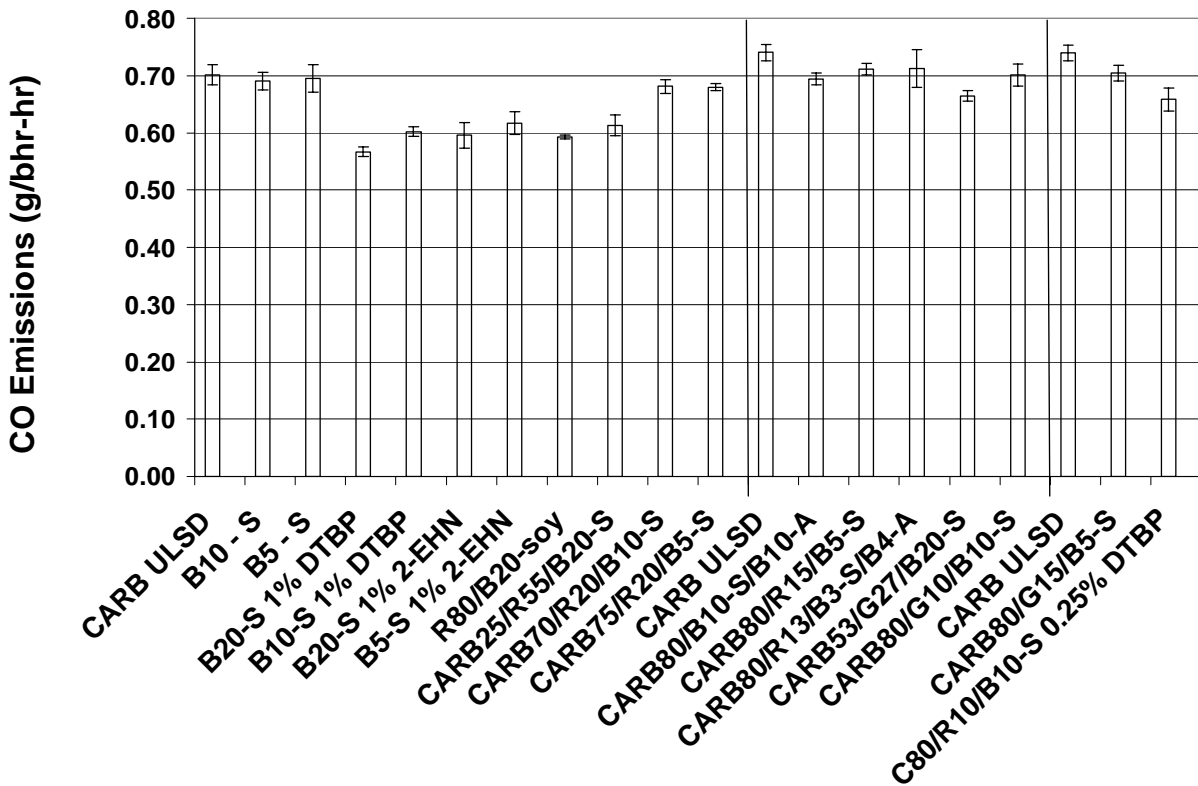
Figure 5-4. Average CO Emission Results for the NO$_x$ Mitigation Formulations

All formulations used for the NO$_x$ mitigation showed reductions in CO compared to the CARB fuel ranging from 3 to 19%. The formulations with higher percentages of renewable/GTL diesel fuel (R80, R55, and GTL27) with B20 and those with additives all showed statistically significant reductions in CO emissions of 10% or greater.

CARB vs.	% Difference	P-values
B5 – S	-1%	0.471
B10 - S	-2%	0.171
B20 - S	-3%	0.078
B20-S 1% DTBP	-19%	0.000
B10-S 1% DTBP	-14%	0.000
B20-S 1% 2-EHN	-15%	0.000
B5-S 1% 2-EHN	-12%	0.000
R80/B20-soy	-16%	0.000
CARB25/R55/B20-S	-13%	0.000
CARB70/R20/B10-S	-3%	0.013
CARB75/R20/B5-S	-3%	0.048
CARB80/B10-S/B10-A	-6%	0.000
CARB80/R15/B5-S	-4%	0.000
CARB80/R13/B3-S/B4-A	-4%	0.005
CARB53/G27/B20-S	-10%	0.000
CARB80/G10/B10-S	-5%	0.000
CARB80/G15/B5-S	-5%	0.000
CARB80/R10/B10-S 0.25% DTBP	-11%	0.000

* From testing with soy-biodiesel feedstock

Table 5-4. CO Percentage Differences Between the Blends used for the NO$_x$ Mitigation and the CARB ULSD base fuel.

5.5 CO$_2$ Emissions

The CO$_2$ emission results for the various mitigation strategies are presented in Figure 5-5 on a gram per brake horsepower hour basis. Table 5-5 shows the percentage differences for the various mitigation strategies for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.
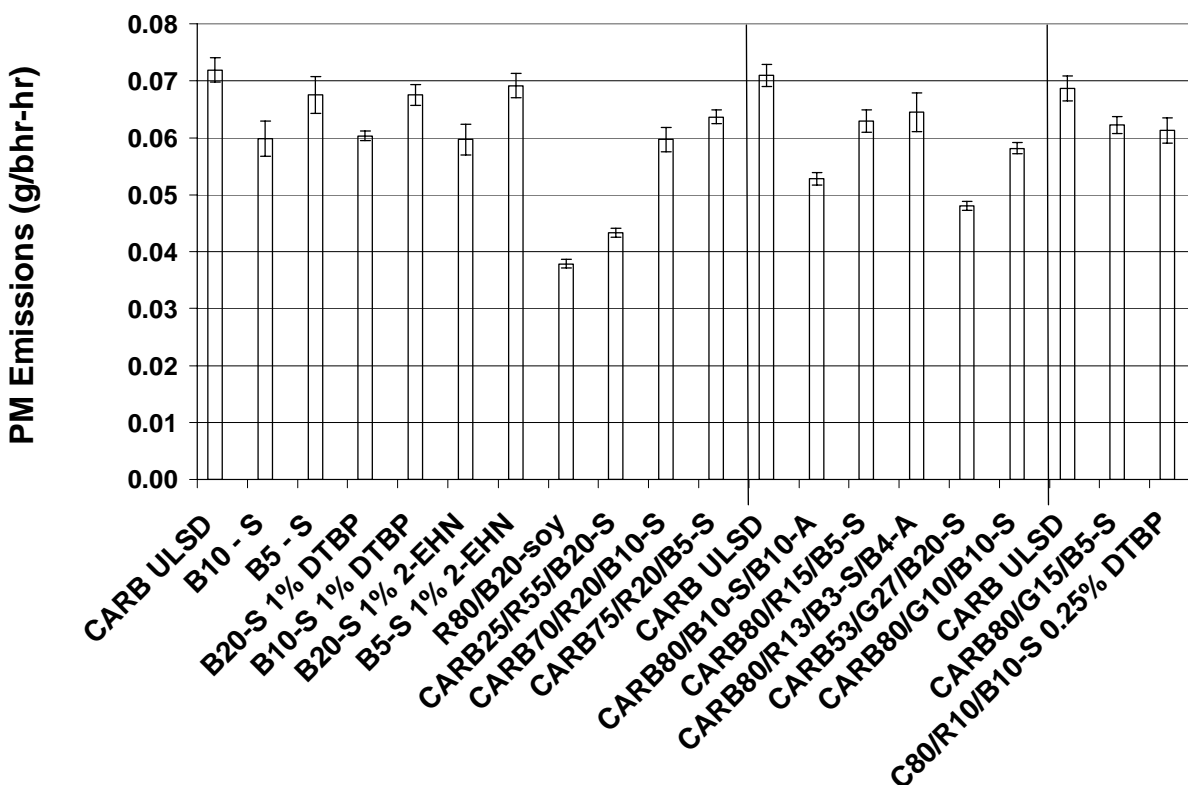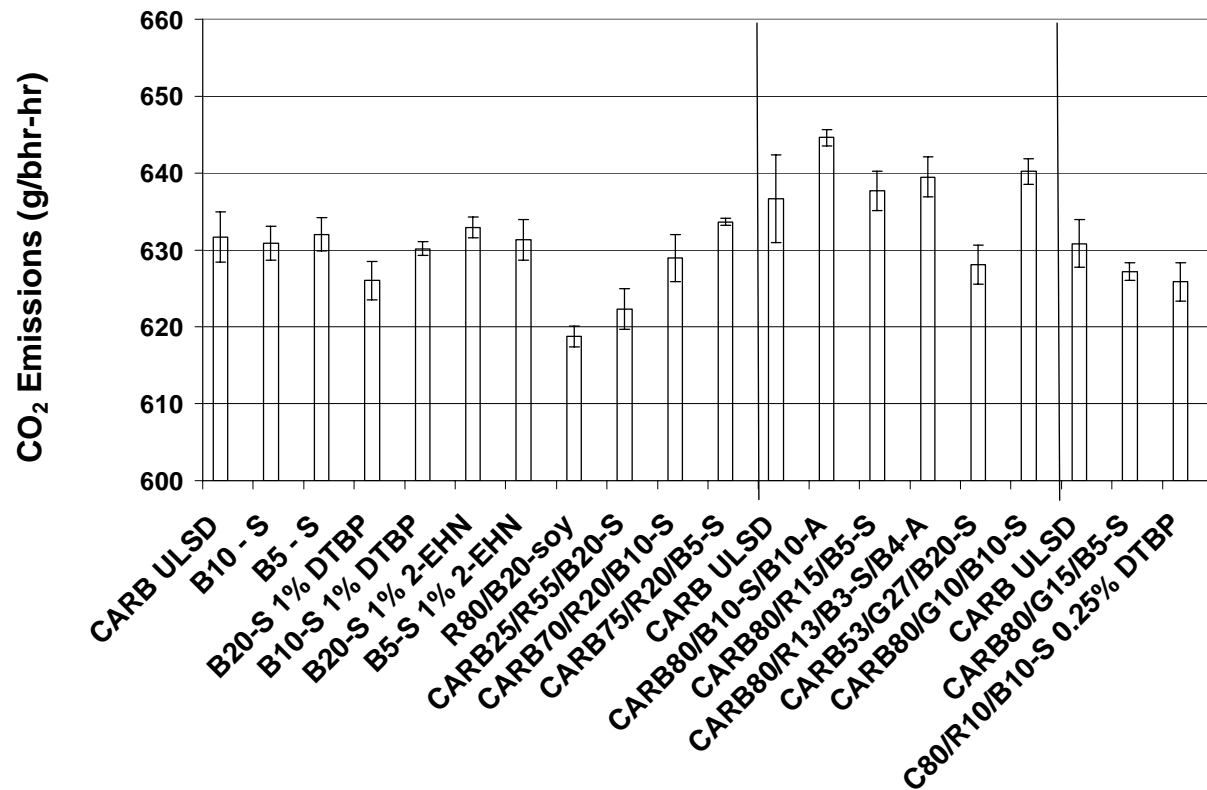
Figure 5-5. Average CO$_2$ Emission Results for the NO$_x$ Mitigation Formulations

