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Effects of Biodiesel Blends on Vehicle Emissions

Fiscal Year 2006 Annual Operating Plan Milestone 10.4

R.L. McCormick, A. Williams, J. Ireland,
M. Brimhall, and R.R. Hayes

Milestone Report
NREL/MP-540-40554
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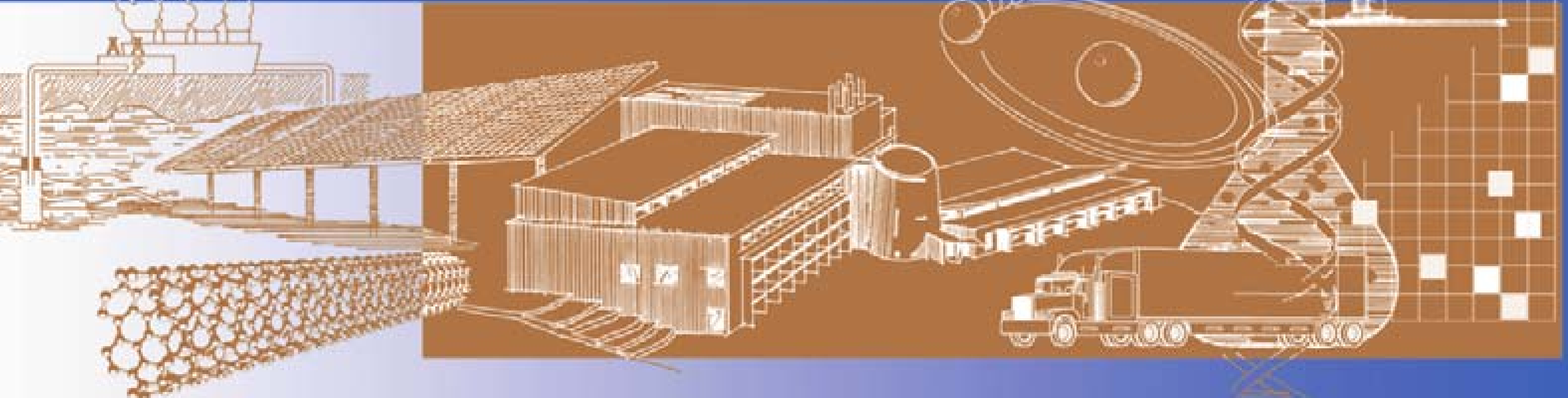

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Executive Summary

Biodiesel is a fuel-blending component produced from vegetable oils, animal fats, or waste grease by reaction with methanol or ethanol to produce methyl or ethyl esters. Pure biodiesel contains approximately 10 weight percent oxygen. It is typically blended with petroleum diesel at levels up to 20% (B20). The presence of oxygen in the fuel leads to a reduction in emissions of hydrocarbons (HC) and toxic compounds, carbon monoxide (CO), and particulate matter (PM) when biodiesel blends are burned in diesel engines. These reductions are robust and have been observed in numerous engine and vehicle testing studies. Engine dynamometer studies reviewed in a 2002 report from EPA show a 2% increase in oxides of nitrogen (NO_x) emissions for B20. This perceived small increase in NO_x is leading some state regulatory agencies to consider banning the use of biodiesel. Therefore, the issue of NO_x emissions is potentially a significant barrier to expansion of biodiesel markets.

The objective of this study was to determine if testing entire vehicles, vs. just the engines, on a heavy-duty chassis dynamometer provides a better, more realistic measurement of the impact of B20 on regulated pollutant emissions. This report also documents completion of the National Renewable Energy Laboratory's Fiscal Year 2006 Annual Operating Plan Milestone 10.4. This milestone supports the U.S. Department of Energy, Fuels Technologies Program Multiyear Program Plan Goal of identifying fuels that can displace 5% of petroleum diesel by 2010.

We reviewed more recently published engine testing studies (Table 3) and found an average change in NO_x for all recent B20 studies of -0.6%±2.0% (95% confidence intervals are used throughout this report). Restricting the average to recent studies of B20 with soy biodiesel yields an average NO_x impact of 0.1%±2.7%. The EPA review also includes summary of a smaller vehicle testing dataset that shows no significant impact of biodiesel on NO_x. We reviewed several recently published vehicle (chassis) testing studies (Tables 4 and 5) and found an average change in NO_x of 1.2%±2.9% for B20 from soy-derived biodiesel. In addition, we reviewed three portable emissions measurement system (PEMS) studies that do not find NO_x to increase.

Eight heavy-duty diesel vehicles were tested, including three transit buses, two school buses, two Class 8 trucks, and one motor coach. Four met the 1998 heavy-duty emissions requirement of 4 g/bhp-h NO_x and four met the 2004 limit of 2.5 g/bhp-h NO_x+HC. Driving cycles that simulate both urban and freeway driving were employed. Each vehicle was tested on a petroleum-derived diesel fuel and on a 20 volume percent blend of that fuel with soy-derived biodiesel. On average B20 caused PM and CO emissions to be reduced by 16% to 17% and HC emissions to be reduced by 12% relative to petroleum diesel. Emissions of these three pollutants nearly always went down, the exception being a vehicle equipped with a diesel particle filter that showed very low emissions of PM, CO, and HC; and there was no significant change in emissions for blending of B20. The NO_x impact of B20 varied with engine/vehicle technology and test cycle ranging from -5.8% to +6.2%. A preliminary examination of real-time NO_x emission data did not reveal any consistent reason for the wide range. On average NO_x emissions did not change (0.6%±1.8%). If the results of this study are combined with the soy B20 chassis results from Tables 4 and 5 (recently published studies), the average change in NO_x is 0.9%±1.5%, based on data for 15 vehicles.

Based on the studies reviewed and new data reported here, there does not appear to be a discrepancy between engine and chassis testing studies for the effect of B20 on NO_x emissions. Individual engines may show NO_x increasing or decreasing, but on average there appears to be no net effect, or at most a very small effect on the order of ±0.5%. The small apparent increase in NO_x reported for engine-testing results in EPA's 2002 review occurred because the dataset was not adequately representative of on-highway engines. In particular, nearly half of the NO_x observations included in the review were for engines from a single manufacturer (DDC). Newer engine and chassis studies, which on average show no B20 effect on NO_x, are not representative samples either. However, considering all of the data available, we conclude that B20 has no net impact on NO_x.

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Acronyms and Abbreviations

Bxx	biodiesel blend containing xx% biodiesel
CARB	California Air Resources Board
CFR	Code of Federal Regulations
CILCC	combined international local and commuter cycle
CO	carbon monoxide
CO_2	carbon dioxide
CSHVC	city-suburban heavy-vehicle cycle
CVS	constant volume sampling
DC	direct current
DDC	Detroit Diesel Corporation
DOC	diesel oxidation catalyst
DPF	diesel particle filter
EGR	exhaust gas recirculation
EPA	U.S. Environmental Protection Agency
FTP	federal test procedure
g/bhp-h	grams per brake horsepower-hour
g/cc	grams per cubic centimeter
HC	hydrocarbon
hp	horsepower
IDI	indirect injection
L	liter
lb	pounds mass
LSD	low-sulfur diesel (<500 ppm S)
mph	miles per hour
NO	nitric oxide
NO_x	oxides of nitrogen
NREL	National Renewable Energy Laboratory
O_2	oxygen
PEMS	portable emissions measurement system
PM	particulate matter
ppm	parts per million
REE	rapeseed ethyl ester
ReFUEL	Renewable Fuels and Lubricants Laboratory
RME	rapeseed methyl ester
RTD	Regional Transportation District
RUCSBC	Rowan University Composite School Bus Cycle
SME	soy methyl ester
TDI	turbocharged-direct injected
THC	total hydrocarbon (the same as HC in this study)
TxLED	Texas low emissions diesel
UDDS	urban dynamometer driving schedule
ULSD	ultra-low-sulfur diesel (<15 ppm S)
WVU	West Virginia University

Introduction

Biodiesel is a fuel-blending component produced from vegetable oils, animal fats, or waste grease by reaction with methanol or ethanol to produce methyl or ethyl esters (transesterification). In the United States, essentially all biodiesel is fatty acid methyl esters. Biodiesel production was 75 million gallons in 2005 and is expected to grow rapidly with market size, reaching 300 million gallons in 2006 [1]. Roughly 90% of the biodiesel produced in the United States today is made from soybean oil. An assessment of the resource available to produce biodiesel indicates that today there is adequate feedstock available to produce more than 1.7 billion gallons per year [2]. Life cycle analysis shows that for soy-derived biodiesel the energy available in the biodiesel product is more than three times the fossil energy used in its production [3].

Pure biodiesel contains approximately 10 weight percent oxygen. It is typically used as a blend with petroleum diesel at levels up to 20% (B20). The presence of oxygen in the fuel leads to a reduction in emissions of hydrocarbons (HC) and toxic compounds, carbon monoxide (CO), and particulate matter (PM) when biodiesel blends are burned in diesel engines [4]. These reductions are robust and have been observed in numerous engine and vehicle testing studies. Engine dynamometer studies conducted mainly in the 1990s have shown a small increase (2%) in oxides of nitrogen (NO_x) emissions for B20, and most studies of the impact of biodiesel on pollutant emissions have employed engine dynamometer tests. This perceived small increase in NO_x is leading some state regulatory agencies to consider banning the use of biodiesel. Therefore the issue of NO_x emissions is potentially a significant barrier to expansion of biodiesel markets. However, a 2% increase in NO_x is only slightly greater than the measurement repeatability of many heavy-duty test labs. Additionally, several engine testing studies have found no increase, or even a decrease in emissions of NO_x.

The objective of this study was to determine if testing entire vehicles on a heavy-duty chassis dynamometer provides a better, more realistic measurement of the impact of B20 on regulated pollutant emissions.

Background

Engine Dynamometer Studies

A number of studies have examined the emission impacts of biodiesel in 4-stroke, electronically controlled, turbocharged, direct injected diesel engines [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]. These studies as well as others using 2-stroke, indirect injection (IDI), and naturally aspirated engines have been reviewed by the U.S. Environmental Protection Agency (EPA) [16] and statistical analysis indicated the average emission changes for B20 shown in Table 1. Figure 1, taken from the EPA report, shows the overall trends with biodiesel blending level for all four regulated pollutants. The small increase in NO_x emissions for B20 listed in Table 1 is notable because a 2% change in NO_x is only slightly greater than the test repeatability (coefficient of variation) for NO_x measurements at the best test laboratories.

Table 1. Average Change in Emissions for B20 as Estimated from Published Engine Dynamometer Data in the EPA Study [16].

Pollutant	Percent Change
HC	-21.1
CO	-11.0
NO_x	+2.0
PM	-10.1

The results are derived from published data on 43 different engines of varying model year. These are grouped by emission standard or technology in Table 2. The dataset is dominated by 26 engines in the 1991 to 1993 group (5 g/bhp-h NO_x and 0.25 g/bhp-h PM) and the 1994 to 1997 group (5 g/bhp-h NO_x and 0.1 g/bhp-h PM). Fifteen out of the group of 26 engines were from a single manufacturer, Detroit Diesel Corporation (DDC). Fully 64% of the 546 NO_x observations for this model year range are for DDC engines, and these observations make up 44% of the total NO_x observations. Because of the high concentration of engines from a single manufacturer and in a limited range of model years, this group of engines cannot be considered to be representative of on-highway engines in the United States. Notably the dataset includes only two engines certified at 4 g/bhp-h NO_x and no engines in technology group B certified at 2.5 g/bhp-h NO_x+HC. This later group typically employs exhaust gas recirculation (EGR) to obtain lower NO_x levels. The majority of the engines were on-highway heavy-duty engines and were tested over the heavy-duty federal test procedure (FTP) or multimode steady-state cycles.

Figures 2 and 3 show the NO_x and PM emission curves, respectively, as a function of biodiesel blend content, along with the individual data points. Examining the B20 results, a wide range of -60% to +5% is observed for PM; however, PM emissions increased in only one test. A wide range is also observed for NO_x emissions with percentage change ranging from roughly -7% to +7%.

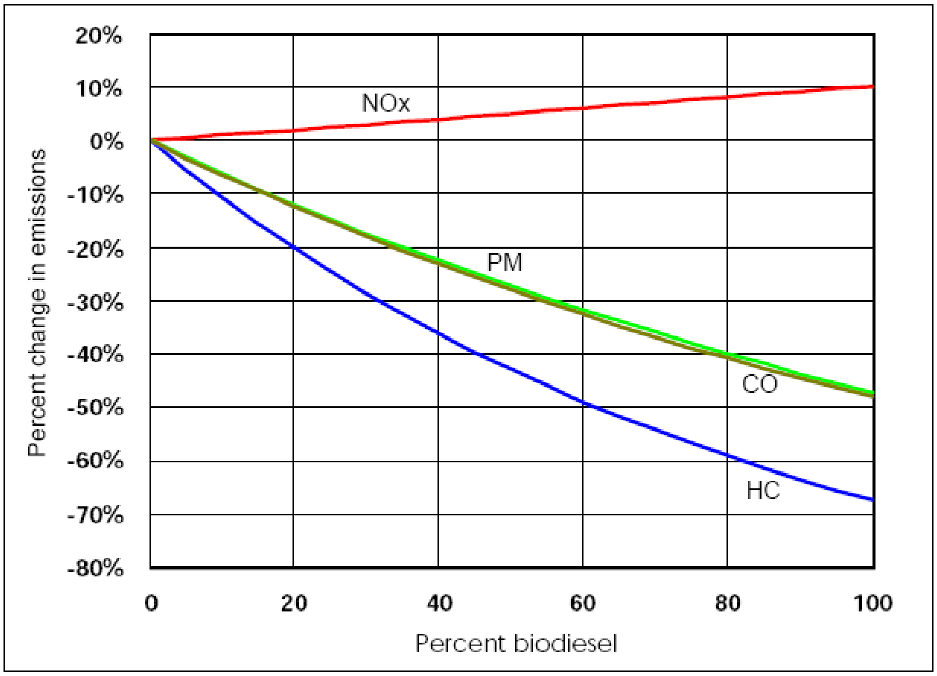

Figure 1. Trends in percentage change in pollutant emissions with biodiesel content as estimated from published engine dynamometer data in the EPA study [16].

Table 2. Number of Engines and NO_x Emissions Observations for the Data Reviewed by EPA [16].

Standards group	Model years	HD highway engines	NOx observations
B	2002 - 2006	0	0
C	1998 - 2001	2	14 (2)[α]
D	1994 - 1997	10	152 (19)
E	1991 - 1993	16	394 (50)
F	1990	3	87 (11)
G	1988 - 1989	8	112 (14)
H	1984 - 1987	2	16 (2)
I	- 1983	2	10 (1)

[α] Values in parentheses are percent of total observations

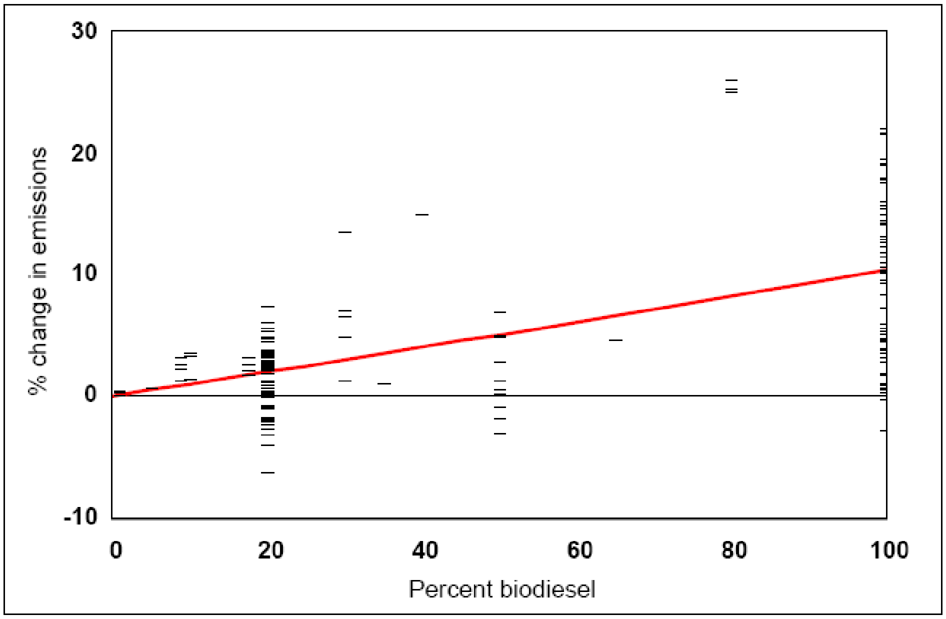

Figure 2. Percent change in NO_x emissions for the engine dynamometer data reviewed by EPA [16].