The NO$_x$ mitigation formulations showed statistically significant changes for about half of the formulations tested. The statistically significant changes were all reductions in CO$_2$ that were 2% or less. This included some for the formulations with higher blends (55 and 80%) of renewable diesel. This is consistent with the CO$_2$ reductions seem for the higher blends of the renewable diesel and GTL fuels discussed above.

CARB vs.	% Difference	P-values
B5 - S	0.1%	0.816
B10 - S	-0.1%	0.569
B20 – S	0.4%	0.309
B20-S 1% DTBP	-0.9%	0.000
B10-S 1% DTBP	-0.2%	0.258
B20-S 1% 2-EHN	0.2%	0.362
B5-S 1% 2-EHN	-0.1%	0.782
R80/B20-soy	-2.0%	0.000
CARB25/R55/B20-S	-1.5%	0.000
CARB70/R20/B10-S	-0.4%	0.059
CARB75/R20/B5-S	0.3%	0.309
CARB80/B10-S/B10-A	1.2%	0.003
CARB80/R15/B5-S	0.2%	0.686
CARB80/R13/B3-S/B4-A	0.4%	0.251
CARB53/G27/B20-S	-1.4%	0.001
CARB80/G10/B10-S	0.6%	0.150
CARB80/G15/B5-S	-0.6%	0.018
CARB80/R10/B10-S 0.25% DTBP	-0.8%	0.006

* From testing with soy-biodiesel feedstock

Table 5-5. CO$_2$ Percentage Differences Between the Blends used for the NO$_x$ Mitigation and the CARB ULSD fuel.

5.6 Brake Specific Fuel Consumption

The brake specific fuel consumption results for the various mitigation strategies are presented in Figure 5-6 on a gal./bhp-hr basis. **Error! Reference source not found.** shows the percentage differences for the various mitigation strategies for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.
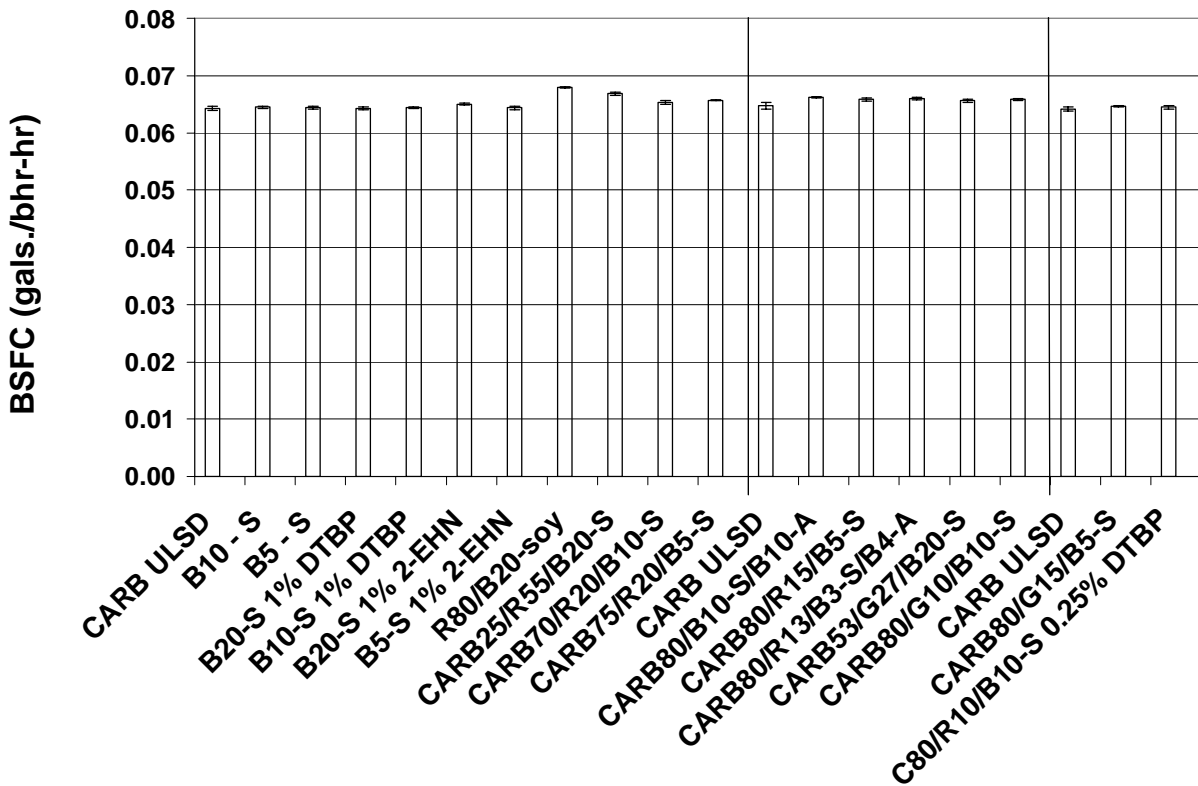
Figure 5-6. Average Brake Specific Fuel Consumption Results for the NO$_x$ Mitigation Formulations

The fuel consumption for the NO$_x$ mitigations formations was either higher than or not statistically different from the CARB fuel. This is not surprising given that the fuel consumption increased with higher blend levels of the biodiesel fuels, the renewable diesel, and the GTL. The increase in fuel consumption was highest for the fuels with the highest combined percentages of the renewable/GTL diesel and biodiesel. The B5 and B10 biodiesel blends, and the formulations with the DTBP additive did not show statistically significant increases in fuel consumption.

CARB vs.	% Difference	P-values
B5 - S	0.3%	0.228
B10 - S	0.3%	0.167
B20 – S*	1.4%	0.001
B20-S 1% DTBP	0.1%	0.748
B10-S 1% DTBP	0.2%	0.445
B20-S 1% 2-EHN	1.2%	0.000
B5-S 1% 2-EHN	0.1%	0.564
R80/B20-soy	5.7%	0.000
CARB25/R55/B20-S	4.1%	0.000
CARB70/R20/B10-S	1.7%	0.000
CARB75/R20/B5-S	2.2%	0.000
CARB80/B10-S/B10-A	2.2%	0.000
CARB80/R15/B5-S	1.6%	0.000
CARB80/R13/B3-S/B4-A	1.9%	0.000
CARB53/G27/B20-S	1.3%	0.002
CARB80/G10/B10-S	1.7%	0.000
CARB80/G15/B5-S	0.6%	0.010
CARB80/R10/B10-S 0.25% DTBP	0.5%	0.081

* From testing with soy-biodiesel feedstock

Table 5-6. Brake Specific Fuel Consumption Percentage Differences Between the Blends used for the NO$_x$ Mitigation and the CARB ULSD base fuel.

6.0 Summary

The California Air Resources Board is conducting a comprehensive study to better characterize the emissions impacts of renewable fuels under a variety of conditions in support of government initiates to increase the use of alternative fuels. The goal of this study is to understand and, to the extent possible, mitigate any impact that biodiesel has on NO_x emissions from diesel engines. This memorandum summarizes the results from the first test engine under this comprehensive program. The testing described in this memorandum was conducted on a 2006 Cummins ISM engine in CE-CERT's engine dynamometer laboratory. The testing included a baseline CARB ultralow sulfur diesel (ULSD) fuel, two biodiesel feedstocks (one soy-base and one animal-based) tested on blend levels of B5, B20, B50, and B100, and a renewable and a GTL diesel fuel tested at 20%, 50%, and 100% blend levels. Testing was also conducted on up to 4 different engine test cycles including a light loaded UDDS cycle, the FTP, and 40 mph and 50 mph CARB cruise cycles. These cycles represent different operating conditions, and low, medium, and high loads.

A summary of the results is as follows:

Biodiesel Characterization:

- The average NO_x emissions show trends of increasing NO_x emissions with increasing biodiesel blend level, but the magnitude of the effects differ between the different feedstocks. The soy-based biodiesel blends showed a higher increase in NO_x emissions for essentially all blend levels and test cycles in comparison with the animal-based biodiesel blends.
- For the soy-based biodiesel over the FTP, the NO_x impact ranged from an increase of 2.2% at the B5 level, to 6.6% at the B20 level, to 27% at the B100 level. The biodiesel emissions impacts for the other cycles were comparable to but less than those found for the FTP for the different blend levels. These increases were higher than the EPA base case estimates for all of the test cycles. The NO_x impacts found for the soy-based biodiesel were consistent, however, with the EPA estimates for the "clean base fuel" case, which would be more representative of a CARB diesel fuel.
- For the animal-based biodiesel feedstock, the NO_x emission increases with biodiesel for the FTP cycle were consistent with the EPA base case estimates. The NO_x impact for the animal-based biodiesel over the FTP ranged from an increase of 1.5% at the B20 level to 14% at the B100 level. For the lower load UDDS cycle for the animal-based biodiesel feedstock, the emissions differences were not statistically significant for any of the blend levels. For the 50 mph cruise cycle, a statistically significant increase in NOx emissions was only found for the B100 animal-based biodiesel. The 50 mph cruise results were obscured, however, by changes in the engine control strategy that appeared to occur over a segment of this cycle.
- NO_x emissions were found to increase as a function of engine load, as expected. Comparing different cycles, the FTP seemed to show the strongest NO_x increases for biodiesel for both soy-based and animal-based blends. The impact of biodiesel on NO_x emissions was not found to be a strong function of engine load, as was observed in previous studies by EPA (Sze et al., 2007). It is possible that different engine mapping procedures were utilized in the EPA study. Additionally, the results in this study for the

highest load cycle are obscured by the differences in engine operation that were observed for the 50 mph cruise cycle.

- PM emissions showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. This is consistent with a majority of the previous studies of emissions from biodiesel blends. The PM reductions for both the soy-based and animal-based biodiesel blends were generally larger than those found in the EPA study, and are closer to the estimates for an base case fuel than a clean base fuel. Over the FTP, the PM reductions for the soy-based biodiesel ranged from 6% for a B5 blend, to 25% for a B20 blend, to 58% for B100. For the animal-based biodiesel over the FTP, the PM reductions ranged from 19% for the B20 blend to 64% for B100.

- For PM, the smallest reductions were seen for the UDDS, or the lightest loaded cycle. The PM reductions for biodiesel for the FTP and the cruise cycles were comparable for both fuels. Although there were some differences in the percent reductions seen for the soy-based and animal-based biodiesel fuels, there were no consistent differences in the PM reductions for these two feedstocks over the range of blend levels and cycles tested here.

- THC emissions showed consistent and significant reductions for the biodiesel blends, with the magnitude of the reductions increasing with blend level. The THC reductions over the FTP for the soy-based biodiesel ranged from 6% for a B10 blend, to 11% for a B20 blend, to 63% for B100. For the animal-based biodiesel over the FTP, the THC reductions ranged from 13% for the B20 blend to 71% for B100. Overall, the THC reductions seen in this study are consistent with and similar to those found by EPA. The THC reductions for both the soy-based and animal-based biodiesel blends for B100 were closer to those found in the EPA study for the B100 level for the base case fuels, while the lower blend levels (i.e., B20 and B50), were in between those estimated by EPA for the clean and base case fuels. For the soy-based biodiesel, the reductions are slightly less for the lower load UDDS, but for the animal-based biodiesel the THC reductions for all the test cycles were similar. There was not a strong trend in the THC reductions with biodiesel as a function of either power or fuel consumption.

- CO emissions showed consistent and significant reductions for the animal-based biodiesel blends, consistent with previous studies. Over the FTP, the THC reductions for the animal-based biodiesel ranged from 7% for a B5 blend, to 14% for a B20 blend, to 27% for B100. The CO reductions seen for the animal-based biodiesel are comparable to those seen for the EPA clean base fuel estimates, but are lower than those for the EPA base case.

- The CO trends for the soy-based biodiesel were less consistent. The CO emissions for the soy-based biodiesel did show consistent reductions with increasing biodiesel blend levels for the highest load, the 50 mph cruise cycle. For the FTP and 40 mph cruise cycles, the biodiesel blends did not show any strong trends relative to the CARB ULSD and a number of differences were not statistically significant. Interestingly, the CO emissions for the lowest load UDDS cycle showed higher emissions for the biodiesel blends, with the largest increase (62%) seen for the highest blend level. Additional testing would likely be needed to better understand the nature of these results, which are opposite the trends seen in most previous studies.

- Throughout the course of testing on the first engine some outliers were observed in the testing that appeared to be related to conditions set within the engine control module

(ECM). The first condition occurred when the temperature of the coolant water to the charge air cooler dropped below 68°F. These tests were removed from the subsequent analyses. A second condition was also observed where changes in engine operation were observed within the 50 mph CARB HHDDT cycle. For this test cycle, for a period of the test cycle from approximately 300 to 400 seconds, two distinct modes of operation were observed. These tests were not removed from the analysis, as it was surmised that these conditions could potentially occur in real-world operation.

- The biodiesel fuels showed a slight increase in CO_2 emissions for the higher blends. This increase ranged from about 1-4% with the increases being statistically significant for the B100 fuels for all of the tests, and for the B50 fuel for the cruise cycles and some of the other cycles.

- The biodiesel blends showed an increase in fuel consumption with increasing levels of biodiesel. This is consistent with expectations based on the lower energy density of the biodiesel. The fuel consumption differences were generally slightly higher for the soy-based biodiesel in comparison with the animal-based biodiesel. The increases in fuel consumption for the soy-based biodiesel blends range from 1.4 to 1.8% for the B20 to 6.8 to 9.8% for the B100. The increases in fuel consumption for the animal-based biodiesel blends range from no statistical difference to 2.6% for the B20 to 4.4 to 6.7% for the B100.

Renewable and GTL Diesel Fuels:

- For the renewable and GTL diesel fuels, the results show a steady decrease in NO_x emissions with increasingly higher levels of renewable diesel fuel. Over the FTP cycle, the NO_x reductions for the renewable and GTL diesel were comparable for each of the blend levels. For the FTP, the NO_x reductions for the renewable diesel ranged from 2.9% for the 20% blend to 9.9% for the 100% blend, while the NO_x reductions for the GTL ranged from ~1% for the 20% blend to 8.7% for the 100% blend. Larger emissions reductions were found over the UDDS and Cruise cycles, where only the renewable diesel fuel was tested. The reductions in NO_x for the renewable diesel fuel are comparable to those found in previous studies of heavy-duty engines.

- In comparison with the biodiesel feedstocks, the levels of NO_x reduction for the renewable and GTL fuels are less than the corresponding increases in NO_x seen for the soy-base biodiesel, but are more comparable to the increases seen for the animal-based biodiesel blends. With respect to NO_x mitigation, this suggests that the renewable and GTL diesel fuel levels need to be blended at slightly higher levels than the corresponding biodiesel in order to mitigate the associated NO_x increase, as discussed in further detail below. This is especially true for the soy-based biodiesel blends.

- PM emissions showed consistent and significant reductions for the renewable blends, with the magnitude of the reductions increasing with blend level. The reductions for the renewable diesel were statistically significant for the higher blends and ranged from 12-15% for the R50 and from 24-34% for the R100. A statistically significant 4% reduction was also found for the R20 over the FTP. The GTL fuel showed a statistically significant reduction over the FTP, with reductions ranging from 8% for the 20% blend to 29% for the 100% blend. Similar reductions are found for the UDDS, FTP, and Cruise cycles indicating that cycle load does not have a significant impact on the PM reductions.