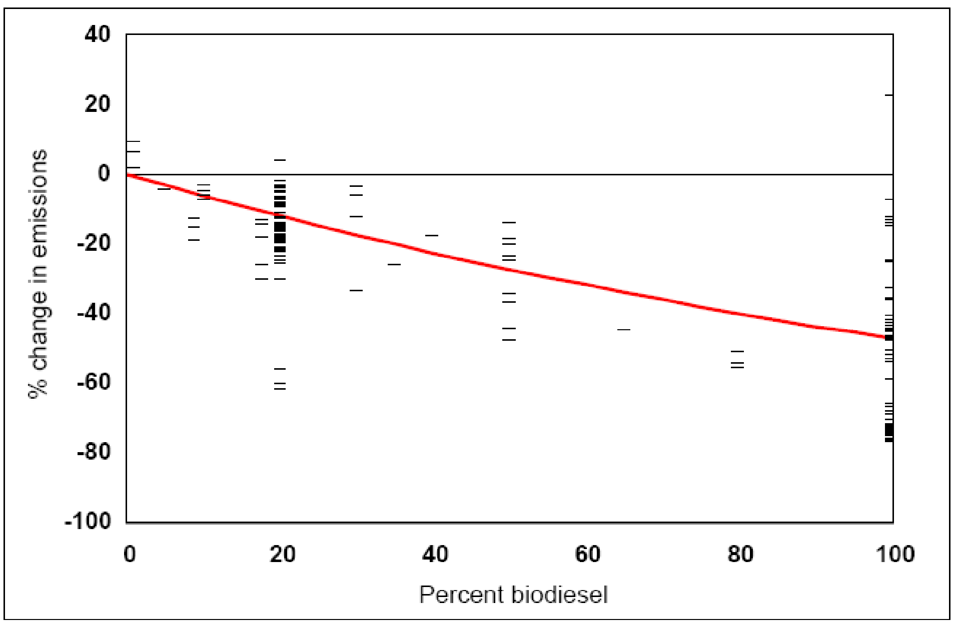

Figure 3. Percent change in PM emissions for the engine dynamometer data reviewed by EPA [16].

Additional engine testing studies have been published since the release of the EPA review. McGill and coworkers tested two heavy-duty engines (4- to 5-g/bhp-h NO_x emission range) [17]. Additional details for a Euro 2 Volvo 9.6-L engine are given in reference 18. NO_x emissions were unchanged for a 5-g/bhp-h NO_x Navistar 7.3-L engine (B100) but increased for a Euro 2 Volvo engine on B30. Frank and coworkers tested a 4-g/bhp-h NO_x International DT466 and observed NO_x to decrease significantly for B20 when configured with DOC, no change when configured with DPF, and to increase slightly when configured with EGR and DPF [19]. A second study tested two 4-g/bhp-h NO_x Cummins engines and found statistically significant reductions in NO_x for B20 in some tests, and small increases in NO_x in others [20]. Notably, the NO_x reductions were observed for biodiesel from more saturated feedstocks, in agreement with previous studies [4]. Researchers at Penn State University tested a 4-g/bhp-h NO_x Cummins engine and observed a 3% reduction in NO_x for a low sulfur base fuel and no change for an ultra-low sulfur base fuel [21]. Results for two engines meeting the 2.5-g/bhp-h NO_x+HC level have also been reported, with NO_x found to increase by 3 to 6% [22]. Environment Canada has reported testing of a 1998 Caterpillar 3126E with no change in NO_x [23].

The percent change in emissions for these studies relative to the base petroleum fuel is listed in Table 3. The average change in NO_x for all B20 studies reported in this table is -0.6%±2.0% (95% confidence interval). Restricting the average to studies of B20 with soy biodiesel only yields an average NO_x impact of 0.1%±2.7%. Clearly recent engine testing studies continue to see NO_x emission results that vary widely and appear to depend upon engine manufacturer or engine design. The average PM emission change for all B20 studies reported in the table is -14.1%, excluding the two DPF points the PM reduction was 16.4%.

Table 3. Summary of Percent Change in Emissions for Recent Engine Dynamometer Studies of Biodiesel.

Reference	Engine	Cycle	%Biodiesel	NO_x	HC	CO	PM
17	Navistar 7.3-L (5 g/bhp-h NO_x)	AVL 8-Mode	100 (RME)	≈0	--	--	≈-20%
18	Volvo 9.6-L (Euro 2)	ECE R49	30 (RME)	1.7	0	-9.4	-24
19	International DT466 (4 g/bhp-h NO_x with DOC)	Hot FTP	20 (SME)	-10.3	-20	-38	-2.9
	-with DPF		20 (SME)	0	≈0	≈0	≈0
	-with EGR and DPF		20 (SME)	1.8	≈0	≈0	≈0
20	Cummins 8.3-L (4 g/bhp-h NO_x Mech)	Hot FTP	20 (SME)	1.1	-12	-25	-31
			20 (Waste Grease)	0.3	-7.0	-25	-20
			20 (Animal Fat)	-1.5	-13	-17	-22
	Cummins 8.3-L (4 g/bhp-h NO_x Elec)	Hot FTP	20 (SME)	1.7	-21	-28	-17
			20 (Waste Grease)	-4.5	-25	-31	-14
			20 (Animal Fat)	-2.9	-30	-25	-7.8
21	Cummins 5.9-L (4 g/bhp-h NO_x)	AVL 8-Mode	20 (SME, 325 ppm S Base)	0	--	--	-27
			20 (SME, 15 ppm S Base)	-3	--	--	-6
22	Cummins 5.9-L (2.5 g/bhp-h NO_x)	Hot FTP	20 (SME)	3.6	-4.2	-10.5	-22
	DDC S60 (4 g/bhp-h NO_x)	Hot FTP	20 (SME)	6.0	0	0	-26
23	Caterpillar 3126E (4 g/bhp-h NO_x)	Hot FTP	20 (SME)	0	-16	-6.7	-1.1

Vehicle Testing Studies

EPA's review [16] also included a summary of chassis dynamometer vehicle testing studies. The studies reviewed included data for three transit buses and eight pickup trucks and the data for percent change in NO_x emissions are shown in Figure 4. While a fitted trend line shows a negative slope (i.e., NO_x emissions being reduced as biodiesel is blended with diesel fuel), the slope of this line is not significantly different from zero ($p \approx 0.5$), thus for these vehicles blending of biodiesel had no impact on NO_x.

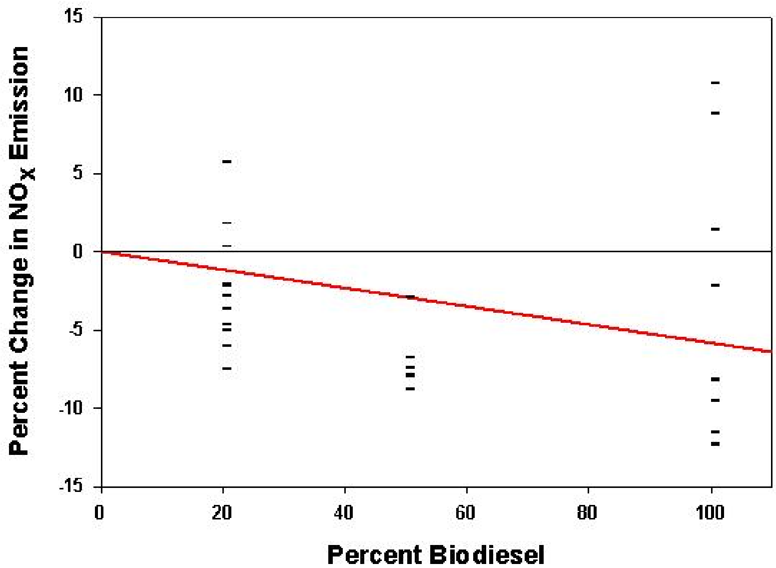

Figure 4. Summary of NO_x impact of biodiesel blending from chassis dynamometer studies reviewed by EPA [16].

A number of chassis studies have been published since the publication of EPA's review, or were not included in that review. Careful review of the data in these publications reveals large variation in data quality, with some studies exhibiting extremely poor repeatability (likely because an inadequate number of control tests were conducted), or basing conclusions on only one or two replicate tests. Application of strict quality criteria, and rejection of studies that do not meet them, is required for any discussion of chassis testing data.

Data from many of these studies are shown in Table 4. Clark and Lyons reported testing eight Class 8 tractors, ranging in model year from 1989 to 1994 on conventional diesel and B35 [24]. NO_x emissions over the WVU 5-peak cycle decreased for two vehicles, increased for five vehicles and were unchanged for one vehicle. A second report from the same research group includes testing of additional vehicles and suggests that NO_x emissions decrease for vehicles with early 1990s DDC engines, but increase for late 1980s Cummins engines [25]. However, no individual vehicle results are reported in this study, and it is not clear if intake air humidity was controlled or measured in these tests, hence they are not considered further. Petersen and coworkers report test results for a Dodge pickup equipped with a 1994 Cummins B5.9 [26] (it is not clear if these results were included in EPA's review). Biodiesel from several different sources was tested and reductions in NO_x were observed in all cases for B20 blends. Three replicate tests were run only for the B20 produced from rapeseed ethyl ester (REE), which produced a 3.1% decrease in NO_x. Durbin and coworkers present light-duty FTP results for testing B20 in seven light heavy-duty diesel vehicles with model year ranging from 1983 to 1993 [27]. However, this study is based on only two replicate runs with inadequate controls and thus will not be considered further. Finnish researchers reported testing an Audi turbocharged direct injected (TDI) vehicle on the light-duty FTP with B30 and adequate replication and controls. They observed no significant change in NO_x [18]. Environment Canada tested three heavy-duty trucks on B20 and showed that NO_x could go up or down depending on engine design [28]. Most recently Holden and coworkers have presented a significant study of on- and off-highway nontactical vehicles used at military bases [29]. All vehicles were tested multiple times with California Air Resources Board (CARB) diesel base fuel tests at regular intervals. For the study results taken as a whole, and taking into account only changes in emissions that are significant at 90% confidence or better, there was no significant impact of B20 on NO_x. Results from this study are shown in Table 5. The results in Tables 4 and 5 for soy-derived B20 show an average change in NO_x of 1.2%±2.9% (95% confidence interval). Both the chassis studies reviewed by EPA and the more recent studies described here are showing no significant impact of B20 on NO_x.

Table 4. Summary of Percent Change in Emissions from Recent Vehicle Testing Studies of Biodiesel.

Reference	Engine	Cycle	%Biodiesel	NO_x	HC	CO	PM
26	1994 Cummins ISB	UDDS	20 (REE)	-3.1	-36	-37	-12
18	Audi TDI	FTP75	30 (RME)	0	-13	5.5	-22
28	2003 Cummins ISM	UDDS	20 (SME)	-3.1	-8.2	-16	-20
		WVU 5 Pk	20 (SME)	-2.5	-23	-19	12
	2004 MBE4000	UDDS	20 (SME)	14	-23	-19	-20
	1999 Caterpillar C12	UDDS	20 (SME)	3	-21	-17	-27
		WVU 5 Pk	20 (SME)	1.5	-21	-7.6	-2.9

Another approach to vehicle testing is the use of portable emissions measurement systems (PEMS). These are systems that reside on board the vehicle during normal operation or operation on a test track, and measure concentrations of pollutants in the raw exhaust. EPA will use PEMS to assess in-use compliance of heavy-duty vehicles with emission standards beginning in the 2007 model year [30]. Several measurements of the impact of B20 on emissions have been conducted using PEMS. Frey and Kim reported on testing 12 Department of Transportation dump trucks during their normal operation in North Carolina [31]. These included engines from four manufacturers and model years from 1998 to 2004. The study measured HC, CO, and NO emissions, but not NO_x emissions, such that emissions of NO_2 are not included. On average, emissions of all measured pollutants decreased, with both NO and PM emissions declining by 10%. This strongly implies that NO_x emissions also decreased because it has been shown that the cycle average NO_2/NO_x ratio does not change for B20 [23]. Researchers at Rowan University tested three school buses on a test track with emissions measurement by PEMS using a highly aggressive driving cycle developed from bus activity data [32]. The school buses included a 1996 Cummins B-series engine and two 1997 International engines. NO_x emissions went up slightly for two buses and down slightly for the third. Researchers at the Texas Transportation Institute tested five school buses selected to be representative of the school bus fleet in Texas, on a test track using cycles derived from bus activity data and emissions measurement by PEMS [33]. All were equipped with in-line, 6-cylinder International engines ranging in model year from 1987 to 2004. The tests used Texas low emissions diesel (TxLED) as the base fuel (a low aromatic, high cetane number fuel), biodiesel derived from soy, and a market average biodiesel blend (compositional details were not specified). Changes in NO_x emissions were small and not statistically significant.

Table 5. Summary of Percent Change in Emission Results from U.S. Navy Study of B20 Emission Impacts [29].

Vehicle	Cycle		YGA - B20				Soy - B20				YGB - B20			
			HC	CO	NOx	PM	HC	CO	NOx	PM	HC	CO	NOx	PM
F350	FTP	% change	-19%	-8%	0%	-15%								
		p-value	0.15	0.03	0.65	0.21								
	US06	% change	-18%	-3%	24%	-13%								
		p-value	0.31	0.53	0.32	NA								
Model A2 Humvee	FTP	% change	93%	17%	1%	0%	113%	26%	-1%	-9%				
		p-value	0.17	0.06	0.48	0.99	0.06	0.04	0.61	0.05				
	US06	% change	2%	19%	2%	-44%	3%	44%	-1%	-57%				
		p-value	0.91	0.01	0.01	0.32	0.88	0.01	0.09	0.23				
F700	AVL 8-mode	% change					4.8%	2.7%	3.2%	5.6%	0.4%	-2.1%	-0.9%	8.4%
		p-value					0.14	0.33	0.14	0.90	0.96	0.63	0.40	0.81
F9000	AVL 8-mode	% change	3.2%	-6.7%	11.7%	-19.4%					-9.5%	-13.5%	8.6%	-35.5%
		p-value	0.72	0.01	0.16	0.05					0.21	0.02	0.22	0.04
Camp Pendleton Bus	AVL 8-mode	% change	1.3%	-6.8%	-0.4%	-10.8%	13.3%	-6.7%	-3.7%					
		p-value	0.96	0.29	0.91	0.28	0.62	0.20	0.29					
250 kW Generator	5 -mode	% change	-6.6%	5.8%	2.3%	17.1%								
		p-value	0.20	0.25	0.21	0.48								
60 kW Generator	5-mode	% change	6.3%	13.0%	8.2%	10.9%								
		p-value	0.69	0.41	0.40	0.57								
Cheyenne Mountain Bus – UCR	Custom	% change					-22.0%	-17%	3.0%	-29%				
		p-value					0.18	0.01	0.12	0.00				
Cheyenne Mountain Bus- NREL	Custom	% change					-11.2%	-1.3%	0.2%	-8.4%				
		p-value					0.00	0.87	0.81	0.39				
Aircraft tow	In-use	% change	9%	-18%	-1%									
		p-value	0.91	0.31	0.83									
Forklift	In-use	% change					-10%	20%	-8%					
		p-value					**	**	**					
Model A1 Humvee	In-use	% change	NA	5%	6%									
		p-value	**	**	**									

Comparison of Engine and Vehicle Test Results

The results in EPA's 2002 compilation of published studies suggested a discrepancy between engine and vehicle tests for B20. In particular, engine tests as reviewed by EPA indicate a 2% increase in NO_x emissions for B20 while vehicle tests on average tend to indicate a smaller or even zero increase. However, a close examination of the data included in the review reveals that results are dominated by engines from a single manufacturer with a very limited range of model years. Nearly half of the observations (44%) were for DDC engines in the 1991to 1997 model year range, and a large majority of these are for the Series 60 model. Engine manufacturers certified more than 700 heavy-duty engine families and 5,000 engine models in 2006 alone [34], although not all of these were on-highway or diesel engines. In 2002 there were more than 5 million medium, light-heavy, and heavy-heavy duty trucks registered in the United States [35], and roughly 50% were 10 years old or older. These vehicles typically stay on the road for 15 years or longer. We believe that EPA's conclusion of a NO_x increase is influenced by the unrepresentative composition of the engine dataset. A hallmark of the B20 emission test results is that NO_x is highly variable, with percentage change ranging from roughly -7% to +7%. Data for the DDC Series 60 engine, which typically exhibits a small NO_x increase for B20, makes up a large fraction of the data reviewed. Therefore, EPA draws a conclusion that is at odds with the results of the more recent studies reviewed here.

An examination of all of the published data suggests that there is no discrepancy between engine and vehicle testing and that for B20 on average there is no net impact on NO_x. However, the reasons for the variability in NO_x with engine model are not understood and are worthy of further study. It is possible that the variation is caused by differences in how engine fuel injection systems and electronic controls respond to the lower energy content or other properties of B20.

Fundamental Studies of Biodiesel and NO_x Emissions

A combustion analysis study of biodiesel and biodiesel blends concluded that biodiesel blends had a shorter ignition delay than diesel alone, at both full and light load, and a lower premixed burn fraction at full load. However, diffusion burn rates were similar [36]. The shorter ignition delay, caused by biodiesel's higher cetane number, has been suggested as being the cause of the NO_x increase observed in many studies because the advanced combustion timing increases peak pressure and temperature. However, this is inconsistent with EPA's review of cetane number effects, which shows decreasing NO_x for increasing cetane number [37], although benefits are less for newer engines with more highly retarded injection timing. Use of cetane enhancing additives has been shown to reduce NO_x for B20 in older, more cetane-sensitive engines [15].

A number of other hypotheses on the cause of the increase in NO_x observed for biodiesel under some engine operating conditions have been advanced. Increasing NO_x may be caused by an increase in flame temperature in either premixed or diffusion burn, which is caused by reduction in the concentration of carbonaceous soot – a highly effective heat radiator. The net result of the PM reduction caused by supplying oxygen to the fuel rich zone of the diffusion flame may be to increase flame temperature because of this loss of radiant heat transfer [10]. This hypothesis has been investigated by Cheng and coworkers using an optically accessible engine and fuels with identical ignition delay [38]. NO_x emissions were higher for B100, even with matched ignition delay, especially at lower loads. Flame luminosity measurement suggested less radiation from the B100 flame, particularly under light load conditions where NO_x was shown to increase.

The double bonds present in biodiesel may cause a higher adiabatic flame temperature, and hence a higher temperature at the flame front in the diffusion flame. This hypothesis is consistent with results showing higher levels of NO_x emissions for biodiesel from more highly unsaturated feedstocks [14]. Cheng and coworkers present results of equilibrium calculations that refute this hypothesis [38]. However, Ban-Weiss and coworkers performed calculations of adiabatic flame temperature based on chemical kinetic models that suggest a significant impact of unsaturation [39].

A second fuel chemistry effect might be enhancement of the formation of prompt (or Fenimore) NO, which can account for up to 30% of NO_x formation [40]. Prompt NO is formed by reaction of radical HC species with nitrogen, ultimately leading to formation of NO. Hess and coworkers noted that unsaturated compounds may form higher levels of radicals during pyrolysis and combustion, and investigated the potential of radical scavenging antioxidant additives for NO_x reduction [41]. Some, but not all, antioxidants were shown to reduce NO_x emissions for their engine.

Van Gerpen and collaborators have shown that NO_x can increase as a result of a shift in fuel injection timing caused by different mechanical properties of biodiesel [42, 43]. Biodiesel has a higher bulk modulus of compressibility (or speed of sound) than petroleum diesel and this was proposed to cause a more rapid transfer of the fuel pump pressure wave to the injector needle. This caused earlier needle lift and a small advance in injection timing that was proposed to account for a fraction of the NO_x increase observed under some conditions. Sybist and Boehman also examined this effect [44]. They found that soy B100 produces a 1° advance in injection timing and a nearly 4° advance in the start of combustion. The bulk modulus effect appears to be applicable to pump-line nozzle and unit injection systems, but not for high-pressure common rail systems where "rapid transfer of a pressure wave" does not occur.

A number of more speculative hypotheses have been proposed. For example, reduction of the soot concentration in the flame may eliminate NO-carbon reactions. The importance of NO-carbon reactions in diesel combustion is unknown. Also, biodiesel has been shown to alter injection duration, spray properties, and other aspects of spray fluid flow [44]. The impact of these phenomena on NO_x emissions in this context is uncertain.

These studies indicate that there may be more than one factor contributing to the effect of biodiesel on NO_x. Furthermore, which factor is dominant may change with engine speed and load or with certain engine design parameters. Given the results of chassis and engine tests reviewed in previous sections, fundamental studies of biodiesel's impact on NO_x may be most relevant to B100, where it seems clear that an increase in NO_x occurs in most cases. Additional study is required to quantitatively understand the underlying factors causing biodiesel's impact on NO_x. Future studies should include a comparison of results from engine operating conditions where NO_x increases and where it does not.

Methodology

Vehicle Emissions Test Lab

All testing was conducted on a heavy-duty chassis dynamometer at NREL's ReFUEL test facility. The chassis dynamometer test facility includes analytical equipment for emissions and fuel economy measurements of on-road heavy-duty diesel vehicles. All emissions measurements are conducted in accordance with the Code of Federal Regulations (CFR), title 40, part 86, subpart N.

Chassis Dynamometer

The chassis dynamometer, as illustrated in Figure 5, is composed of three major components: the rolls – which are in direct contact with the vehicle tires during testing, the direct current (DC) electric motor (380 hp absorbing/360 hp motoring) dynamometer, and the flywheels. The DC electric motor and flywheels are installed in a pit below the ground level, such that the only exposed part of the dynamometer is the top of the 40–inch-diameter rolls. Two sets of rolls are installed, so that twin-axle vehicles can be tested. The dynamometer can simulate up to 80,000-lb vehicles at speeds up to 60 mph.

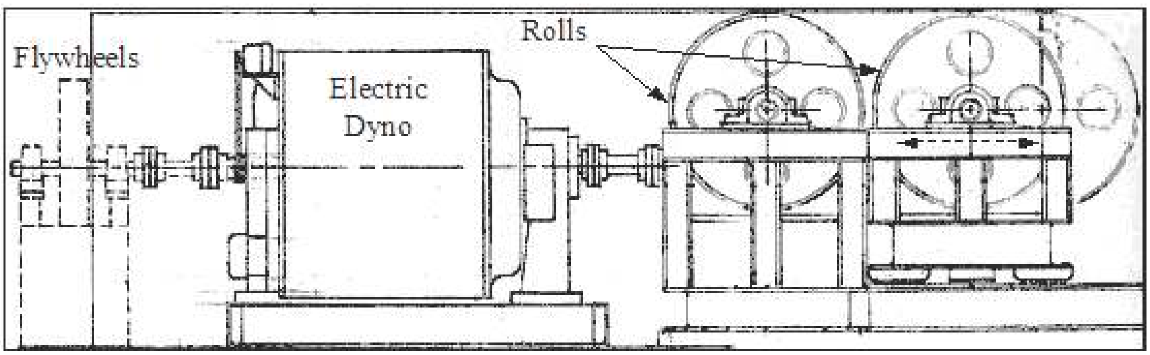

Figure 5. Chassis Dynamometer Schematic

The rolls are the means by which power is absorbed from the vehicle. The rolls are attached to gearboxes that increase the speed of the central shaft by a factor of 5. The flywheels, mounted on the back of the dynamometer, provide a mechanical simulation of the vehicle inertia.

The energy absorption capability of the dynamometer is used to apply the road load, which is a summation of the aerodynamic drag and friction losses that the vehicle experiences, as a function of speed. The road load for each test vehicle was estimated from standard equations. The electric dynamometer is also used to adjust the simulated inertia, either higher or lower than the 31,000-lb base dynamometer inertia. The inertia simulation range of the chassis dynamometer is 8,000 to 80,000 lbs.

The test vehicle is secured with the drive axles over the rolls. A driver's aid monitor in the cab is used to guide the vehicle operator in driving the test trace. A large fan is used to cool the vehicle radiator during testing. The chassis dynamometer is supported by 72 channels of data acquisition, in addition to the emissions measurement, fuel metering, and combustion analysis subsystems.

With the vehicle jacked up off the rolls, an automated dynamometer warm-up procedure is performed daily, prior to testing, to ensure that parasitic losses in the dynamometer and gearboxes have stabilized at the appropriate level to provide repeatable loading. An unloaded coast-down procedure is also conducted to confirm that inertia and road load are being accurately simulated by the dynamometer control system. Between test runs a loaded coast-down procedure is performed to further ensure stability of vehicle and dynamometer parasitic losses and accurate road load simulation during testing.

Fuel Handling

Fuel supply from the vehicle's tank is interrupted, allowing for delivery of conditioned and metered fuel to the test vehicle. Test fuels are stored and blended, in drum quantities, in a temperature-conditioned shed. Test fuels are blended gravimetrically to the 20 volume percent level (B20). The fuel is delivered from the supply drum to the fuel metering and conditioning system, from which fuel is supplied to the vehicle's fueling system. The fuel metering system measures volumetric flow to an accuracy of +/- 0.5% of the reading. An in-line sensor measures the density with an accuracy of +/- 0.001 g/cc, allowing an accurate mass measurement over the test cycle.

Air Handling and Conditioning

Dilution air and the air supplied to the test vehicle for combustion are derived from a common source, a roof-mounted system that conditions the temperature of the air and humidifies as needed to meet desired specifications. This air is passed through a HEPA filter, in accordance with the (2007) CFR specifications, to eliminate background PM as a source of uncertainty in particulate measurements. The average inlet air temperature to the vehicle was maintained within a window of 24ºC +/- 2ºC for all test runs, and average humidity was controlled to 75 grains/lb (absolute) +/- 4 grains/lb.

Emissions Measurement

The emissions measurement system is based on the full-scale exhaust dilution tunnel method with a Constant Volume Sampling (CVS) system for mass flow measurement. The system is designed to comply with the requirements of the 2007 Code of Federal Regulations, title 40, part 86, subpart N. Exhaust from the vehicle flows through insulated piping to the full-scale 18-inch-diameter stainless steel dilution tunnel. A static mixer ensures thorough mixing of exhaust with conditioned, filtered, dilution air prior to sampling of the dilute exhaust stream to measure gaseous and particulate emissions.

A system with three Venturi nozzles is employed to maximize the flexibility of the emissions measurement system. Featuring 500-cfm, 1,000-cfm, and 1,500-cfm Venturi nozzles and gas-tight valves, the system flow can be varied from 500-cfm to 3,000-cfm flow rates in 500-cfm increments. This allows the dilution level to be tailored to the engine size being tested, maximizing the accuracy of the emissions measurement equipment.

The gaseous emissions bench is a Pierburg model AMA-2000. It features continuous analyzers for total HC, NO_x, CO, carbon dioxide (CO_2) and oxygen (O_2). The system features auto-ranging, automated calibration, zero check and span check features, as well as integration functions for calculating cycle emissions. There are two heated sample trains for gaseous emissions measurement: one for HC, and another for the other gaseous emissions. NO_x and HC measurements are performed on a wet basis, while CO, CO_2 and O_2, are done on a dry basis. Sample probes are located in the same plane in the dilution tunnel.

The PM sample control bench maintains a desired sample flow rate through the PM filters in proportion to the overall CVS flow, in accordance with the CFR. Stainless steel filter holders designed to the 2007 CFR requirements house 47-mm-diameter Teflon membrane filters through which the dilute exhaust sample flows.

The PM sampling system is capable of drawing a sample directly from the large full-scale dilution tunnel or utilizing secondary dilution to achieve desired temperature, flow, and concentration characteristics. A cyclone separator, as described in the CFR requirements, is employed to mitigate tunnel PM artifacts. PM filters are handled, conditioned, and weighed in a Class 1000 clean room with precise control over the temperature and humidity (+/- 1°C for temperature and dew point). The microbalance for weighing PM filters features a readability of 0.1 µg (a CFR requirement), a barcode reader for filter identification and tracking, and a computer interface for data acquisition. The microbalance is installed on a specially designed table to eliminate variation in the measurement due to vibration.

Test Vehicles

This study includes data collected from chassis dynamometer testing of eight different heavy-duty on-road vehicles. Test vehicles included three transit buses, two school buses, two Class 8 trucks, and one motor coach. This collection of test vehicles captures a variety of engine makes, sizes, emissions control technologies and transmission types, but still cannot be considered as representative of on-road heavy-duty vehicles. Engine model year varied from 2000 to 2006. Accumulated mileage also varied for each of the test vehicles, ranging from 2,274 to 503,468 miles. Information detailing each of the test vehicles is provided in Table 6.

The three transit buses incorporated identical engine and transmission combinations, only differing in the accumulated mileage and biodiesel fuel type. This allowed for some assessment of the dependence of emission differences on vehicle-to-vehicle and fuel-to-fuel variability.

Table 6. Description of Vehicles Tested.

	Motor Coach	Freightliner Class 8	Conventional School Bus	Green Diesel School Bus	International Class 8	Transit Bus #1	Transit Bus #2	Transit Bus #3
Vehicle MY	Jan-04	May-99	Jul-04	Jan-06	Jan-06	Sep-00	Sep-00	Jun-00
Make	Sports Coach 37'	Freightliner	International	International	International	Orion	Orion	Orion
Odometer	33,320	503,468	30,441	2,274	3,165	136,610	205,387	108,451
Test Weight	23,500	64,000	26,000	26,000	64,000	35,000	35,000	35,000
Engine Manufacturer	Cummins	Detroit Diesel	International	International	Cummins	Cummins	Cummins	Cummins
Displacement	5.9 L	12.7 L	7.6 L	7.6 L	10.8 L	10.8 L	10.8 L	10.8 L
Engine MY	2003	2000	2004	2006	2005	2000	2000	2000
Engine Model	ISB 300	Series 60	D 285	DG 285	ISM 330	ISM 280	ISM 280	ISM 280
Rated HP	300	470	285	285	330	280	280	280
Test Fuels:	Certification, B20 Agland	Certification, B20	Certification, B20	Certification, B20	#2 Diesel, B20	#2 Diesel, B20	#2 Diesel, B20	#2 Diesel, B20
Petroleum	2007 Cert	2007 Cert	2007 Cert	2007 Cert	Local LSD C	Local LSD A	Local LSD A	Local LSD A & B
Biodiesel	Agland	Agland	Agland	Agland	Agland	BlueSun	BlueSun	Agland/BlueSun
Transmission Type	Allison Auto	Rockwell 10spd Manual	Allison Auto	Allison Auto	Eaton 10spd Manual	Friedrichshafen	Friedrichshafen	Friedrichshafen
Aftertreatment			DOC	DPF				

Driving Cycles

Several different driving cycles were employed in this study. Driving cycles were chosen to mimic in-use operation for a given vehicle. The City-Suburban Heavy-Vehicle Cycle (CSHVC) was used for testing all but one of the vehicles in this study. This cycle, developed by West Virginia University (WVU), represents low-speed, stop-and-go driving events [45] and is shown in Figure 6. The Urban Dynamometer Driving Schedule for Heavy-Duty Vehicles (UDDS) was also employed. This cycle was developed from the same dataset used for development of the transient test portion of the heavy-duty FTP and is described in the Code of Federal Regulations [46], shown in Figure 7.

The Combined International Local and Commuter Cycle (CILCC) was developed by NREL for testing Class 4 to 6 hybrid electric delivery vehicles [47]. The only part of the cycle that is specific to hybrids is the length (>45 min). Otherwise, it is intended to simulate urban delivery driving for heavy-duty vehicles in general. The cycle was developed to use larger amounts of fuel energy so that changes in state of charge (battery energy) would be minimal in comparison. The acceleration events of this cycle were slightly modified to allow the Class 8 vehicle to achieve the drive trace; the cycle used is shown in Figure 8.

The Rowan University Composite School Bus Cycle (RUCSBC) [32], shown in Figure 9, was developed from school bus activity data. Note that the RUCSBC has the highest average and maximum acceleration rates and is therefore the most aggressive of these driving cycles. The Freeway Cycle [45] was developed from activity data on two heavy-duty trucks and includes four-lane highway driving with entrance and exit ramps, shown in Figure 10. The Freeway cycle has the highest average and maximum speed, and the longest distance. Cycle statistics for each of the drive cycles are shown in Table 7. The chosen drive cycles are representative of a wide range of driving styles, including high speed interstate driving to low-speed, stop-and-go driving.

Table 7. Cycle Statistics for Various Driving Cycles Used in this Study.

	CSHVC	UDDS	CILCC mod	RUCSBC	Freeway
Total Time (sec)	1,700	1,060	3,192	1,310	1,640
Time at Idle (%)	23.24	36.32	15.57	21.15	9.27
Average Cycle Speed (mph)	14.15	18.81	14.25	20.95	34.03
Average Speed While Driving (mph)	18.44	29.56	16.89	26.59	37.52
Maximum Speed (mph)	43.8	58	55	49.7	60.7
Total Distance (mi)	6.68	5.54	12.64	7.63	15.51
Number of Stops (stops/mi)	1.95	1.26	1.98	1.44	0.58
Average Acceleration Rate (ft/sec^2)	1.31	1.57	1.44	2.1	0.67
Maximum Acceleration Rate (ft/sec^2)	3.81	6.01	3.67	12.17	4.69

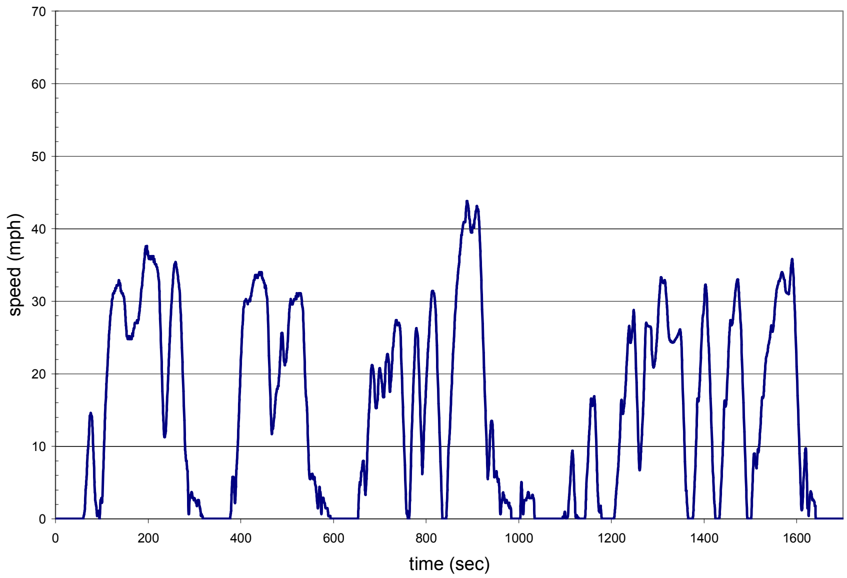

Figure 6. The CSHVC cycle.