- For the THC emissions, the GTL fuel showed statistically significant reductions over the FTP that increased with increasing blend level. These reductions ranged from 5% for the 20% blend to 28% for the 100% blend. The renewable diesel did not show consistent trends for THC emissions over the different test cycles. This finding was consistent with predictions based on the EPA's Unified Model and the associated distillation temperatures and other parameters of the fuels that showed there should not be any significant differences between the THC emissions for the CARB fuel in comparison with the renewable winter blend used in the study (Hodge, 2009). Statistically significant THC reductions were found for the renewable diesel fuel for the lowest load UDDS cycle, with the THC reductions increasing with increasing levels of the renewable diesel fuel.
- Reductions in CO emissions with the renewable diesel fuel were found for the UDDS and FTP cycles, but not for the cruise cycle. Over these cycles, the percentage reductions increased with increasing renewable diesel fuel blend. Over the FTP, these reductions ranged from 4% for the R20 to 12% for the R100. The comparisons of CO emissions over the 50 mph cruise may have been complicated by the changes in engine operation that were seen for that cycle. The GTL fuel also showed similar reductions over the FTP, with reductions ranging from 6% for the 20% blend to 14% for the 100% blend.
- The CO_2 emissions for the neat or 100% blend renewable and GTL fuels were lower than those for the CARB ULSD for each of the test cycles. The reduction was on the order of 2-4% for the 100% blends. This slight reduction in CO_2 emissions is consistent and comparable to previous studies of the renewable diesel fuel.
- The brake specific fuel consumption data showed increasing fuel consumption with increasing levels of renewable and GTL fuels. The increases in fuel consumption range from 1.0-1.4% for the R20 and 5.1 to 6.6% for the R100. The increases in fuel consumption with blend level are slightly higher for the cruise cycle compared to the lower load UDDS and FTP. The fuel consumption increases for the GTL ranged from 1.3% for the 20% blend to 3.3% for the 100% blend. The fuel consumption differences are consistent with the results from previous studies, and can be attributed to the lower density or energy density of the renewable and GTL fuels compared to the CARB baseline fuel.

NO_x Mitigation:

- The impact of biodiesel on NO_x emissions depends on the feedstock or fundamental properties of the biodiesel being blended. Blends of two biodiesels with different emissions impacts for NO_x provides a blend that shows a NO_x impact that is intermediate between the two primary biodiesel feedstocks. This indicates that the NO_x impact for a particular biodiesel feedstock can be mitigated in part by blending with another biodiesel feedstock with a lower tendency for increasing NO_x.
- Two additives were tested for NO_x mitigation, 2-EHN and DTBP. Of these two additives, the DTBP was the most effective in this testing configuration. A 1% DTBP additive blend was found to fully mitigate the NO_x impacts for a B20 and B10 soy biodiesel. The 2-EHN was tested at 1% level in both a B20-soy and B5-soy blend and did not show any significant NO_x reductions from the pure blends.
- The testing showed that renewable diesel fuels can be blended with biodiesel to mitigate the NO_x impact. This included higher levels of renewable diesel (R80 or R55) with a

B20-soy biodiesel. Several lower level blends, designed to be more comparable to those that could potentially be used to meet the low carbon fuel standard, also showed NO_x neutrality, including a CARB75/R20/B5-soy blend, a CARB80/R13/B3-soy/B4-animal blend, a CARB80/R15/B5-soy blend, and a CARB80/GTL15/B5-soy blend. Overall, the renewable and GTL diesels provide comparable levels of reductions for NO_x neutrality at the 15% blend level with a B5-soy.

- The level of renewable or GTL diesel fuels can be reduced if a biodiesel fuel with more favorable NO_x characteristics is used. This is demonstrated by the success of the CARB80/R13/B3-S/B4-A blend that combined both the soy and animal-based biodiesel. The use of an additive in conjunction with lower levels of renewable diesel and GTL can also be used to provide NO_x neutrality, as shown by the success of the CARB80/R10/B10-S 0.25% DTBP blend.

- The PM emissions for all of the NO_x mitigation formulations all showed reductions in PM for both the additive blends and the renewable blends. The largest reductions were found for the formulations with higher percentages of both biodiesel (B20) and the renewable diesel (55%-80%). Most of the other blends provided PM reductions that are slightly greater than those found for the corresponding B20 or lower soy biodiesel blends.

- THC emissions showed consistent reductions for most of the NO_x mitigation blends ranging from 3 to 21%. These reductions were highest for the blends with the B20 blend level. Generally, the blends of biodiesel with either a renewable diesel, a GTL diesel, or an additive showed THC reductions that were either higher than or equivalent to the levels found for the biodiesel by itself at a particular blend level.

- All formulations used for the NO_x mitigation showed reductions in CO compared to the CARB fuel ranging from 3 to 19%. The formulations with higher percentages of renewable diesel fuel (R80, R55, and GTL27) with B20 and those with additives all showed statistically significant reductions in CO emissions of 10% or greater.

- The NO_x mitigation formulations showed statistically significant changes in CO_2 for about half of the formulations tested. The statistically significant changes were all reductions in CO_2 that were 2% or less. This included some for the formulations with higher blends (55 and 80%) of renewable diesel. This is consistent with the CO_2 reductions seen for the higher blends of the renewable diesel and GTL fuels discussed above.

- The fuel consumption for the NO_x mitigations formations was either higher than or not statistically different from the CARB fuel. The increase in fuel consumption was highest for the fuels with the highest combined percentages of the renewable diesel and biodiesel. This is consistent with the fuel consumption increased seen for the higher blend levels of the biodiesel fuels, the renewable diesel, and the GTL diesel.

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Appendix A – Full Fuel Properties
Table A-1 CARB ULSD and Renewable Diesel D975 Specifications

	Units	Test Method	CARB ULSD	NExBTL	GTL
Sulfur Content	Mass ppm	D5453-93	3.3	0.3	0.9
Total Aromatic Content	mass%	D5186-96	18.6	0.4	0.5
PAH	mass%	D5186-96	1.6	0.1	<0.27
Nitrogen Content	Mass ppm	D4629-96	0.8	1.3	<1
Natural Cetane #	Rating	D613-94	56.9	72.3	>74.8
Cetane Index	Rating		57.4	76.9	76.3
Gravity, API	API @ 60°F	D287-82	39.0	51.3	48.4
Viscosity	Mm2/sec @ 40°C	D445-83	2.9	2.5	3.6
Flash Point	°C	D93-80	153	146	98.5
Distillation		D86-96			
ibp			337	326	419
10%	°F		408	426	482
50%	°F		526	521	568
90%	°F		615	547	648
ep	°F		661	568	673
Cloud point	°C	D2500	-13.7	-27.1	-1
Pour Point	°C	D-97	-17	-47	-6
Ash	Mass %	D-482	<0.001%	<0.001	<0.001
Ramsbottom Residue		D524	0.03	0.0	0.023
Water and Sediment	mL	D1796	< 0.02	< 0.02	< 0.02
Conductivity	pS/m	D2624	55	135	10
Corrosion	3 hr @ 50°C	D130	1b	1a	1a

Table A-2 Neat Biodiesel ASTM 6751 Specifications

		Test Method	Soy-based	Animal based
Calcium & Magnesium	5 max ppm (ug/g)	EN 14538	<2	<2
Flash Point	93 oC min	D93	169.3	164.3
Kin. Viscosity, 40 oC	1.9-6.0 mm2/sec	D445	4.2	4.41
Sulfate Ash	0.02 max % mass	D874	0.0	0.000%
Sulfur S15	0.0015 max % mass ppm	D5453	0.7	2
Copper Corrosion	No. 3 max	D130	1a	1a
Cetane number	47 min	D613	47.7	57.9
Cloud Point	Report oC	D2500	0	12.5
Carbon Residue	0.05 max % mass	D4530	0.033%	0.015%
Acid Number	0.50 max mg KOH/g	D664	0.20	0.26
Free Glycerin	.020 % mass	D6854	0.001%	0.008%
Total glycerin	.240 % mass	D6874	0.080%	0.069%
Phosphorous	0.001 max % mass	D4951	<0.001%	<0.001%
Distillation, T90 AET	360 oC max	D1160	350	347.5
Na/K, combined	5 max ppm (ug/g)	EN 14538	<2	<2
water and sediment		D2709	<0.01	<0.01
API Gravity		D1298/D287	29	28.5
Oxidation Stability	3 hour min (6 hr min1)	EN 14112	6.7	3.9
Visual Appearance*		D4176	1, 72F	1, 72F