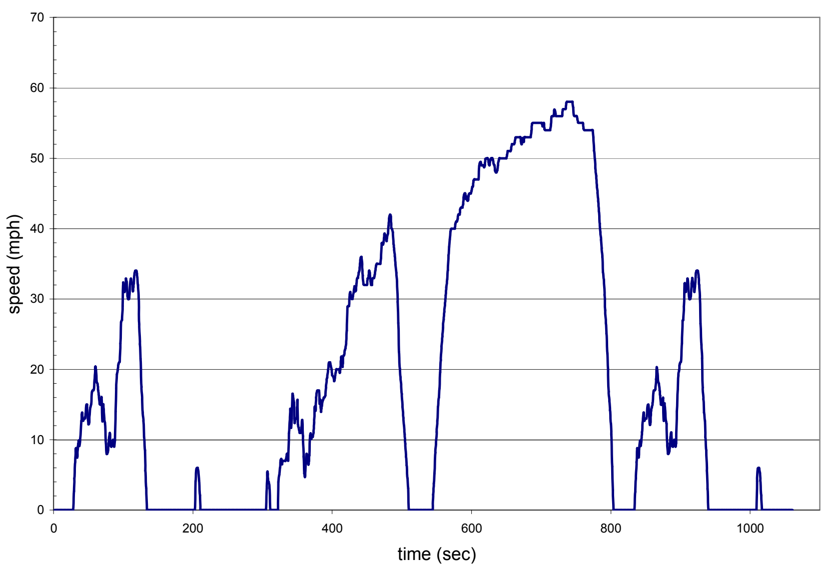

Figure 7. The UDDS cycle.

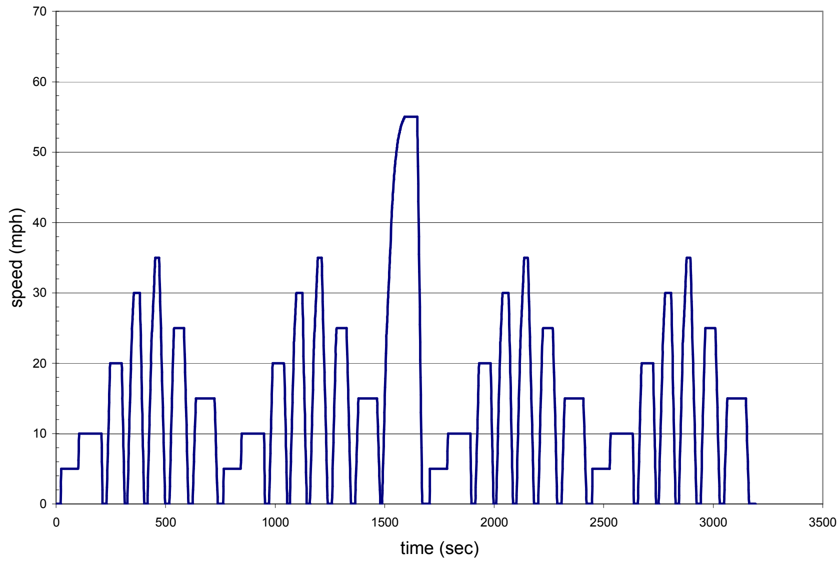

Figure 8. The CILCC modified cycle.

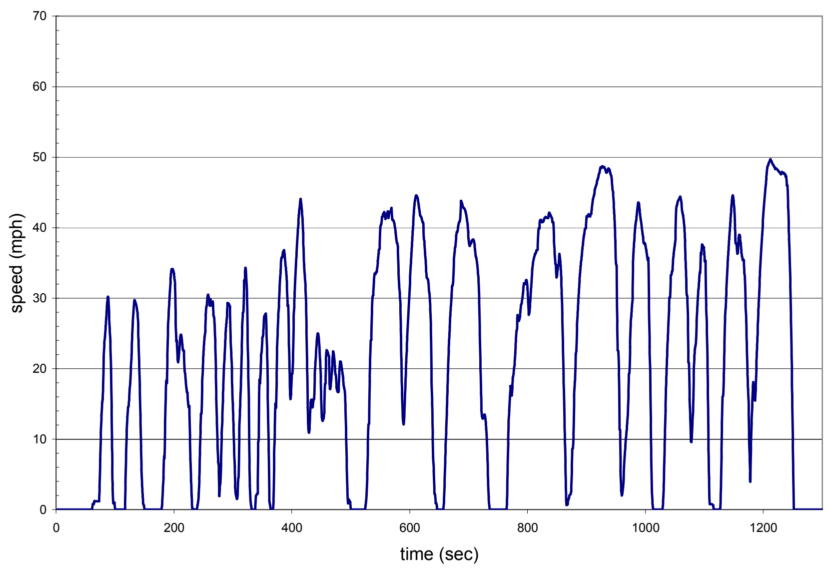

Figure 9. The RUCSBC cycle.

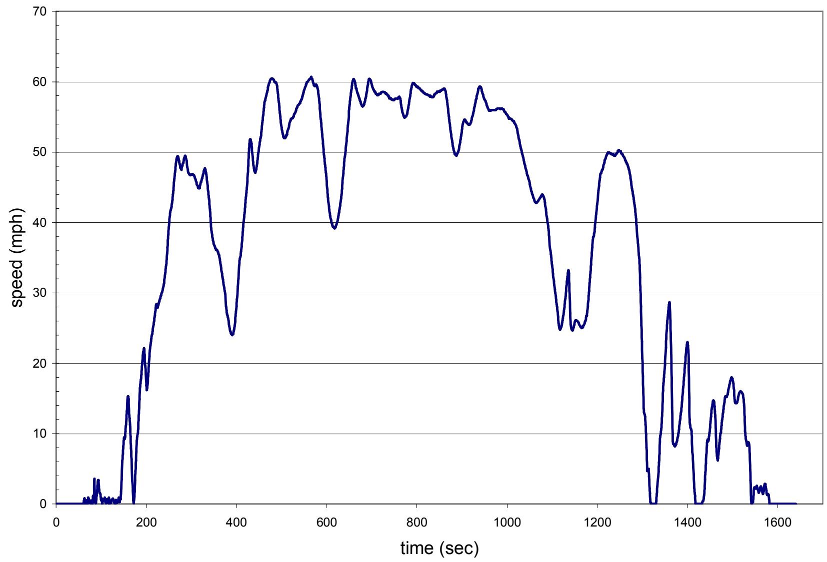

Figure 10. The Freeway cycle.

Test Fuels

Each vehicle was tested with a petroleum-derived diesel fuel and a 20% blend of soy-based biodiesel blended with the petroleum diesel base fuel (B20). In each case the B20 was splash blended on a volumetric basis. Two supplies of the soy-based biodiesel were used: a standard commercial grade fuel supplied by Agland, and a specialized biodiesel containing a proprietary multifunctional additive package supplied by BlueSun Biodiesel. Four separate supplies of petroleum diesel were used. Three on-highway low-sulfur diesels (LSD) were obtained locally, with LSD A and LSD B obtained from the local bus company at different times. LSD C was obtained from a local fuel jobber. The fourth fuel was ultra low sulfur 2007 certification diesel (2007 Cert) obtained from ChevronPhillips. Properties of these test fuels are listed in Table 8, while Table 6 notes which fuels were tested in each vehicle. The B20 blends were prepared using a highly accurate gravimetric procedure. Note that aromatic content is not reported for the B20 blends because the method used to measure fuel aromatic content, ASTM D1319, gives false high values for biodiesel and biodiesel blends. The aromatic content of B100 is zero, thus B20 blends will have 20% lower aromatic content than the diesel fuel in which they are blended.

Table 8. Properties of Test Fuels.

	LSD A	B20 LSD A/ BlueSun	LSD B	B20 LSD B/ Agland	LSD C	B20 LSD C/ Agland	2007 Cert	B20 Cert/ Agland
Distillation T90, ºC (D86)	325	340	310	331	316	333	299	327
Flash Point, ºC (D93)	66	71	59	63	58	64	82	81
Copper Corrosion (D130)	1a	1a	1a	1a	1a	1a	--	1a
Kinematic Viscosity, cSt@40ºC (D445)	2.438	2.726	2.247	2.548	2.382	2.687	2.3	2.527
Ash, %Mass (D482)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Carbon Residue, %mass (D524)	0.04	<0.010	0.11	0.08	0.13	0.11	--	0.09
Cetane Number (D613)	40.6	47	44.4	45.8	47.0	52.3	41	47.3
Cloud Point, ºC (D5773)	-18	-14	-20	-28	-17	-13	--	-19
Total Sulfur, ppm (D5453)	364	280	320	264	304	245	12	8.6
Water & Sediment, %Vol (D2709)	0.010	0.010	0.01	0.01	0.010	0.010	--	0.010
Aromatics, %Vol (D1319)	--	28.5	25.0	--	23.8	--	28.8	--
Acid Number, mg KOH/gram (D664)	0.01	0.16	<0.05	<0.05	<0.05	<0.05	--	<0.05
Peroxide Number, ppm (D3703)	0	8.1	2.6	24.8	0	39.0	--	57.7

Results

Average results for each vehicle and drive cycle are shown in Tables 9 through 22. Percent differences as a result of biodiesel are also shown. Graphical representations of relative NO_x, PM, CO and HC emissions for each vehicle and drive cycle are shown in Figures 11 through 14. All results are averages of three or more individual runs, and a tabulation of individual run results is found in the Appendix.

Transit Bus Results

Data showing average emissions and fuel economy results for the three transit buses tested on the CSHVC are in Tables 9 through 12. Buses #1 and #2 were initially tested as part of a fleet evaluation project with the goal of measuring the effect of biodiesel usage with the actual in-use fuels [48]. Thus, these buses were tested on LSD A used by the bus company and the same fuel blended with soy biodiesel obtained from BlueSun Biodiesel and containing a proprietary multifunctional diesel additive. Both exhibit the roughly 2% fuel economy reduction expected for B20 based on fuel volumetric energy content. NO_x was reduced by 5.8% for bus #1 and by 3.9% for bus #2. To determine if the multifunctional additive was responsible for the NO_x reduction, a third, identical bus was tested using LSD A and biodiesel from BlueSun containing the additive LSD B with biodiesel from a second source (Agland) with no additive. These results are shown in Tables 11 and 12. Biodiesel from both sources produced a roughly 3 to 4% reduction in NO_x, suggesting that the NO_x reduction occurs generally for biodiesel for this engine-transmission combination on this drive cycle. However, because the base fuels are not identical, this is not a definitive comparison. All changes in NO_x are significant at 95% confidence or better. PM emission reductions were in the 15 to 20% range for all three buses with all changes significant at 90% confidence or better.

Table 9. Emission Test Results for Transit Bus #1 on CSHVC Comparing LSD A and B20/BlueSun Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**19.80**	**0.2740**	**3.60**	**0.871**	**4.67**	**688**
95% conf	*0.34*	*0.0333*	*0.31*	*0.071*	*0.07*	*11*
B20	**18.65**	**0.2264**	**2.63**	**0.625**	**4.56**	**708**
95% conf	*0.15*	*0.0195*	*0.22*	*0.080*	*0.08*	*9*
% Difference	**-5.8%**	**-17.4%**	**-26.8%**	**-28.3%**	**-2.2%**	**2.9%**
p-value	0.0001	0.0363	0.0006	0.0011	0.0809	0.0214

Table 10. Emission Test Results for Transit Bus #2 on CSHVC Comparing LSD A and B20/BlueSun Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**19.44**	**0.3210**	**3.43**	**0.794**	**4.54**	**709**
95% conf	*0.41*	*0.1170*	*0.47*	*0.065*	*0.13*	*21*
B20	**18.67**	**0.2150**	**2.73**	**0.571**	**4.45**	**730**
95% conf	*0.26*	*0.0393*	*0.32*	*0.022*	*0.09*	*15*
% Difference	**-3.9%**	**-33.0%**	**-20.3%**	**-28.0%**	**-2.0%**	**3.0%**
p-value	0.0073	0.0832	0.0276	0.0001	0.2635	0.1304

Table 11. Emission Test Results for Transit Bus #3 on CSHVC Comparing LSD A and B20/BlueSun Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**19.78**	**0.3079**	**3.04**	**0.824**	**4.60**	**695**
95% conf	*0.17*	*0.0267*	*0.14*	*0.018*	*0.02*	*3*
B20	**19.04**	**0.2447**	**2.48**	**0.592**	**4.51**	**715**
95% conf	*0.15*	*0.0125*	*0.18*	*0.046*	*0.04*	*7*
% Difference	**-3.7%**	**-20.5%**	**-18.6%**	**-28.1%**	**-1.9%**	**2.8%**
p-value	0.0001	0.0018	0.0007	0.0001	0.0044	0.0005

Table 12. Emission Test Results for Transit Bus #3 on CSHVC Comparing LSD B and B20/Agland Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**20.24**	**0.2805**	**3.07**	**0.824**	**4.59**	**696**
95% conf	*0.26*	*0.0252*	*0.26*	*0.017*	*0.04*	*6*
B20	**19.70**	**0.2324**	**2.70**	**0.659**	**4.50**	**716**
95% conf	*0.28*	*0.0100*	*0.17*	*0.049*	*0.04*	*6*
% Difference	**-2.7%**	**-17.2%**	**-11.9%**	**-20.0%**	**-1.9%**	**2.8%**
p-value	0.0185	0.0109	0.0423	0.0001	0.0124	0.0014

Class 8 Truck Results

Results for the International Class 8 truck are shown in Tables 13 and 14. This vehicle was tested as a baseline vehicle for a heavy-duty hybrid electric vehicle study. Thus the CILCC, which was developed to simulate urban driving generally but with features designed to exercise hybrid vehicles, was used. Additionally, the Freeway cycle was used so that both city and freeway driving were simulated. This vehicle exhibited no significant change in NO_x for the stop and go CILCC but a 2.3% increase in NO_x for freeway driving ($p<0.05$). PM emission reductions on both cycles were quite high, on the order of 30%. Fuel economy reduction was the expected 2% on the CILCC but only 0.5% on the Freeway cycle.

Results for the Freightliner Class 8 truck are shown in Tables 15 and 16. This vehicle was tested exclusively for this study of biodiesel emissions and the CSHVC and Freeway cycles were employed. NO_x emissions increased 2.1% and 3.6% on these cycles, respectively ($p<0.05$). PM emission reductions were in the 20 to 25% range. Fuel economy reduction was about 1.5% on both cycles.

Table 13. Emission Test Results for International Class 8 on CILCCmod Comparing LSD C and B20/Agland Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**11.04**	**0.2890**	**4.98**	**1.192**	**4.32**	**740**
95% conf	*0.14*	*0.0083*	*0.19*	*0.032*	*0.05*	*12*
B20	**11.03**	**0.2103**	**4.22**	**0.992**	**4.22**	**762**
95% conf	*0.19*	*0.0052*	*0.09*	*0.034*	*0.04*	*7*
% Difference	**-0.1%**	**-27.2%**	**-15.3%**	**-16.8%**	**-2.3%**	**2.9%**
p-value	0.9528	0.0001	0.0020	0.0011	0.0402	0.0429

Table 14. Emission Test Results for International Class 8 on Freeway Cycle Comparing LSD C and B20/Agland Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**6.75**	**0.2163**	**2.13**	**0.515**	**5.44**	**586**
95% conf	*0.02*	*0.0104*	*0.04*	*0.003*	*0.02*	*3*
B20	**6.90**	**0.1412**	**1.82**	**0.452**	**5.41**	**594**
95% conf	*0.10*	*0.0010*	*0.03*	*0.009*	*0.03*	*3*
% Difference	**2.3%**	**-34.7%**	**-14.5%**	**-12.4%**	**-0.5%**	**1.4%**
p-value	0.0340	0.0001	0.0002	0.0002	0.2410	0.0180

Table 15. Emission Test Results for the Freightliner Class 8 on CSHVC Comparing 2007 Certification Diesel and B20/Agland Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**29.65**	**1.8303**	**27.41**	**0.536**	**3.49**	**913**
95% conf	*0.40*	*0.2139*	*1.51*	*0.022*	*0.04*	*11*
B20	**30.26**	**1.4761**	**24.49**	**0.454**	**3.44**	**935**
95% conf	*0.32*	*0.0821*	*20.3*	*0.019*	*0.04*	*12*
% Difference	**2.1%**	**-19.4%**	**-10.7%**	**-15.2%**	**-1.5%**	**2.4%**
p-value	0.0412	0.0129	0.0867	0.0003	0.1283	0.0253

Table 16. Emission Test Results for the Freightliner Class 8 on the Freeway Cycle Comparing 2007 Certification Diesel and B20/Agland Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**22.27**	**0.4826**	**8.14**	**0.200**	**5.90**	**539**
95% conf	*0.36*	*0.0650*	*0.29*	*0.013*	*0.03*	*3*
B20	**23.08**	**0.3563**	**7.58**	**0.168**	**5.81**	**553**
95% conf	*0.37*	*0.0219*	*0.12*	*0.014*	*0.03*	*2*
% Difference	**3.6%**	**-26.2%**	**-6.9%**	**-16.0%**	**-1.6%**	**2.6%**
p-value	0.0124	0.0048	0.0058	0.0095	0.0007	0.0001

Motor Coach Results

The motor coach (or recreational vehicle) was tested on the CSHVC and UDDS cycles. This vehicle exhibited a roughly 3% increase in NO_x and 30% reduction in PM for both cycles. Fuel economy reduction was roughly 1%.

Table 17. Emission Test Results for the Motor Coach on CSHVC Comparing 2007 Certification Diesel and B20/Agland Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**7.75**	**0.2538**	**4.05**	**0.228**	**6.63**	**485**
95% conf	*0.11*	*0.0179*	*0.31*	*0.019*	*0.03*	*2*
B20	**7.96**	**0.1825**	**3.15**	**0.195**	**6.54**	**495**
95% conf	*0.13*	*0.0058*	*0.15*	*0.007*	*0.03*	*3*
% Difference	**2.8%**	**-28.1%**	**-22.3%**	**-14.5%**	**-1.3%**	**2.0%**
p-value	0.0368	0.0001	0.0005	0.0092	0.0048	0.0002

Table 18. Emission Test Results for the Motor Coach on the UDDS Comparing 2007 Certification Diesel and B20/Agland Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**6.99**	**0.2387**	**3.66**	**0.138**	**7.05**	**456**
95% conf	*0.10*	*0.0079*	*0.18*	*0.014*	*0.18*	*12*
B20	**7.22**	**0.1672**	**2.95**	**0.133**	**7.00**	**462**
95% conf	*0.19*	*0.0128*	*0.09*	*0.019*	*0.09*	*6*
% Difference	**3.4%**	**-30.0%**	**-19.2%**	**-3.4%**	**-0.6%**	**1.4%**
p-value	0.0576	0.0001	0.0001	0.6993	0.6734	0.3700

School Bus Results

The two school buses tested in this study were the only vehicles equipped with exhaust aftertreatment devices. The conventional International school bus was equipped with a diesel oxidation catalyst and the International Green Diesel school bus was equipped with a diesel particle filter (DPF). Results for the Green Diesel school bus are shown in Tables 19 and 20 for the CSHVC and the highly aggressive RUCSBC, respectively. NO_x emissions were essentially unchanged on the CSHVC but increased by 2.3% for the RUCSBC. The DPF was highly effective at reducing PM emissions with values below 0.002 g/mile in all cases. This is roughly a factor of 100 below PM emissions measured for the other vehicles in this study. While examination of percent change in PM emissions for B20 suggests that PM has increased, the actual magnitude of these changes is extremely small and not statistically significant ($p>0.05$). Fuel economy was decreased by 1 to 2% for B20 in this vehicle.

Results for the conventional school bus are shown in Tables 21 and 22. This bus exhibited much more highly variable emissions than any of the other vehicles tested, reducing our ability to make definitive statements about emission differences. Examination of individual run results in the Appendix indicates some difficulty in controlling intake air humidity for this test sequence, but also shows large shifts in PM emissions with no apparent cause. Results are no change in NO_x for the CSHVC but a 6.2% increase for the RUCSBC. PM emissions were unchanged for the CSHVC but decreased by 24% for the RUCSBC. Fuel economy declined by up to 1%.

Table 19. Emission Test Results for the International Green Diesel School Bus on CSHVC Comparing 2007 Certification Diesel and B20/Agland Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**7.70**	**0.0009**	**0.15**	**0.023**	**5.86**	**549**
95% conf	*0.14*	*0.0002*	*0.07*	*0.015*	*0.06*	*6*
B20	**7.64**	**0.0012**	**0.12**	**0.031**	**5.74**	**565**
95% conf	*0.09*	*0.0001*	*0.05*	*0.008*	*0.06*	*6*
% Difference	**-0.8%**	**28.0%**	**-15.9%**	**35.2%**	**-2.0%**	**2.8%**
p-value	0.5484	0.1032	0.5158	0.7179	0.0328	0.0051

Table 20. Emission Test Results for the International Green Diesel School Bus on RUCSBC Comparing 2007 Certification Diesel and B20/Agland Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**8.93**	**0.0014**	**0.10**	**0.023**	**4.97**	**648**
95% conf	*0.08*	*0.0002*	*0.03*	*0.005*	*0.03*	*4*
B20	**9.14**	**0.0017**	**0.06**	**0.021**	**4.93**	**659**
95% conf	*0.16*	*0.0003*	*0.02*	*0.009*	*0.04*	*5*
% Difference	**2.3%**	**15.6%**	**-41.7%**	**-7.0%**	**-0.8%**	**1.7%**
p-value	0.0346	0.2209	0.0547	0.7331	0.1561	0.0081

Table 21. Emission Test Results for the International Conventional School Bus on CSHVC Comparing 2007 Certification Diesel and B20/Agland Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**9.85**	**0.1929**	**5.22**	**0.439**	**5.93**	**534**
95% conf	*0.10*	*0.0210*	*0.37*	*0.041*	*0.04*	*3*
B20	**9.79**	**0.1977**	**5.72**	**0.434**	**5.86**	**549**
95% conf	*0.12*	*0.0176*	*0.46*	*0.047*	*0.03*	*3*
% Difference	**-0.7%**	**2.5%**	**9.5%**	**-1.1%**	**-1.1%**	**2.7%**
p-value	0.4145	0.7368	0.1198	0.8802	0.0074	0.0001

Table 22. Emission Test Results for the International Conventional School Bus on RUCSBC Comparing 2007 Certification Diesel and B20/Agland Biodiesel.

	NOx (g/mile)	PM (g/mile)	CO (g/mile)	THC (g/mile)	Fuel Econ (mpg)	Fuel Cons (g/mile)
Diesel	**9.78**	**0.6954**	**8.95**	**0.373**	**5.01**	**633**
95% conf	*0.12*	*0.0324*	*0.49*	*0.074*	*0.03*	*4*
B20	**10.39**	**0.5284**	**6.93**	**0.300**	**4.99**	**645**
95% conf	*0.17*	*0.0393*	*1.12*	*0.100*	*0.05*	*6*
% Difference	**6.2%**	**-24.0%**	**-22.6%**	**-19.6%**	**-0.3%**	**1.9%**
p-value	0.0001	0.0001	0.0014	0.2665	0.5937	0.0049

Results Summary

Figures 11 through 14 summarize the results for NO_x, PM, CO, and HC (or total hydrocarbon, THC), respectively. As can be seen in the data, not only is the impact of B20 on NO_x emissions highly dependent on the test vehicle, but it is also dependent on the chosen drive cycle. All three of the transit buses demonstrated reductions in NO_x emissions, regardless of biodiesel supply. The motor coach and the Freightliner Class 8 truck both showed increases in NO_x emissions over each of their test cycles. The International Class 8 and both school buses showed increases over one test cycle, and reductions or no change over the other test cycle. However, PM emission reductions are quite robust, independent of technology and driving cycle with the exception of the DPF-equipped vehicle.

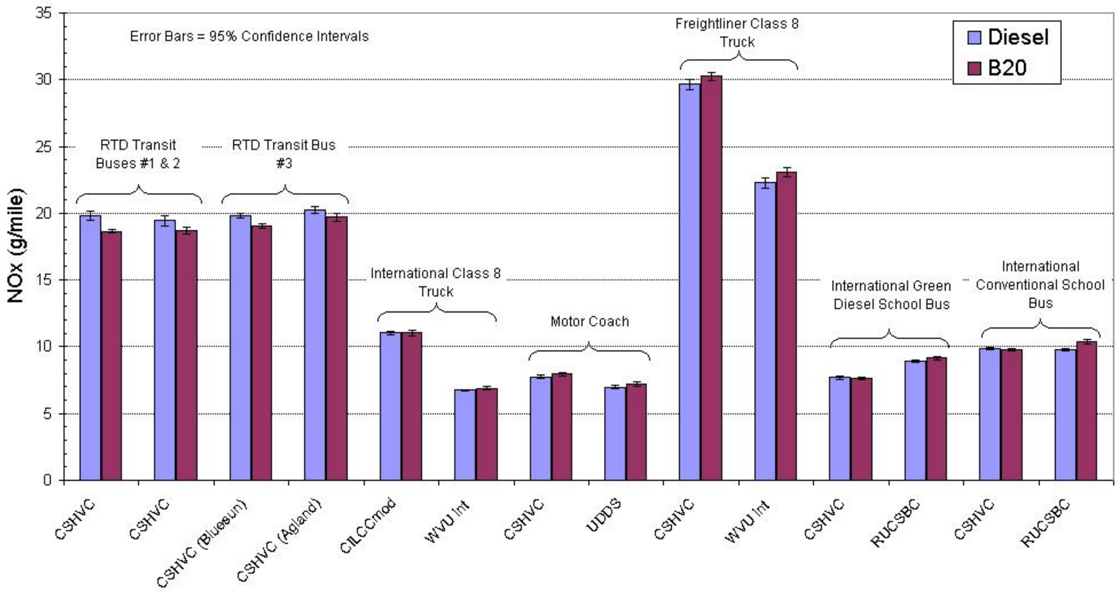

Figure 11. Comparison of NO_x emissions for conventional diesel and B20 for each vehicle tested and each cycle.

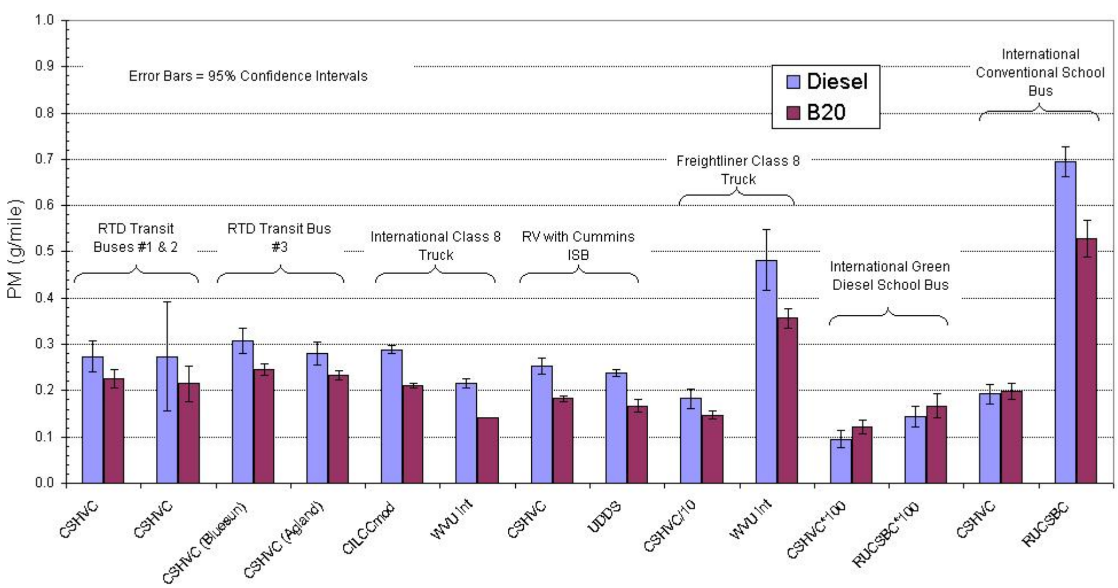

Figure 12. Comparison of PM emissions for conventional diesel and B20 for each vehicle tested and each cycle.

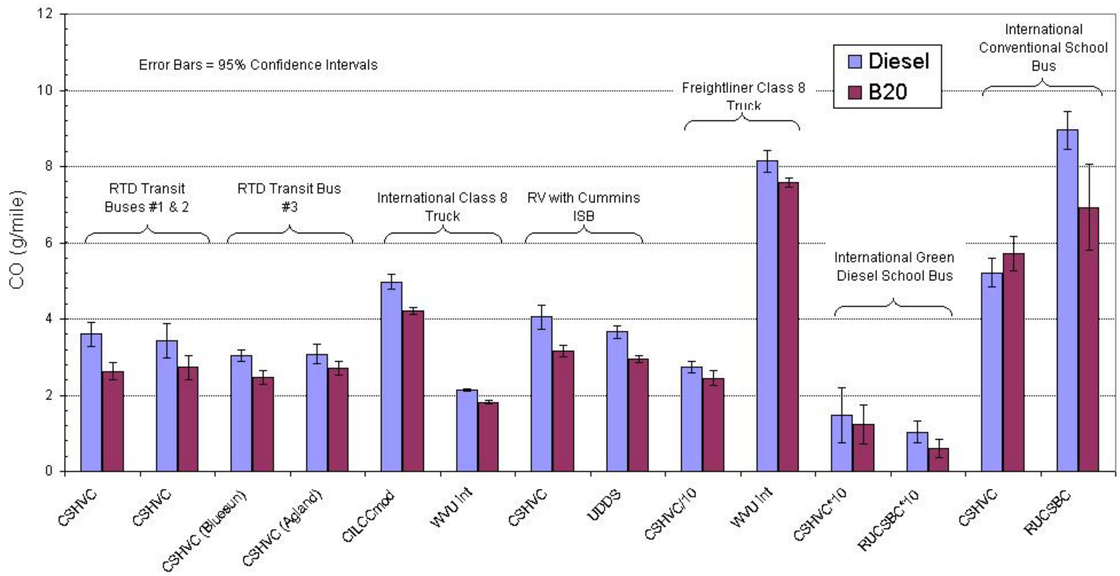

Figure 13. Comparison of CO emissions for conventional diesel and B20 for each vehicle tested and each cycle.

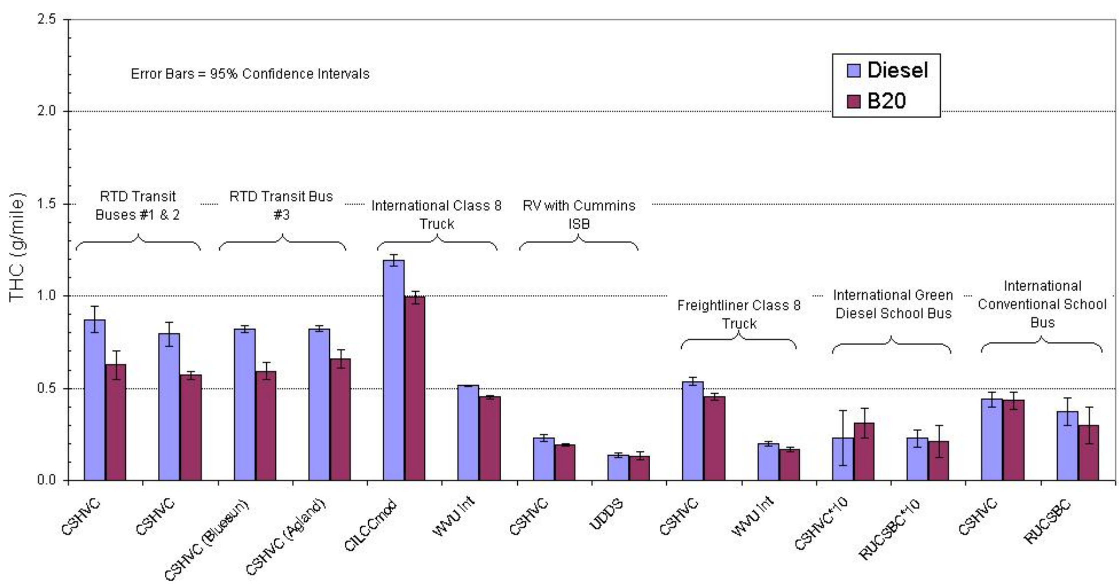

Figure 14. Comparison of THC emissions for conventional diesel and B20 for each vehicle tested and each cycle.

Discussion

The average percent change in emissions and fuel economy for each vehicle and drive cycle are summarized in Table 23. Note that for Transit Bus #3 results for both B20A and B20B have been averaged so that this vehicle is not counted twice in the average. Across all vehicle/drive cycle combinations PM, CO and THC showed average reductions of 16.4%, 17.1%, and 11.6% respectively. NO_x increased on average by 0.6%. Fuel economy was reduced by an average of 1.4%. Table 23 also shows 95% confidence limits for these average values. Note that the confidence interval for NO_x emissions includes zero, or no change in NO_x. It is important to keep in mind, however, that this eight-vehicle dataset cannot in any way be considered as representative of in-use heavy-duty vehicles, or even of model year 2000 to 2006 vehicles. Nevertheless, the results confirm the robustness of PM, CO, and HC reductions found in most other studies, and support the conclusion that the impact of B20 on NO_x is not significant. Additionally, if the results in Table 23 are combined with the soy B20 results from Tables 4 and 5, the average change in NO_x is 0.9%±1.5% (95% confidence interval).

Table 23. Average Percent Change in Emissions and Fuel Economy for All Vehicles Tested.