*Free of un-dissolved water, sediment and suspended matter

Table A-3 Characteristics of Biodiesel Blends

		B5 - soy	B20 - soy	B50 - soy	B5 - animal	B20 - animal	B50 - animal
Flash Point, °C, min	ASTM D93	67.2	67.2	78.9	66.1	67.2	89.4
Water and sediment, vol%, max.	ASTM D2709 or D1796	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Physical Distillation, T90, °C, max	ASTM D86	624.1	635.1	641.1	627.5	633.6	637.4
Kinematic Viscosity, cST@40 °C	ASTM D445	2.828	2.969	3.384	2.855	3.038	3.508
Ash, mass%, max	ASTM D482	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Sulfur, ppm, max	ASTM D5453	3.2	2.5	2.2	3.8	3.7	3.8
Copper strip corrosion	ASTM D130	1B	1A	1B	1A	1A	1B
Cetane Number, min.	ASTM D613	56	55.4	56	58.4	59.8	59.7
Cloud point[2]	ASTM D2500	-16	-15	-1	-15	-14	2
Ramsbottom carbon residue 10% distill. residue, wt%, ma	STM D524	0.05	0.07	0.07	0.06	0.06	0.05
Acid number, mg KOH/g, max.	ASTM D664	<0.05	<0.05	0.07	<0.05	<0.05	0.11
Phosphorus, wt%, max.	ASTM D4951	<5	<5	<5	<5	<5	<5
FAME Content (IR)	EN 14078	5.3	20.8	52.5	5.4	21.2	52.8
Oxidation Stability, Induction time, hours min	EN14112 (Rancimat)	12	12	12	12	12	12

Table A-4 Characteristics of Renewable Diesel Blends

	TEST		R-20 Bio-Diesel	R-50 Bio-Diesel	GTL50
Sulfur	D5453	ppm	3.1	2.1	
Cetane Number	D613		59.3	65.0	61.5*
Total Aromatics	D5186	Mass%	15.2	10.2	
PolyArom		Mass%	1.2	0.9	
API_60F	D287	degAPI	41.7	45.1	
SPGr@60F	D4052s		0.82	0.80	
Copper	D130		1a	1a	
Wat_Sed1	D1796	ml	< 0.02	< 0.02	
Cloud Pt	D2500	Deg C	-15.0	-18.0	
EConduct	D2624	pS/m	23.3	38.3	
Temperat		deg C	21.1	21.1	
Viscosty	D445 40c	cSt	2.7	2.8	
Nitrogen	D4629	ppm	<1.0	<1.0	
Ash	D482	mass %	0.0	0.0	
RamsBottom	D524_10%	wt%	0.0	0.0	
IBP	D86	degF	345.0	337.2	
FBP		degF	656.5	637.7	
D10		degF	419.4	425.0	
D50		degF	521.7	523.3	
D90		degF	605.2	583.4	
Flash Point	D93	degF	153.3	145.7	
Pour Point	D97	Deg C	-18.0	-24.0	
Cetane Index	D976		60.0	66.3	

* 50% GTL blend with a CARB basefuel with a 46.7 cetane number

Appendix B – Development of the Light Load UDDS and CARB Heavy Heavy-Duty Diesel Truck Engine Dynamometer Test Cycles

Collection of Data on Engine Operating Parameters

The light load UDDS and the heavily loaded 40 mph CARB heavy heavy-duty diesel truck (HHDDT) cruise cycles were both developed from engine operating parameters. The engine operating parameters were obtained by operating the test vehicle with the specific engine installed on a chassis dynamometer while recording the J1939 signal from the engine ECM. This allowed the development on an engine dynamometer test cycle that had a direct correspondence to the loads the engine would experience when operated on a chassis dynamometer.

The 2006, 11 liter Cummins ISM was equipped in an International truck chassis. This truck had an empty weight of 13,200 lbs. and a fully loaded capacity of 66,000 lbs.

The chassis dynamometer test cycles were run at CARB's Heavy-Duty Vehicle Emissions Testing Laboratory in Los Angeles, CA. The vehicle was operated over the UDDS and 40 mph CARB cruise cycles while the J1939 signal was collected to obtained the engine parameters. The "light" UDDS was run with the truck loaded to its empty weight, without a trailer. For the 40 mph CARB cruise cycle, the truck was loaded on the dynamometer to its fully loaded capacity.

A total of at least 7 iterations were performed for each test cycle to obtain a sufficiently robust data set for the development of the engine dynamometer test cycles. During each test run, regulated and standard gas phase data were collected including NMHC, CO, NO_x, and CO_2.

The speed/time traces for the UDDS and the 40 mph CARB cruise cycle are provided below in Figures B-1 and B-2, respectively. Federal heavy-duty vehicle Urban Dynamometer Driving Schedule (UDDS) is a cycle commonly used to collect emissions data on engines already in heavy, heavy-duty diesel (HHD) trucks. This cycle covers a distance of 5.55 miles with an average speed of 18.8 mph and maximum speed of 58 mph.

The CARB Heavy Heavy-Duty Diesel Truck (HHDDT) 40 mph Cruise schedule is part of a four mode test cycle developed for chassis dynamometer testing by the California Air Resources Board with the cooperation of West Virginia University. This cycle covers a distance of 23.1 miles with an average speed of 39.9 mph and maximum speed of 59.3 mph.
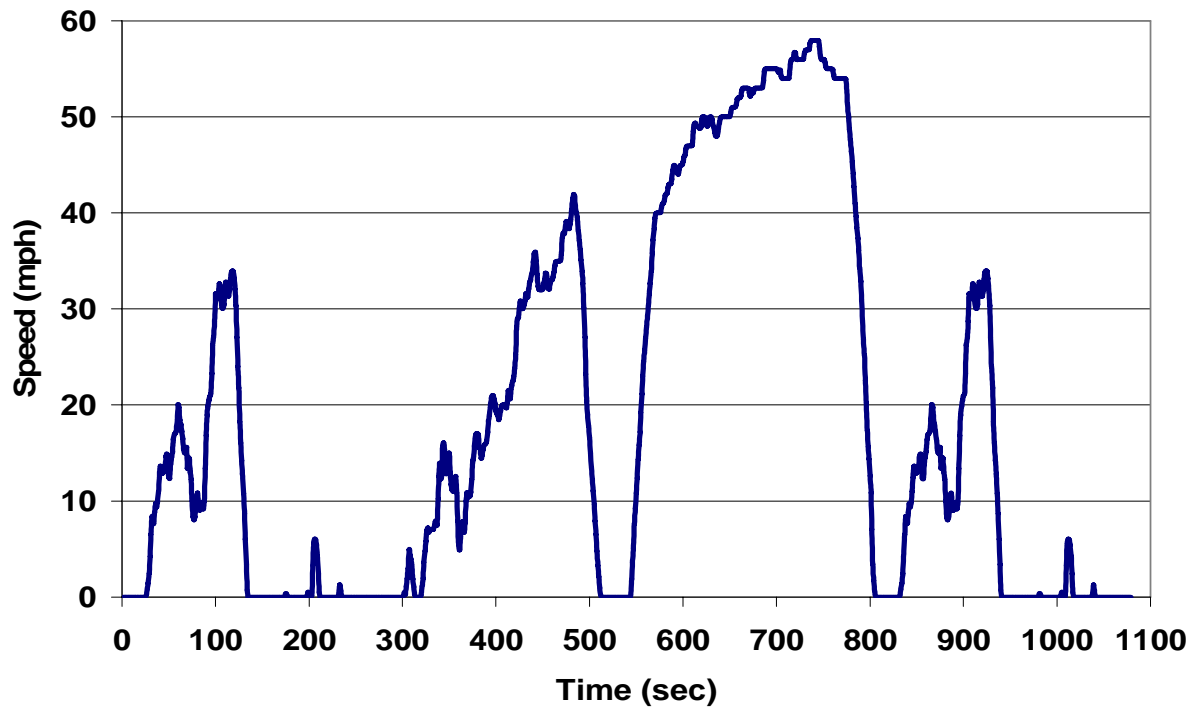
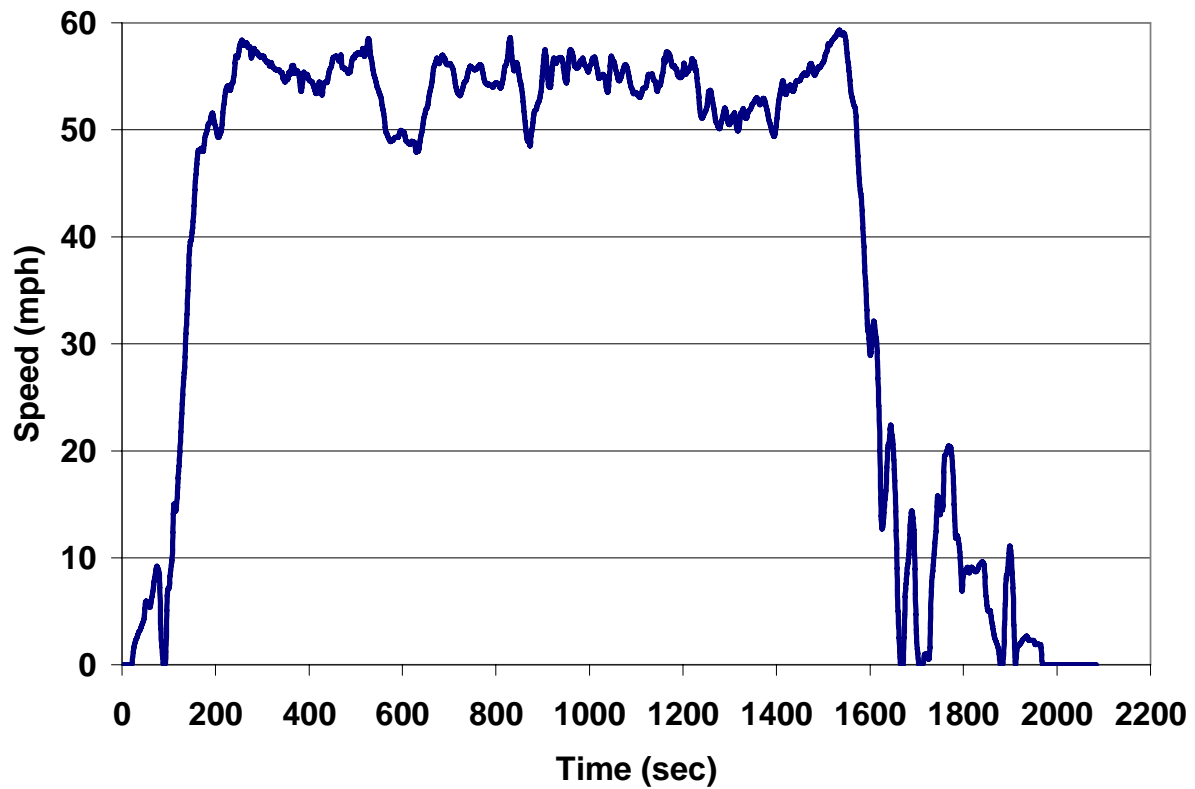**Figure B-1. Speed/Time Trace for UDDS cycle for the chassis dynamometer.**