Vehicle	Cycle	NO_x % Change	PM % Change	CO % Change	THC % Change	Fuel Econ % Change
Transit Bus #1	CSHVC	-5.8	-17.4	-26.8	-28.3	-2.2
Transit Bus #2	CSHVC	-3.9	-33.0	-20.3	-28.0	-2.0
Transit Bus #3 (Average)	CSHVC	-3.2	-18.9	-15.3	-25.1	-1.9
Freightliner Class 8	CSHVC	2.1	-19.4	-10.7	-15.2	-1.5
	Freeway	3.6	-26.2	-6.9	-16.0	-1.6
Motor Coach	CSHVC	2.8	-28.1	-22.3	-14.5	-1.3
	UDDS	3.4	-30.0	-19.2	-3.4	-0.6
International Class 8	CILCCmod	-0.1	-27.2	-15.3	-16.8	-2.3
	Freeway	2.3	-34.7	-14.5	-12.4	-0.5
Green Diesel School Bus	CSHVC	-0.8	28.0	-15.9	35.2	-2.0
	RUCSBC	2.3	15.6	-41.7	-7.0	-0.8
Conventional School Bus	CSHVC	-0.7	2.5	9.5	-1.1	-1.1
	RUCSBC	6.2	-24.0	-22.6	-19.6	-0.3
Overall Average % Difference		0.6	-16.4	-17.1	-11.6	-1.4
95% Confidence Interval		±1.8	±10	±6.1	±8.6	±0.36

Table 24 shows average change in emissions and fuel economy for subsets of the overall dataset. The vehicles tested include four meeting the 4-g/bhp-h NO_x requirement that went into effect in 1998, and four meeting the 2.5-g/bhp-h NO_x+HC requirement that went into effect in 2004 (or as early as 2002 for some manufacturers). The first two rows of Table 24 examine average emission changes for B20 in vehicles from these two technology groups. The most obvious observation is the reduction in NO_x observed for the 4-g/bhp-h engines compared to the increase observed for 2.5-g/bhp-h engines. However, three out of the four 4-g/bhp-h NO_x vehicles were identical transit buses. Comparisons made with this subset of vehicles may therefore not be applicable to 4-g/bhp-h NO_x vehicles in general and again highlight the fact that this small group of vehicles is not a representative sample.

Table 24. Average Percent Change in Emissions for Specific Subsets of the Total Dataset, 95% Confidence Interval is Shown.

Vehicle Cycle	NOx % Change	PM % Change	CO % Change	THC % Change	Fuel Econ % Change
4.0-g/bhp-h Engines Only	-1.4±3.3	-23.0±5.2	-16.0±6.3	-22.3±5.1	-1.8±0.2
2.5-g/bhp-h Engines Only	1.9±1.7	-12.2±17	-17.8±9.7	-5.0±12	-1.1±0.5
CSHVC Only	-1.4±2.2	-12.3±15	-14.5±8.2	-10.9±16	-1.7±0.3

All but one of the vehicles was driven on the CSHVC, thus it is of interest to examine results for this urban/suburban driving cycle separately, and the results are shown in Table 24. Percent changes for the CSHVC are quite similar to the changes observed overall. However, for the CSHVC, NO_x emissions decrease slightly. A number of other comparisons might be made, for example comparing emission changes for LSD versus ULSD, but the eight-vehicle dataset presented here is too small for meaningful comparisons of this type to be made.

Examination of Real Time NO_x Emissions Data

The impact of biodiesel on NO_x emissions varies with vehicle, engine technology, and chosen drive cycle. An analysis of real-time NO_x data illustrates this impact relative to different driving events. Figures 15 through 19 show snapshots of real-time NO_x data for portions of various drive traces and with different vehicles. In each case, the data is presented for both test fuels in order to show comparisons of how biodiesel impacts NO_x emissions through different driving events.

Figure 15 shows NO_x traces for a portion of the CSHVC cycle driven by RTD transit bus #3. This is a 4.0-g/bhp-h NO_x engine, thus it does not incorporate EGR for NO_x control. NO_x emissions, shown in grams/second, differ under several driving events. During idle portions of the drive cycle, B20 causes a significant decrease in NO_x emissions. During most acceleration events, the peaks in NO_x emissions are higher for B20, particularly at or just before peak speed. However, for some acceleration events NO_x is lower for B20, especially during longer accelerations but before peak speed (i.e., 1,140 to1,150 seconds and 1,210 to 1,220 seconds in Figure 15). The combination of these effects causes overall NO_x emissions to decrease with the use of B20 in this vehicle. The 4-g/bhp-h Freightliner Class 8 truck (Figure 16) shows no difference at idle or during acceleration, but higher NO_x for B20 at speed peaks.

Figure 17 shows real-time NO_x traces for the same portion of the CSHVC cycle, driven by the motor coach. This is a 2.5-g/bhp-h NO_x engine, thus incorporating EGR. As can be seen, NO_x emissions at the idle conditions are controlled to nearly zero grams/second, thus there is no difference in NO_x emissions between the two fuels. However, this vehicle still experiences the higher peaks in NO_x emissions with B20 under acceleration events or near peak speed, leading to an overall increase in NO_x emissions.

Figure 18 shows the real-time NO_x traces for the International Class 8 Truck driven over the CILCC drive cycle. Like the motor coach, this vehicle also incorporates a 2.5-g/bhp-h NO_x engine. However, this engine shows slight decreases in the NO_x peaks during the acceleration events. NO_x emissions during steady-state and idle operation are the same. The overall NO_x emissions for the International Class 8 truck on this drive cycle showed slight reductions with B20, but not with statistical confidence ($p = 0.9528$).

These results do not reveal any obvious, consistent factor that is causing the variability observed for NO_x with these vehicles. A much more detailed analysis will be required. In particular we recommend an analysis that examines factors such as acceleration rate, wheel horsepower, and rate of change of horsepower. A study that employs a transmission model to estimate engine torque at various driving conditions may also prove valuable [49].

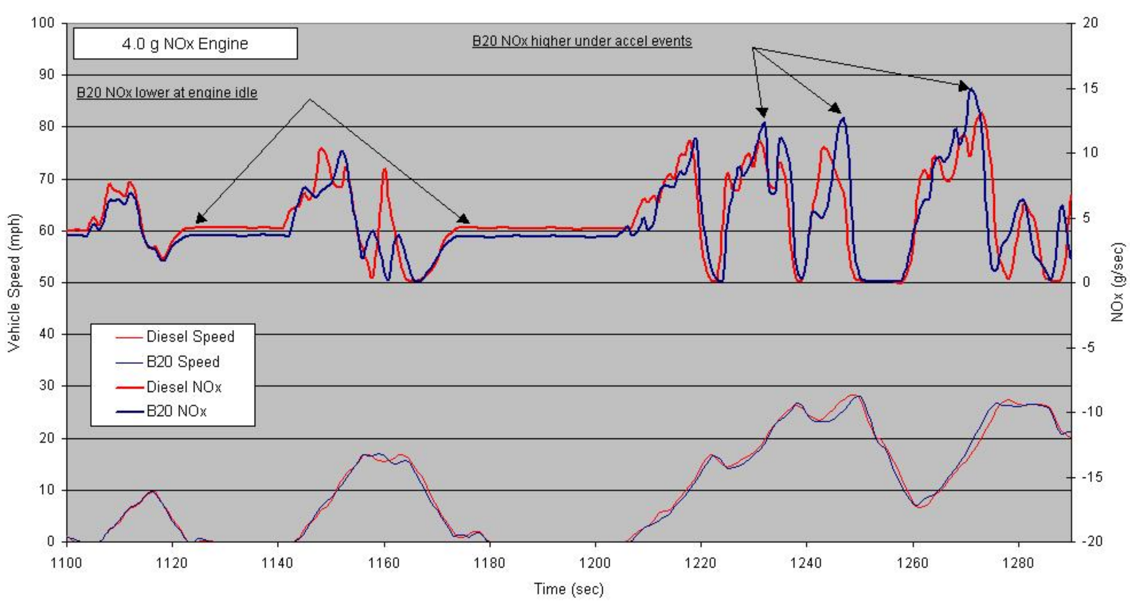

Figure 15. Portions of the CSHVC real-time NO_x traces for RTD Transit Bus #3.

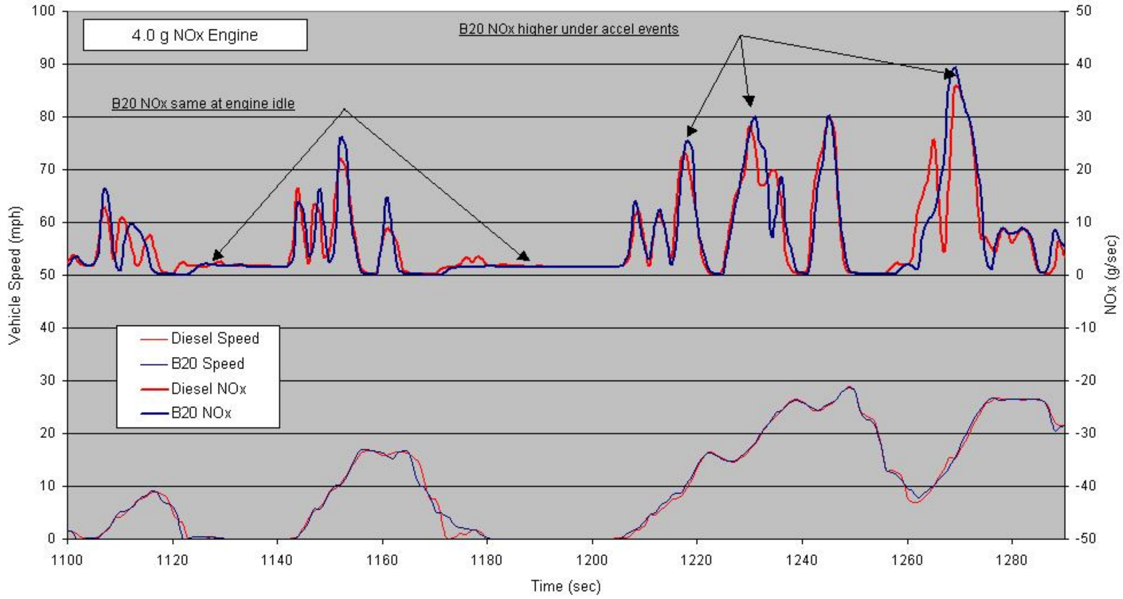

Figure 16. Portions of the CSHVC real-time NO_x traces for the Freightliner Class 8 truck.

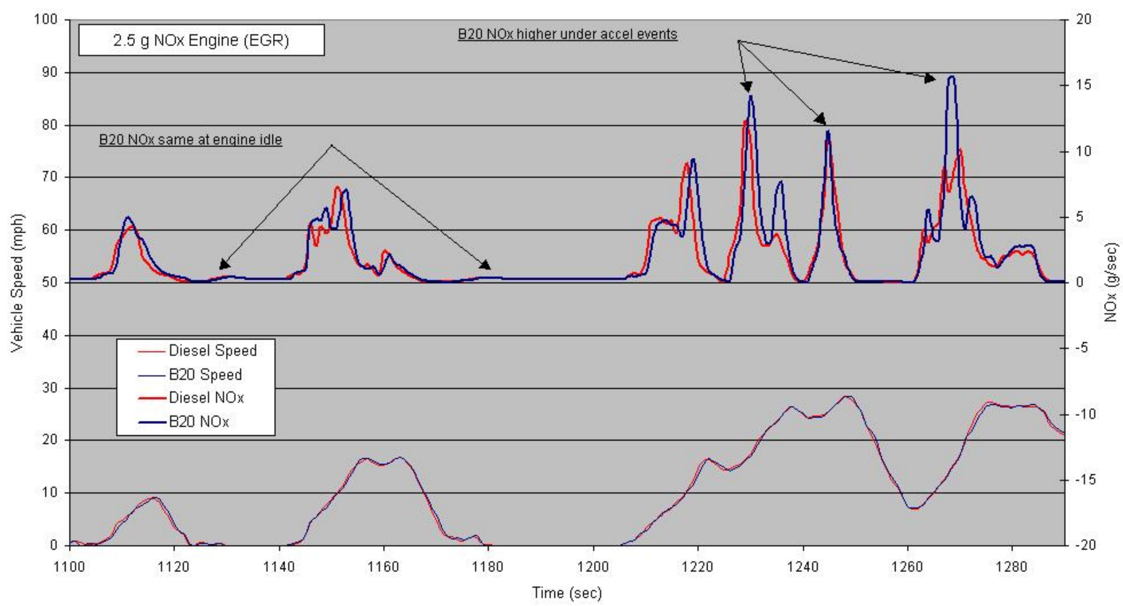

Figure 17. Portions of the CSHVC real-time NO_x traces for the motor coach.

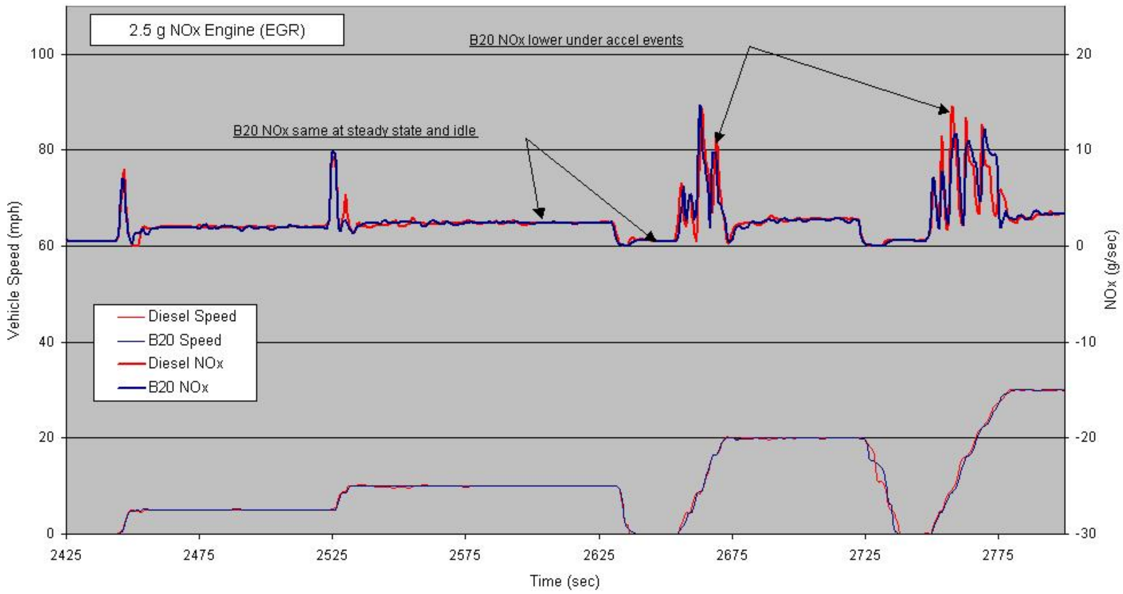

Figure 18. Portions of the CILCC real-time NO_x traces for the International Class 8 truck.

Summary and Recommendations

The objective of this study was to determine if testing entire vehicles on a heavy-duty chassis dynamometer provides a better, more realistic measurement of the impact of B20 on regulated pollutant emissions. This report also documents completion of the National Renewable Energy Laboratory's Fiscal Year 2006 Annual Operating Plan Milestone 10.4. This milestone supports the U.S. Department of Energy, Fuels Technologies Program Multiyear Program Plan Goal of identifying fuels that can displace 5% of petroleum diesel by 2010.

An EPA review of engine testing studies on biodiesel concluded that on average, for soy biodiesel, NO_x emissions increase by 2% [16]. Careful examination of the test data on which this conclusion is based shows that nearly half of the observations (44%) were for DDC engines in the 1991 to 1997 model year range, and a large majority of these are for the Series 60 model. We believe that EPA's conclusion of a NO_x increase is influenced by the unrepresentative composition of the engine dataset. A hallmark of the B20 emission test results is that NO_x is highly variable, with percentage change ranging from roughly -7% to +7%. Because data for the DDC Series 60 engine, which typically exhibits a small NO_x increase for B20, makes up such a large fraction of the data reviewed, EPA draws a conclusion that is at odds with the results of more recent studies.

Here we review more recently published studies (Table 3) and find an average change in NO_x for all recent B20 studies of -0.6%±2.0% (95% confidence interval). Restricting the average to recent studies of B20 with soy biodiesel yields an average NO_x impact of 0.1%±2.7%. The EPA review also includes summary of a smaller vehicle testing dataset that shows no significant impact of biodiesel on NO_x. We reviewed several more recently published vehicle (chassis) testing studies (Tables 4 and 5) and found an average change in NO_x of 1.2%±2.9% (95% confidence interval).

In the work reported here, eight heavy-duty diesel vehicles were tested, including three transit buses, two school buses, two Class 8 trucks, and one motor coach. Four of these vehicles met the 1998 heavy-duty emissions requirement of 4 g/bhp-h NO_x and four met the 2004 limit of 2.5 g/bhp-h NO_x+HC. Driving cycles that simulate both urban and freeway driving were employed. Each vehicle was tested on a petroleum-derived diesel fuel and on a 20 volume percent blend of that fuel with soy derived biodiesel. On average B20 caused PM and CO emissions to be reduced by 16% to 17% and HC emissions to be reduced by 12% relative to petroleum diesel. Emissions of these three regulated pollutants nearly always went down, the one exception being a vehicle equipped with a DPF that showed very low emissions of PM, CO, and HC. Furthermore, there was no significant change in these emissions for blending of B20. The NO_x emissions impact of B20 varied widely with engine/vehicle technology and test cycle ranging from -5.8% to +6.2%. On average, NO_x emissions did not change (statistically insignificant 0.6% average change). If the results of this study are combined with the soy B20 results from Tables 4 and 5 (recently published studies), the average change in NO_x is 0.9%±1.5% (95% confidence interval).

Based on the studies reviewed and the new data reported here, there does not appear to be a discrepancy between engine and chassis testing studies for the effect of B20 on NO_x emissions. The apparent disagreement that exists between engine testing results and chassis testing results in EPA's 2002 review occurred because neither of these datasets is representative of the on-road fleet. Newer studies are not more representative, but if all of the available data are viewed together we conclude that B20 has no significant impact on NO_x.

A preliminary examination of real-time NO_x emissions data did not reveal any consistent reason for the wide range in NO_x emission results for different vehicles. It is recommended that the real-time data be more fully analyzed in a study that considers the effect of vehicle speed and acceleration, as well as wheel horsepower and rate of change of horsepower. Additionally, modeling of the vehicle transmission to estimate actual engine torque output is recommended. Given the significant amount of additional data now available, an updating and revision of the EPA review is also recommended. And it is further recommended that strict quality criteria be applied, and studies with inadequate documentation, methodology, or controls be rejected.

Appendix: Detailed Chassis Test Data

Table 25. RTD Transit Bus #1 – CSHVC – LSD A

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
2/1/2005	Base	332	John	2002	19.90	0.906	4.18	0.2380	6.65	686	4.68	72	69
2/1/2005	Base	333	Stuart	2007	20.56	1.033	3.74	0.2185	6.63	683	4.70	74	68
2/2/2005	Base	337	John	2058	19.69	0.816	3.48	0.3055	6.65	714	4.50	67	73
2/2/2005	Base	338	Stuart	2023	19.81	0.854	3.08	0.2616	6.64	686	4.68	69	74
2/2/2005	Base	339	John	2031	19.33	0.789	3.78	0.3263	6.68	688	4.67	69	74
2/2/2005	Base	340	Stuart	1971	19.54	0.829	3.32	0.2940	6.67	672	4.77	71	75
Average				**2015**	**19.80**	**0.871**	**3.60**	**0.2740**	**6.65**	**688**	**4.67**	**70**	**72**
Standard Deviation				*29*	*0.42*	*0.089*	*0.39*	*0.0416*	*0.02*	*14*	*0.09*	*3*	*3*
Coefficient of Variation				1.5%	2.1%	10.2%	10.8%	15.2%	0.3%	2.0%	1.9%	3.6%	4.3%

Table 26. RTD Transit Bus #1 – CSHVC – B20 (LSD A and BlueSun Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
2/1/2005	B20	326	Stuart	2,003	18.78	0.604	2.48	0.2421	6.62	719	4.43	69	73
2/1/2005	B20	328	John	1,979	18.54	0.598	2.94	0.2200	6.66	712	4.54	70	73
2/1/2005	B20	329	John	2,013	18.83	0.581	2.69	0.2365	6.67	719	4.50	69	74
2/2/2005	B20	345	John	2,012	18.36	0.485	2.97	0.2603	6.71	712	4.55	69	76
2/2/2005	B20	346	Stuart	1,985	18.83	0.729	2.35	0.1961	6.64	696	4.65	70	76
2/2/2005	B20	347	Stuart	1,952	18.57	0.754	2.36	0.2037	6.68	691	4.69	71	76
Average				**1,991**	**18.65**	**0.625**	**2.63**	**0.2264**	**6.66**	**708**	**4.56**	**70**	**75**
Standard Deviation				*24*	*0.19*	*0.100*	*0.28*	*0.0244*	*0.03*	*12*	*0.09*	*1*	*2*
Coefficient of Variation				1.2%	1.0%	16.0%	10.6%	10.8%	0.5%	1.7%	2.1%	0.9%	2.1%

Table 27. RTD Transit Bus #2 – CSHVC – LSD A

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
2/4/2005	Base	364	Stuart	1,955	19.81	0.806	2.84	0.2178	6.65	689	4.67	71	73
2/4/2005	Base	365	Stuart	1,941	19.86	0.818	2.77	0.2001	6.68	689	4.67	71	73
2/4/2005	Base	366	John	1,975	19.24	0.724	3.64	0.2901	6.66	704	4.57	72	72
2/4/2005	Base	367	John	1,977	19.08	0.938	3.60	0.2804	6.66	699	4.60	73	71
2/7/2005	Base	371	Stuart	2,035	19.97	0.731	3.37	0.6017	6.64	760	4.23	69	73
2/7/2005	Base	372	John	1,968	18.68	0.747	4.35	0.3358	6.69	712	4.52	73	72
Average				**1,975**	**19.44**	**0.794**	**3.43**	**0.3210**	**6.66**	**709**	**4.54**	**72**	**72**
Standard Deviation				*32*	*0.52*	*0.081*	*0.58*	*0.1462*	*0.02*	*26*	*0.16*	*2*	*1*
Coefficient of Variation				1.6%	2.7%	10.2%	17.0%	45.6%	0.3%	3.7%	3.6%	2.3%	1.1%

Table 28. RTD Transit Bus #2 – CSHVC – B20 (LSD A and BlueSun Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
2/4/2005	B20	358	John	2,070	19.01	0.542	3.18	0.2583	6.66	765	4.24	73	73
2/4/2005	B20	359	Stuart	1,960	18.75	0.566	2.37	0.1933	6.65	750	4.33	71	75
2/4/2005	B20	360	John	1,990	18.47	0.546	2.93	0.2439	6.71	743	4.37	71	75
2/4/2005	B20	362	Stuart	1,967	19.17	0.564	2.43	0.1581	6.72	730	4.44	72	73
2/7/2005	B20	377	John	2,044	18.33	0.533	3.61	0.3261	6.70	729	4.45	74	75
2/7/2005	B20	378	Stuart	1,965	18.38	0.597	2.38	0.1868	6.68	707	4.59	74	73
2/7/2005	B20	379	John	1,954	18.20	0.616	2.53	0.1821	6.68	703	4.62	75	71
2/7/2005	B20	380	Stuart	1,978	19.08	0.608	2.42	0.1714	6.68	713	4.55	74	70
Average				**1,991**	**18.67**	**0.571**	**2.73**	**0.2150**	**6.68**	**730**	**4.45**	**73**	**73**
Standard Deviation				*43*	*0.38*	*0.032*	*0.46*	*0.0568*	*0.02*	*22*	*0.13*	*2*	*2*
Coefficient of Variation				2.1%	2.0%	5.6%	16.9%	26.4%	0.4%	3.0%	3.0%	2.2%	2.3%

Table 29. RTD Transit Bus #3 – CSHVC – LSD A

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
9/8/2005	Base	725	Stuart	2,052	19.59	0.781	3.23	0.3421	6.69	693	4.61	73	75
9/8/2005	Base	726	Stuart	2,066	20.02	0.845	3.21	0.3457	6.68	697	4.59	78	77
9/8/2005	Base	727	Stuart	2,051	20.06	0.835	3.05	0.3144	6.68	689	4.64	68	80
9/12/2005	Base	752	Stuart	2,061	19.63	0.831	3.09	0.2954	6.68	700	4.57	76	75
9/12/2005	Base	753	Stuart	2,041	19.78	0.815	2.80	0.2579	6.67	699	4.57	72	76
9/12/2005	Base	754	Stuart	2,045	19.61	0.835	2.87	0.2919	6.67	696	4.59	76	76
Average				**2,053**	**19.78**	**0.824**	**3.04**	**0.3079**	**6.68**	**695**	**4.60**	**73**	**78**
Standard Deviation				*9*	*0.21*	*0.023*	*0.18*	*0.0333*	*0.01*	*4*	*0.03*	*5*	*2*
Coefficient of Variation				0.5%	1.1%	2.8%	5.8%	10.8%	0.1%	0.6%	0.6%	6.5%	3.1%

Table 30. RTD Transit Bus #3 – CSHVC – B20 (LSD A and BlueSun Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
9/8/2005	B20	729	Stuart	2,040	18.92	0.578	2.66	0.2511	6.69	708	4.55	75	76
9/8/2005	B20	730	Stuart	2,032	18.96	0.654	2.63	0.2615	6.67	708	4.55	76	79
9/8/2005	B20	731	Stuart	2,029	18.79	0.666	2.74	0.2612	6.67	706	4.56	78	77
9/12/2005	B20	749	Stuart	2,090	19.32	0.523	2.27	0.2379	6.67	723	4.47	73	74
9/12/2005	B20	750	Stuart	2,095	19.17	0.587	2.23	0.2235	6.69	724	4.46	73	74
9/12/2005	B20	751	Stuart	2,101	19.09	0.546	2.33	0.2332	6.69	723	4.47	74	75
Average				**2,064**	**19.04**	**0.592**	**2.48**	**0.2447**	**6.68**	**715**	**4.51**	**76**	**77**
Standard Deviation				*34*	*0.19*	*0.057*	*0.22*	*0.0157*	*0.01*	*9*	*0.05*	*2*	*1*
Coefficient of Variation				1.7%	1.0%	9.7%	9.0%	6.4%	0.2%	1.2%	1.1%	2.1%	1.6%

Table 31. RTD Transit Bus #3 – CSHVC – LSD B

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
9/9/2005	Base	735	Stuart	2,055	20.40	0.817	2.69	0.2522	6.68	693	4.61	73	76
9/9/2005	Base	736	Stuart	2,042	20.27	0.834	2.80	0.2437	6.67	683	4.68	77	78
9/9/2005	Base	737	Stuart	2,068	20.74	0.818	2.87	0.2631	6.68	696	4.59	75	78
9/12/2005	Base	746	Stuart	2,086	20.20	0.860	3.36	0.3192	6.68	708	4.52	75	76
9/12/2005	Base	747	Stuart	2,032	19.78	0.803	3.45	0.3061	6.67	697	4.59	76	77
9/12/2005	Base	748	Stuart	2,057	20.05	0.810	3.25	0.2989	6.68	699	4.57	77	77
Average				**2,057**	**20.24**	**0.824**	**3.07**	**0.2805**	**6.68**	**696**	**4.59**	**75**	**77**
Standard Deviation				*19*	*0.32*	*0.021*	*0.32*	*0.0314*	*0.01*	*8*	*0.05*	*2*	*1*
Coefficient of Variation				0.9%	1.6%	2.5%	10.4%	11.2%	0.1%	1.2%	1.2%	2.6%	1.3%

Table 32. RTD Transit Bus #3 – CSHVC – B20 (LSD B and Agland Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
9/9/2005	B20	739	Stuart	2,032	19.94	0.685	2.69	0.2316	6.67	706	4.56	78	79
9/9/2005	B20	740	Stuart	2,029	20.07	0.719	2.50	0.2159	6.66	706	4.56	82	76
9/9/2005	B20	741	Stuart	2,040	19.96	0.695	2.46	nm	6.70	721	4.46	74	76
9/12/2005	B20	743	Stuart	2,087	19.48	0.545	2.91	0.2435	6.67	718	4.49	73	74
9/12/2005	B20	744	Stuart	2,055	19.54	0.667	2.66	0.2250	6.66	717	4.49	72	75
9/12/2005	B20	745	Stuart	2,041	19.19	0.644	2.99	0.2458	6.68	724	4.45	76	75
Average				**2,047**	**19.70**	**0.659**	**2.70**	**0.2324**	**6.67**	**716**	**4.50**	**78**	**77**
Standard Deviation				*21*	*0.35*	*0.062*	*0.22*	*0.0126*	*0.02*	*8*	*0.05*	*4*	*2*
Coefficient of Variation				1.0%	1.8%	9.3%	8.0%	5.4%	0.2%	1.1%	1.1%	5.2%	2.4%

Table 33. International Class 8 Truck – CILCCmod – LSD C

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
04/19/06	Base	1,105	Greg	2,347	11.18	1.165	4.79	0.2844	12.70	749	4.28	75	74
04/19/06	Base	1,106	Greg	2,357	10.98	1.222	5.05	0.2975	12.67	744	4.31	78	74
04/19/06	Base	1,107	Greg	2,328	10.96	1.189	5.09	0.2851	12.72	728	4.37	74	76
Average				**2,344**	**11.04**	**1.192**	**4.98**	**0.2890**	**12.70**	**740**	**4.32**	**75**	**75**
Standard Deviation				*15*	*0.12*	*0.029*	*0.16*	*0.0074*	*0.03*	*11*	*0.05*	*2*	*1*
Coefficient of Variation				0.6%	1.1%	2.4%	3.3%	2.6%	0.2%	1.5%	1.0%	2.7%	1.4%

Table 34. International Class 8 Truck – CILCCmod – B20 (LSD C and Agland Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
04/19/06	B20	1,102	Greg	2,321	11.02	1.01	4.28	0.2141	12.72	760	4.23	72	73
04/19/06	B20	1,103	Greg	2,326	11.20	1.01	4.24	0.2052	12.73	756	4.25	72	74
04/19/06	B20	1,104	Greg	2,311	10.87	0.96	4.12	0.2116	12.75	769	4.18	73	74
Average				**2,320**	**11.03**	**0.992**	**4.22**	**0.2103**	**12.73**	**762**	**4.22**	**72**	**73**
Standard Deviation				*8*	*0.16*	*0.030*	*0.08*	*0.0046*	*0.02*	*6*	*0.04*	*0*	*0*
Coefficient of Variation				0.3%	1.5%	3.0%	2.0%	2.2%	0.1%	0.8%	0.9%	0.6%	0.6%

Table 35. International Class 8 Truck – Freeway Cycle – LSD C

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
04/18/06	Base	1,093	Greg	1,899	6.73	0.51	2.13	0.2259	15.40	588	5.42	81	73
04/18/06	Base	1,094	Greg	1,897	6.74	0.52	2.10	0.2077	15.42	583	5.46	80	75
04/18/06	Base	1,095	Greg	1,904	6.76	0.51	2.16	0.2152	15.40	586	5.43	77	75
Average				**1,900**	**6.75**	**0.515**	**2.13**	**0.2163**	**15.41**	**586**	**5.44**	**79**	**74**
Standard Deviation				*4*	*0.02*	*0.003*	*0.03*	*0.0092*	*0.01*	*2*	*0.02*	*2*	*1*
Coefficient of Variation				0.2%	0.2%	0.5%	1.5%	4.2%	0.1%	0.4%	0.4%	2.5%	1.8%

Table 36. International Class 8 Truck – Freeway Cycle – B20 (LSD C and Agland Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
04/18/06	B20	1,097	Greg	1,884	7.00	0.45	1.80	0.1410	15.40	594	5.41	76	74
04/18/06	B20	1,099	Greg	1,867	6.85	0.44	1.85	0.1404	15.42	591	5.44	82	73
04/18/06	B20	1,100	Greg	1,883	6.86	0.46	1.80	0.1422	15.43	596	5.39	81	74
Average				**1,878**	**6.90**	**0.452**	**1.82**	**0.1412**	**15.42**	**594**	**5.41**	**79**	**74**
Standard Deviation				*10*	*0.09*	*0.008*	*0.03*	*0.0009*	*0.02*	*3*	*0.02*	*3*	*0*
Coefficient of Variation				0.5%	1.2%	1.8%	1.6%	0.6%	0.1%	0.4%	0.4%	4.1%	0.6%

Table 37. Freightliner Class 8 Truck – CSHVC – 2007 Cert Diesel

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
06/28/06	Base	1,157	Greg	2,886	28.89	0.541	nm	2.1352	6.64	911	3.50	72	75
06/28/06	Base	1,158	Greg	2,927	29.64	0.517	nm	nm	6.64	923	3.45	70	75
06/28/06	Base	1,159	Greg	2,909	29.26	0.585	nm	nm	6.68	915	3.48	72	76
07/05/06	Base	1,167	Greg	2,910	29.79	0.543	28.83	1.8259	6.66	931	3.42	90	78
07/05/06	Base	1,168	Greg	2,796	30.16	0.519	26.18	1.6310	6.70	890	3.57	89	78
07/05/06	Base	1,169	Greg	2,848	30.15	0.509	27.21	1.7292	6.68	908	3.50	93	79
Average				**2,879**	**29.65**	**0.536**	**27.41**	**1.8303**	**6.67**	**913**	**3.49**	**81**	**77**
Standard Deviation				*49*	*0.50*	*0.028*	*1.34*	*0.2183*	*0.02*	*14*	*0.05*	*11*	*2*
Coefficient of Variation				1.7%	1.7%	5.2%	4.9%	11.9%	0.4%	1.5%	1.5%	13.3%	2.2%