Figure B-2. Speed/Time Trace for the 40 mph CARB Cruise cycle for the chassis dynamometer.

Initial Development of the Engine Dynamometer Test Cycles

The engine dynamometer cycles were developed from the engine speed and torque values from the J1939 data stream. Initially, the engine speed and torque were averaged over all of the test iterations. It was found that slight differences in time alignment between different test iterations resulted in differences in the exact location of the peaks in torque and engine speed. Specifically, the engine parameters would be near a peak in load for one cycle, while the loads for other test cycles would be lower at the same point. As such, the peaks in engine speed and torque could not be adequately represented with a cycle based solely on averaging.

It was decided instead to utilize a single test iteration that was determined to be most representative of the test run series on each cycle. Two main criteria were used in selecting the most representative set of engine parameters for the cycle development.

--- NO_x emissions for the corresponding chassis test set compared with the average value.
--- CO_2 emissions for the corresponding chassis test set compared with the average value.

Since NO_x is the most important parameter of interest for the engine dynamometer testing, engine parameter data sets where the NO_x emissions differed by more than one standard deviation from the mean value were excluded from consideration. From the remaining cycles, the cycle that was most representative of the average NO_x and CO_2 values was selected, with an emphasis on NO_x emissions that were comparable to the average value.

Once the most representative engine parameter data set was selected, the engine RPM and torque values were normalized to develop the engine cycle. The torque values were normalized from 0 to 100% for the maximum torque value based on the reference torque, the actual torque from the J1939 signal, and the frictional torque from the J1939 signal. Engine RPM was normalized from 0 to 100%, where 0 represents idle and 100% represents the maximum engine speed.

Testing and Final Development of Engine Dynamometer Test Cycles

The engine dynamometer test cycles were initially run on the dynamometer without any modification to evaluate how well the cycles could be followed on the engine dynamometer and to provide a comparison with the regression parameters currently used for the FTP. With these initial tests, the cruise cycle showed reasonable agreement between the torque and rpm set points, but the light-duty UDDS showed a greater deviation from the set points than is typically seen for the FTP. The cycle did not meet the regression criteria used for the standard FTP and visual comparisons showed that the measured torque did not follow the setpoint torque during segment of the cycle associated with gearshifts. In an effort to improve the performance of the cycle on the engine dynamometer, additional tests were conducted with varying settings of the dynamometer controls, such as throttle response.

These issues are similar to those identified in the development work for the cycles for the ACES program, and can be attributed to the use of a clutch in the actual vehicle that removes the inertia load from the engine during gear shifting. Since the engine driveshaft is directly coupled to the

dynamometer, this decoupling of the engine driveline cannot be simulated on the engine dynamometer. As such, these events were considered to be representative of the behavior that can be expected when translating engine parameters between a vehicle chassis and an engine dynamometer.

To improve the operation of the cycles on the engine dynamometer, the cycles were modified slightly after the initial runs. Specifically, the rpm and torque values were set to zero for a period of the cycle where the engine was in an idling segment. This eliminated small variations in rpm that occur near the idle point in real operation and small torque values that would likely be associated with auxiliary equipment when the engine was operating in the chassis. The normalized cycles in their final form are presented in Figures B-3 and B-4.
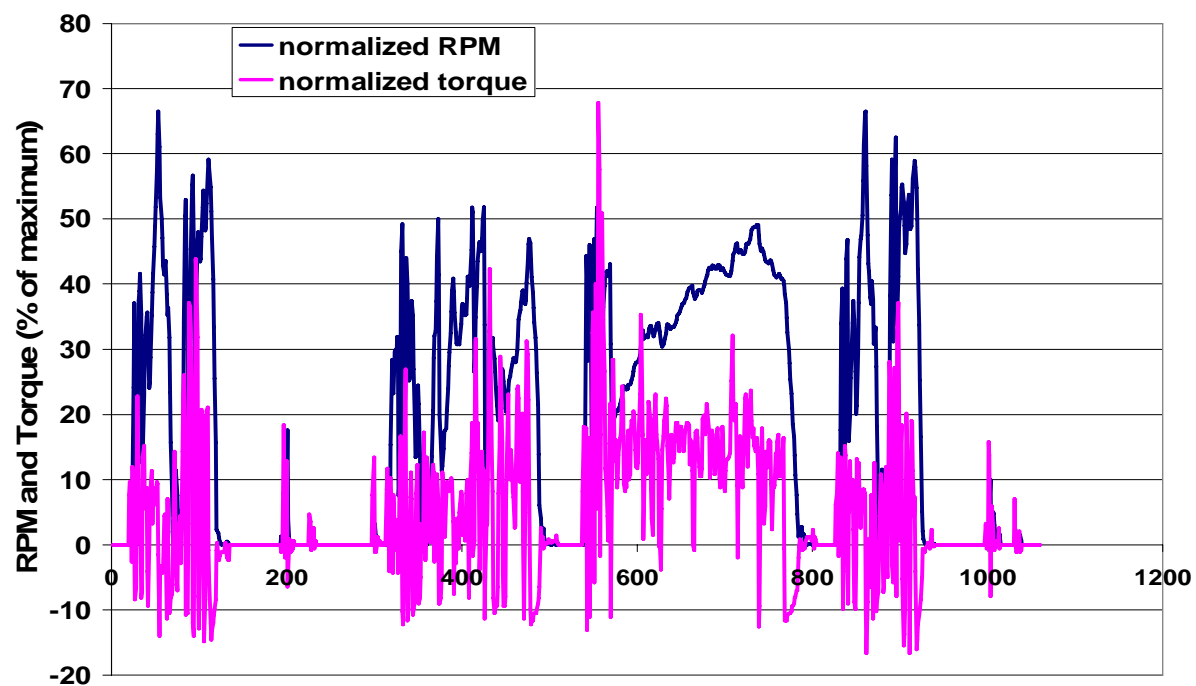
Figure B-3. "Light-Duty" UDDS Engine Dynamometer Test Cycle for the 2006 Cummins ISM
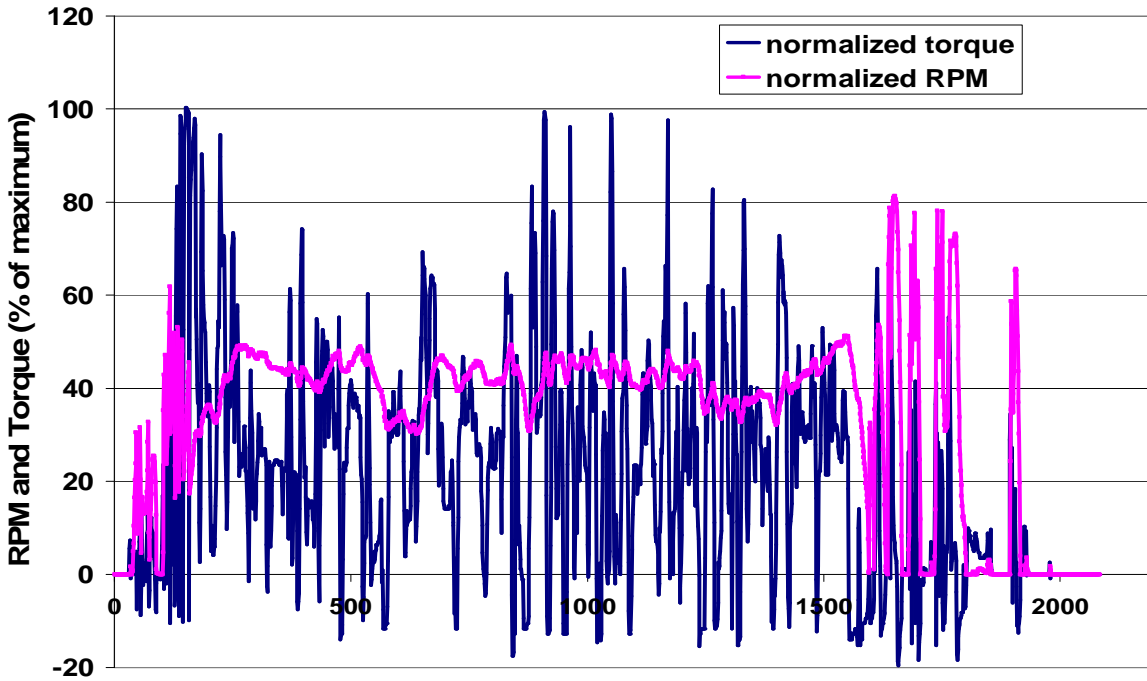
Figure B-4. 40 mph CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Cruise for the 2006 Cummins ISM

An engine dynamometer cycle based on the 50 mph CARB cruise cycle was also utilized for this program. The CARB Heavy Heavy-Duty Diesel Truck (HHDDT) 50 mph Cruise schedule was developed for chassis dynamometer testing by the California Air Resources Board with the cooperation of West Virginia University. This cycle covers a distance of 10.5 miles with an average speed of 48.9 mph and maximum speed of 66.9 mph. The speed/time trace for this cycle is provided in Figure B-5. This cycle was included to allow the biodiesel NO_x impact to be evaluated over a wider range of loads. Since the logistics of placing the engine back into the vehicle to generate the J1939 data for this specific engine were too impractical, an engine dynamometer test cycle version of this cycle that was developed for the ACES program was utilized (Clark et al., 2007). This cycle was developed from data collected through the E55/59 chassis dynamometer study of heavy-duty trucks. The engine rpm/torque profile for the 50 cruise engine dynamometer test cycle that was used is provided in Figure B-6.

Figure B-5. Speed/Time Trace for the 50 mph CARB Cruise chassis dynamometer cycle.

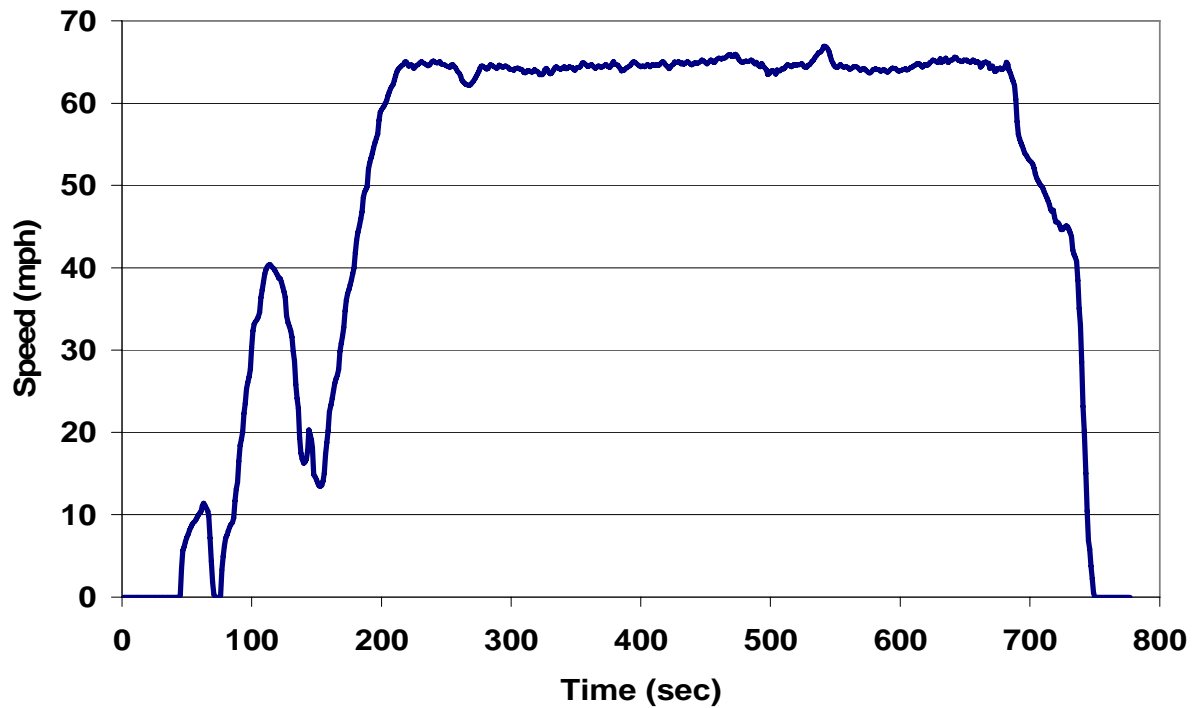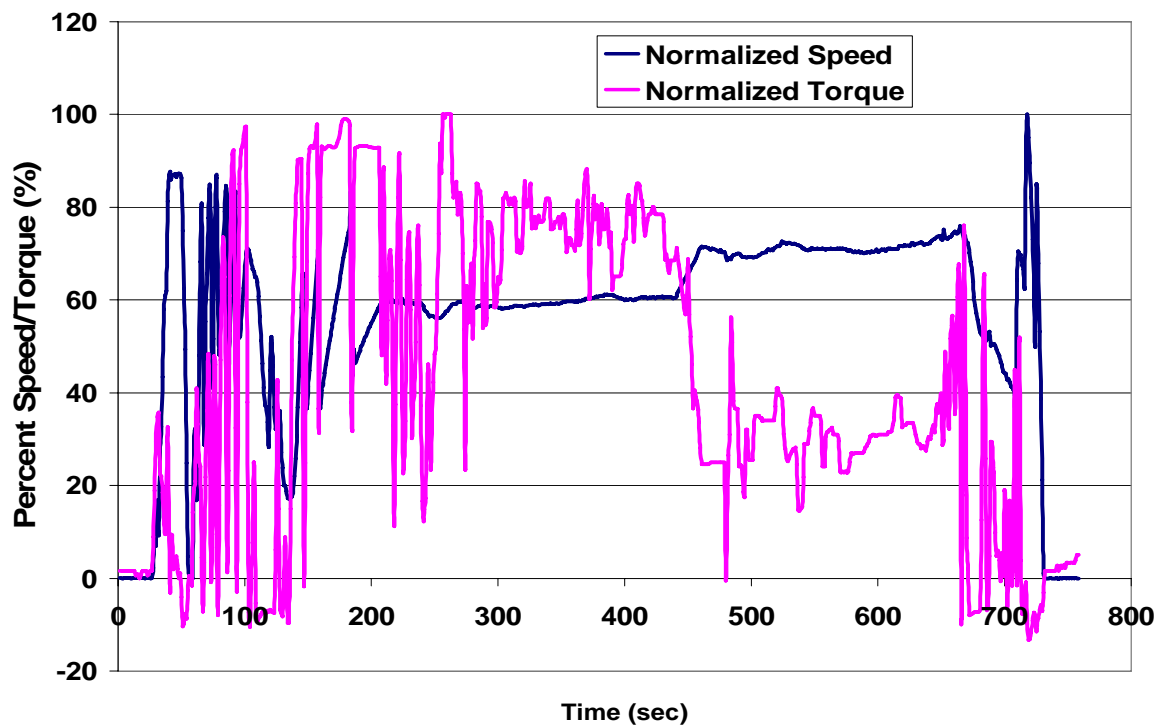**Figure B-6. 50 mph CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Cruise for the 2006 Cummins ISM**

Regression Statistics

Since the two developed cycles were inherently different from the FTP, new regression statistics were developed for each cycle. The new regression statistics were developed based on replicate runs of the cycles and comparisons between the regression runs for these cycles and those used for the FTP.

The techniques used for the development of the new regression statistics were similar to those used in the ACES program cycle development. The new regression statistics were scaled to comparable values for the FTP based on the tolerance, or how closely the parameter was met for the standard FTP. The equations utilized for these comparisons were the same as those utilized in the ACES programs, as provided below. In essence, these equations provide the same margin of error on a percentage basis for the new cycles, as is typically utilized in the FTP. These were utilized in cases where greater tolerance was needed for the statistics than is typically given in the FTP. In cases where the FTP regression statistics could be readily met without modification, the standard FTP criteria were maintained. In the case of the intercept for the power, examination of the data indicated that the power intercept was slightly greater than that for the FTP for the UDDS and cruise, but that the tolerance in this statistic could still be readily met by simply doubling the value of the intercept used in the FTP. A comparison of the FTP regression statistic criteria with the values obtained for the developed cycles is provided in Table B-1.

$$X_{upper} = \left(\frac{EPA_{upper} - FTP_{actual}}{FTP_{actual}} \right) \cdot actual + actual$$

$$X_{lower} = -\left(\frac{FTP_{actual} - EPA_{lower}}{FTP_{actual}} \right) \cdot actual + actual$$

		Speed				Torque				Power			
		Slope	Intercept	SteYX	Rsq	Slope	Intercept	SteYX	Rsq	Slope	Intercept	SteYX	Rsq
FTP	upper	1.03	50	100	1	1.03	15	188.5	1	1.03	5	30.95	1
	lower	0.97	-50	0	0.97	0.83	-15	0	0.88	0.89	-5	0	0.91
UDDS	upper	1.03	41.8	44.1	1.00	0.91	28.9	108.1	0.880	0.92	30.4	13.9	0.89
	lower	0.97	-41.8	0	0.97	0.74	-28.9	0	0.775	0.79	-30.4	0	0.81
Cruise	upper	1.03	-7.9	44.1	1.00	1.05	22.2	153.8	1.01	1.02	26.6	21.7	0.99
	lower	0.97	7.9	0.0	0.97	0.84	-22.2	0.0	0.89	0.88	-26.6	0.0	0.90

value doubled

Table B-1. Comparison of regression statistics criteria for the FTP with values obtained for the UDDS and Cruise. Shaded areas indicate criteria where the values were greater than those for the FTP and were modified for the regression criteria.

Appendix C – Background Information on UCR's Mobile Emission Lab

Extensive detail is provided in (Cocker, et al., 2004a,b) so this section is provided for those that may not have access to that reference. Basically the mobile emissions lab (MEL) consists of a number of operating systems that are typically found in a stationary lab. However the MEL lab is on wheels instead of concrete. A schematic of MEL and its major subsystems is shown in the figure below. Some description follows.

Diluted Exhaust: Temperature, Absolute Pressure, Throat ∆P, Flow.

GPS: Pat, Long, Elevation, # Satellite Precision.

CVS Turbine: 1000-4000 SCFM, Variable Dilution.

Secondary Probe.

Gas Sample Probe.

Secondary Dilution System*
PM (size, Mass).

Drivers Aid.

Gas Measurements: CO_2 %, O_2 %, CO ppm, NO_x ppm, THC ppm, CH_4 ppm.

Other Sensor: Dew Point, Ambient Temperature, Control room temperature, Ambient Baro, Trailer Speed (rpm), CVS Inlet Temperature.

Dilution Air: Temperature, Absolute Pressure, Throat ∆P, Baro (Ambient), Flow, Dew Point (Ambient).

Exhaust: Temperature, ∆P (Exhaust-Ambient), Flow.

Engine Broadcast: Intake Temperature, Coolant Temperature, Boost Pressure, Baro Pressure, Vehicle Speed (mph), Engine Speed (rpm), Throttle Position, Load (% of rated).

Major Systems within the Mobile Emission Lab

The primary dilution system is configured as a full-flow constant volume sampling (CVS) system with a smooth approach orifice (SAO) venturi and dynamic flow controller. The SAO venturi has the advantage of no moving parts and repeatable accuracy at high throughput with low-pressure drop. As opposed to traditional dilution tunnels with a positive displacement pump or a critical flow orifice, the SAO system with dynamic flow control eliminates the need for a heat exchanger. Tunnel flow rate is adjustable from1000 to 4000 scfm with accuracy of 0.5% of full scale. It is capable of total exhaust capture for engines up to 600 hp. Colorado Engineering Experiment Station Inc. initially calibrated the flow rate through both SAOs for the primary tunnel.

The mobile laboratory contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical instruments measure NO_x, methane (CH_4), total hydrocarbons (THC), CO, and CO_2 at a frequency of 10 Hz and were selected based on optimum response time and on road stability. The 200-L Tedlar bags are used to collect tunnel and dilution air samples over a complete test cycle. A total of eight bags are suspended in the MEL allowing four test cycles to

be performed between analyses. Filling of the bags is automated with Lab View 7.0 software (National Instruments, Austin, TX). A summary of the analytical instrumentation used, their ranges, and principles of operation is provided in the table below. Each modal analyzer is time-corrected for tunnel, sample line, and analyzer delay time.

Gas Component	Range	Monitoring Method
NO_x	10/30/100/300/1000 (ppm)	Chemiluminescence
CO	50/200/1000/3000 (ppm)	NDIR
CO_2	0.5/2/8/16 (%)	NDIR
THC	10/30/100/300/1000 & 5000 (ppmC)	Heated FID
CH4	10/30/100/300/1000 & 5000 (ppmC)	Heated FID

Summary of gas-phase instrumentation in MEL

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Appendix D – Quality Assurance/Quality Control

Internal calibration and verification procedures are performed regularly in accordance with the CFR. A partial summary of routine calibrations performed by the MEL as part of the data quality assurance/quality control program is listed in Table D-1. The MEL uses precision gas blending to obtain required calibration gas concentrations. Calibration gas cylinders, certified to 1 %, are obtained from Scott-Marrin Inc. (Riverside, CA). By using precision blending, the number of calibration gas cylinders in the lab was reduced to 5 and cylinders need to be replaced less frequently. The gas divider contains a series of mass flow controllers that are calibrated regularly with a Bios Flow Calibrator (Butler, New Jersey) and produces the required calibration gas concentrations within the required ±1.5 percent accuracy.

In addition to weekly propane recovery checks which yield >98% recovery, CO_2 recovery checks are also performed. A calibrated mass of CO_2 is injected into the primary dilution tunnel and is measured downstream by the CO_2 analyzer. These tests also yield >98% recovery. The results of each recovery check are all stored in an internal QA/QC graph that allows for the immediate identification of problems and/or sampling bias.

Table D-1. Summary of Routine Calibrations

EQUIPMENT	FREQUENCY	VERIFICATION PERFORMED	CALIBRATION PERFORMED
CVS	Daily	Differential Pressure	Electronic Cal
	Daily	Absolute Pressure	Electronic Cal
	Weekly	Propane Injection	
	Monthly	CO_2 Injection	
	Per Set-up	CVS Leak Check	
	Second by second	Back pressure tolerance ± 5 inH$_2$0	
Cal system MFCs	Annual	Primary Standard	MFCs: Drycal Bios Meter
	Monthly	Audit bottle check	
Analyzers	Pre/Post Test Daily Monthly	Zero span drifts Linearity Check	Zero Span
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	Trip Tunnel Banks	
	Monthly	Static and Dynamic Blanks	
Temperature	Daily	Psychrometer	Performed if verification fails
Barometric Pressure	Daily	Aneroid barometer ATIS	Performed if verification fails
Dewpoint Sensors	Daily	Psychrometer Chilled mirror	Performed if verification fails

Appendix E – Additional Information on the Outliers

The 50 mph CARB HHDDT cycles showed emissions at two distinct levels during the 300-400 second period of the cycle, as discussed in section 2.7. A summary table showing the number of tests exhibiting the low vs. the high level are shown in Table E-1.

Table E-1. Breakdown of 50 mph Cruise Cycle Tests for "High" vs. "Low" Tests.

	Low-level Tests	High-level Tests	Total Tests
CARB	10	22	32
B5-soy	3	3	6
B20-soy	5	1	6
B20-animal	6	0	6
R20-renewable	6	0	6
B50-soy	4	2	6
B50-animal	5	1	6
R50-renewable	6	0	6
B100-soy	2	4	6
B100-animal	5	1	6
R100-renewable	6	0	6
Totals	58	34	92

The impact of this event on emissions over the full cycle was characterized for each of the primary testing segments of the testing. The differences in the high/low emissions are summarized in Table E-2 for the CARB base fuel for the different testing segments. The primary impact in the regulated emissions was an increase in NO_x emissions, which ranged from 4.0 to 7.4% over the different test periods. The results also show that the fuel consumption and other regulated emissions such as THC, CO, and PM tend to be reduced for the tests with the corresponding higher NO_x emissions.

Table E-2. Impact of Outlier Events on Total Cruise Cycle Emissions for Each Test Period

Testing Segment	THC	CO	NO_x	PM	CO_2	BSFC
Soy-based	-1.4%	-6.8%	7.4%	-6.2%	-1.5%	-1.5%
Animal-based	-4.2%	-4.6%	5.4%	-4.3%	-2.4%	-1.9%
Renewable-based	-1.0%	-2.4%	4.0%	-1.5%	-0.7%	-0.7%

The percentages are the difference between all CARB tests with the high NO_x emissions and those with the low NO_x emissions

The changes in engine operation can be seen directly in the various engine parameters. The fuel consumption measurements show a reduction in fuel use over the 300-400 seconds segment for the tests showing NO_x at the high level. Figure E-1 shows various independent measures of the fuel used, including the fuel rate from the dynamometer, the ECM and the CO_2 emissions, all showing the differences in fuel use over the relevant period.