Table 38. Freightliner Class 8 Truck – CSHVC – B20 (2007 Cert Diesel and Agland Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
06/28/06	B20	1,160	Greg	2,944	30.44	0.432	nm	nm	6.67	947	3.40	75	75
06/28/06	B20	1,161	Greg	2,860	29.94	0.438	nm	1.5571	6.67	924	3.48	73	77
06/28/06	B20	1,162	Greg	2,910	30.64	0.442	nm	1.4961	6.65	947	3.39	69	76
07/05/06	B20	1,164	Greg	2,951	30.73	0.493	23.29	1.4679	6.43	946	3.40	76	79
07/05/06	B20	1,165	Greg	2,827	30.02	0.447	23.61	1.3207	6.67	911	3.52	89	79
07/05/06	B20	1,166	Greg	2,880	29.78	0.474	26.55	1.5385	6.65	935	3.43	91	78
Average				**2,895**	**30.26**	**0.454**	**24.49**	**1.4761**	**6.62**	**935**	**3.44**	**79**	**77**
Standard Deviation				*49*	*0.40*	*0.024*	*1.80*	*0.0936*	*0.10*	*15*	*0.05*	*9*	*2*
Coefficient of Variation				1.7%	1.3%	5.3%	7.3%	6.3%	1.4%	1.6%	1.6%	11.3%	2.0%

Table 39. Freightliner Class 8 Truck – Freeway Cycle – 2007 Cert Diesel

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
07/06/06	Base	1,171	Greg	1,699	22.25	0.216	8.09	0.4767	15.50	538	5.91	85	77
07/06/06	Base	1,172	Greg	1,745	22.54	0.209	8.17	0.6062	15.50	545	5.84	85	79
07/06/06	Base	1,173	Greg	1,741	22.08	0.172	7.93	0.5470	15.51	542	5.87	96	78
07/07/06	Base	1,183	Greg	1,708	22.11	0.211	8.78	0.4604	15.49	537	5.92	93	79
07/07/06	Base	1,184	Greg	1,689	21.65	0.190	8.19	0.4138	15.51	535	5.95	93	77
07/07/06	Base	1,185	Greg	1,688	22.98	0.201	7.68	0.3913	15.50	538	5.92	94	77
Average				**1,712**	**22.27**	**0.200**	**8.14**	**0.4826**	**15.50**	**539**	**5.90**	**91**	**78**
Standard Deviation				*25*	*0.45*	*0.016*	*0.37*	*0.0813*	*0.01*	*4*	*0.04*	*5*	*1*
Coefficient of Variation				1.5%	2.0%	8.2%	4.5%	16.8%	0.0%	0.7%	0.6%	5.3%	1.2%

Table 40. Freightliner Class 8 Truck – Freeway Cycle – B20 (2007 Cert Diesel and Agland Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
07/06/06	B20	1,176	Greg	1,732	23.31	0.134	7.80	0.4001	15.50	559	5.75	99	78
07/06/06	B20	1,177	Greg	1,720	23.04	0.168	7.64	0.3702	15.50	554	5.79	96	77
07/06/06	B20	1,178	Greg	1,717	23.04	0.166	7.63	0.3646	15.50	552	5.81	101	77
07/07/06	B20	1,180	Greg	1,721	23.69	0.182	7.41	0.3368	15.50	552	5.82	91	77
07/07/06	B20	1,181	Greg	1,713	23.10	0.173	7.55	0.3259	15.50	551	5.83	89	79
07/07/06	B20	1,182	Greg	1,695	22.27	0.184	7.43	0.3401	15.51	551	5.83	89	80
Average				**1,716**	**23.08**	**0.168**	**7.58**	**0.3563**	**15.50**	**553**	**5.81**	**94**	**78**
Standard Deviation				*12*	*0.47*	*0.018*	*0.15*	*0.0274*	*0.00*	*3*	*0.03*	*5*	*1*
Coefficient of Variation				0.7%	2.0%	10.8%	1.9%	7.7%	0.0%	0.5%	0.5%	5.4%	1.5%

Table 41. Motor Coach – CSHVC – 2007 Cert Diesel

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
5/25/2006	Base	1,115	Greg	1,510	7.77	0.21	4.51	0.2686	6.67	487	6.60	71	72
5/25/2006	Base	1,116	Greg	1,492	7.87	0.23	4.41	0.2432	6.68	484	6.64	75	73
5/25/2006	Base	1,117	Greg	1,513	7.49	0.27	4.16	0.2926	6.68	489	6.58	75	73
5/26/2006	Base	1,127	Greg	1,504	7.78	0.22	4.06	0.2397	6.67	486	6.61	76	74
5/26/2006	Base	1,128	Greg	1,489	7.87	0.21	3.63	0.2345	6.68	481	6.68	68	74
5/26/2006	Base	1,129	Greg	1,501	7.70	0.23	3.56	0.2439	6.68	482	6.66	73	74
Average				**1,501**	**7.75**	**0.23**	**4.05**	**0.2538**	**6.68**	**485**	**6.63**	**73**	**73**
Standard Deviation				*10*	*0.14*	*0.02*	*0.39*	*0.0224*	*0.01*	*3*	*0.04*	*3*	*1*
Coefficient of Variation				0.6%	1.8%	10.3%	9.7%	8.8%	0.1%	0.6%	0.6%	4.1%	1.5%

Table 42. Motor Coach – CSHVC – B20 (2007 Cert Diesel and Agland Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
5/25/2006	B20	1,119	Greg	1,484	8.01	0.18	3.40	0.1797	6.68	491	6.59	71	75
5/25/2006	B20	1,120	Greg	1,488	8.23	0.19	3.30	0.1868	6.68	493	6.56	69	75
5/25/2006	B20	1,121	Greg	1,496	7.86	0.20	3.18	nm	6.67	497	6.52	73	75
5/26/2006	B20	1,123	Greg	1,495	7.80	0.20	2.88	0.1740	6.68	495	6.55	83	72
5/26/2006	B20	1,124	Greg	1,503	8.04	0.21	3.10	0.1810	6.67	493	6.57	69	72
5/26/2006	B20	1,125	Greg	1,507	7.82	0.20	3.03	0.1910	6.67	500	6.48	70	73
Average				**1,496**	**7.96**	**0.19**	**3.15**	**0.1825**	**6.67**	**495**	**6.54**	**72**	**74**
Standard Deviation				*9*	*0.16*	*0.01*	*0.19*	*0.0066*	*0.01*	*3*	*0.04*	*5*	*2*
Coefficient of Variation				0.6%	2.1%	4.5%	6.0%	3.6%	0.1%	0.7%	0.6%	7.5%	2.0%

Table 43. Motor Coach – UDDS – 2007 Cert Diesel

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
5/31/2006	Base	1,142	Stuart	1,378	7.18	0.14	3.73	0.2355	5.53	443	7.23	69	78
5/31/2006	Base	1,143	Stuart	1,366	6.98	0.11	4.04	0.2478	5.52	442	7.26	75	76
5/31/2006	Base	1,144	Stuart	1,368	7.07	0.13	3.51	0.2231	5.54	441	7.26	76	75
6/2/2006	Base	1,146	Stuart	1,462	6.80	0.16	3.70	0.2480	5.53	470	6.83	78	71
6/2/2006	Base	1,147	Stuart	1,465	6.97	0.15	3.46	0.2448	5.53	470	6.84	75	72
6/2/2006	Base	1,148	Stuart	1,462	6.94	0.14	3.49	0.2330	5.53	469	6.85	73	71
Average				**1,417**	**6.99**	**0.14**	**3.66**	**0.2387**	**5.53**	**456**	**7.05**	**74**	**74**
Standard Deviation				*51*	*0.13*	*0.02*	*0.22*	*0.0099*	*0.01*	*15*	*0.23*	*3*	*3*
Coefficient of Variation				3.6%	1.9%	12.4%	6.0%	4.2%	0.1%	3.3%	3.2%	3.9%	4.0%

Table 44. Motor Coach – UDDS – B20 (2007 Cert Diesel and Agland Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
5/31/2006	B20	1,136	Stuart	1,390	7.58	0.09	2.82	0.1530	5.52	455	7.12	70	74
5/31/2006	B20	1,137	Stuart	1,401	7.44	0.14	2.93	0.1552	5.52	461	7.02	76	73
5/31/2006	B20	1,140	Stuart	1,445	7.12	0.13	2.85	0.1521	5.53	476	6.80	76	74
6/2/2006	B20	1,149	Stuart	1,418	7.13	0.15	2.99	0.1723	5.53	466	6.95	72	73
6/2/2006	B20	1,150	Stuart	1,406	6.95	0.14	3.04	0.1814	5.53	460	7.04	69	73
6/2/2006	B20	1,151	Stuart	1,399	7.14	0.15	3.09	0.1892	5.53	457	7.09	65	74
Average				**1410**	**7.22**	**0.13**	**2.95**	**0.1672**	**5.53**	**462**	**7.00**	**71**	**73**
Standard Deviation				*20*	*0.24*	*0.02*	*0.11*	*0.0160*	*0.01*	*8*	*0.12*	*4*	*0*
Coefficient of Variation				1.4%	3.3%	17.8%	3.6%	9.6%	0.1%	1.7%	1.7%	6.1%	0.6%

Table 45. Green Diesel School Bus – RUCSBC– 2007 Cert Diesel

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
03/22/06	Base	993	Greg	2,134	8.78	0.03	0.04	0.0016	7.61	651	4.95	66	75
03/22/06	Base	994	Greg	2,149	nm	0.04	0.11	0.0019	7.61	654	4.92	58	76
03/22/06	Base	995	Greg	2,098	nm	0.02	0.06	0.0016	7.61	642	5.02	62	72
03/22/06	Base	996	Greg	2,091	nm	0.02	0.07	0.0013	7.62	644	5.00	67	70
03/23/06	Base	1,007	Greg	2,074	8.90	0.02	0.18	nm	7.63	632	5.10	65	74
03/23/06	Base	1,008	Greg	2,126	8.97	0.03	0.12	nm	7.62	651	4.94	64	74
03/23/06	Base	1,009	Greg	2,121	8.92	0.02	0.18	0.0015	7.62	652	4.93	66	74
03/23/06	Base	1,010	Greg	2,106	9.12	0.03	0.09	0.0015	7.64	651	4.94	63	74
03/24/06	Base	1,017	Greg	2,120	8.84	0.02	0.09	0.0013	7.61	648	4.97	66	74
03/24/06	Base	1,018	Greg	2,134	8.98	0.02	0.10	0.0008	7.62	654	4.92	66	74
Average				**2,115**	**8.93**	**0.02**	**0.10**	**0.0014**	**7.62**	**648**	**4.97**	**65**	**74**
Standard Deviation				*23*	*0.11*	*0.01*	*0.05*	*0.0003*	*0.01*	*7*	*0.06*	*3*	*2*
Coefficient of Variation				1.1%	1.2%	31.9%	45.5%	22.1%	0.1%	1.1%	1.1%	4.1%	2.2%

Table 46. Green Diesel School Bus – RUCSBC– B20 (2007 Cert Diesel and Agland Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
03/22/06	B20	998	Greg	2,098	8.83	0.05	0.09	0.0016	7.61	652	4.98	67	70
03/22/06	B20	999	Greg	2,101	nm	0.02	0.05	0.0019	7.62	647	5.02	64	70
03/22/06	B20	1,000	Greg	2,131	nm	0.01	0.03	0.0016	7.62	667	4.86	64	70
03/22/06	B20	1,001	Greg	2,110	9.14	0.02	0.03	nm	7.61	656	4.94	64	71
03/23/06	B20	1,003	Greg	2,127	9.34	0.02	0.04	0.0019	7.61	660	4.92	58	71
03/23/06	B20	1,004	Greg	2,124	9.21	0.02	0.06	0.0020	7.60	667	4.87	65	73
03/23/06	B20	1,005	Greg	2,120	9.18	0.02	0.12	0.0011	7.62	661	4.91	65	73
Average				**2,116**	**9.14**	**0.02**	**0.06**	**0.0017**	**7.61**	**659**	**4.93**	**64**	**71**
Standard Deviation				*13*	*0.19*	*0.01*	*0.03*	*0.0003*	*0.01*	*7*	*0.06*	*3*	*1*
Coefficient of Variation				0.6%	2.1%	55.0%	55.0%	19.6%	0.1%	1.1%	1.2%	4.2%	1.8%

Table 47. Green Diesel School Bus – CSHVC – 2007 Cert Diesel

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
03/14/06	Base	950	Greg	1,734	7.99	0.03	0.35	0.0014	6.68	567	5.66	64	73
03/14/06	Base	951	Greg	1,700	7.79	0.04	0.09	0.0011	6.70	554	5.80	64	72
03/14/06	Base	952	Greg	1,719	7.38	0.05	0.14	0.0011	6.70	559	5.75	66	72
03/15/06	Base	954	Greg	1,716	7.67	-0.05	0.25	0.0012	6.69	555	5.80	65	71
03/15/06	Base	955	Greg	1,706	7.47	0.04	0.12	0.0009	6.70	565	5.70	67	76
03/15/06	Base	956	Greg	1,693	7.41	0.02	0.07	0.0016	6.70	556	5.78	67	75
03/16/06	Base	966	Greg	1,684	8.00	0.02	0.26	0.0009	6.71	536	6.01	65	72
03/16/06	Base	967	Greg	1,676	7.67	0.03	0.06	0.0008	6.71	539	5.97	69	72
03/16/06	Base	968	Greg	1,670	7.56	0.03	0.08	0.0006	6.71	545	5.91	59	73
03/21/06	Base	988	Greg	1,692	7.99	0.04	0.42	0.0007	6.69	544	5.91	63	73
03/21/06	Base	989	Greg	1,675	nm	-0.01	-0.02	0.0010	6.69	538	5.98	64	75
03/21/06	Base	990	Greg	1,684	nm	0.03	0.02	0.0003	6.69	544	5.91	65	73
03/21/06	Base	991	Greg	1,662	7.83	0.02	0.07	0.0006	6.69	540	5.96	65	71
Average				**1,693**	**7.70**	**0.02**	**0.15**	**0.0009**	**6.70**	**549**	**5.86**	**65**	**73**
Standard Deviation				*21*	*0.23*	*0.03*	*0.13*	*0.0004*	*0.01*	*11*	*0.11*	*2*	*1*
Coefficient of Variation				1.2%	3.0%	118.7%	90.1%	37.3%	0.1%	1.9%	1.9%	3.6%	1.9%

Table 48. Green Diesel School Bus – CSHVC – B20 (2007 Cert Diesel and Agland Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
03/15/06	B20	958	Greg	1,716	7.75	0.02	0.02	0.0011	6.70	568	5.71	72	71
03/15/06	B20	959	Greg	1,707	7.54	0.04	0.18	0.0014	6.70	560	5.78	65	70
03/15/06	B20	960	Greg	1,721	7.77	0.02	0.13	0.0010	6.69	554	5.85	69	67
03/16/06	B20	962	Greg	1,704	7.70	0.04	0.19	0.0012	6.70	574	5.65	57	74
03/16/06	B20	963	Greg	1,689	7.60	0.03	0.12	0.0014	6.70	566	5.72	64	73
03/16/06	B20	964	Greg	1,685	7.49	0.04	0.09	0.0013	6.70	566	5.73	64	73
Average				**1,704**	**7.64**	**0.03**	**0.12**	**0.0012**	**6.70**	**565**	**5.74**	**65**	**71**
Standard Deviation				*14*	*0.12*	*0.01*	*0.06*	*0.0002*	*0.00*	*7*	*0.07*	*5*	*2*
Coefficient of Variation				0.8%	1.5%	31.5%	52.2%	14.5%	0.1%	1.2%	1.2%	8.2%	3.2%

Table 49. Conventional School Bus – RUCSBC – 2007 Cert Diesel

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
08/09/06	Base	1,228	John	1,984	10.10	0.265	8.03	0.6554	7.61	643	4.93	88	76
08/09/06	Base	1,229	John	1,935	9.94	0.266	7.57	0.6193	7.60	622	5.09	84	76
08/09/06	Base	1,230	John	1,937	9.79	0.284	8.31	0.7038	7.65	627	5.05	88	75
08/09/06	Base	1,231	John	1,944	9.94	0.278	8.24	0.6731	7.63	624	5.07	89	75
08/11/06	Base	1,242	John	1,983	9.63	0.402	8.80	0.7604	7.63	636	4.98	87	75
08/11/06	Base	1,243	John	1,990	9.66	0.727	10.10	0.7370	7.63	645	4.91	88	76
08/11/06	Base	1,244	John	1,987	9.75	0.483	9.27	0.7303	7.63	640	4.95	86	75
08/11/06	Base	1,245	John	1,940	9.81	0.526	9.75	0.6841	7.63	625	5.07	86	74
08/17/06	Base	1,268	John	1,998	9.81	0.259	7.97	nm	7.65	640	4.96	89	74
08/17/06	Base	1,269	John	1,989	9.38	0.357	10.36	nm	7.63	636	4.98	88	76
08/17/06	Base	1,270	John	1,968	nm	0.320	9.50	nm	7.62	626	5.06	86	77
08/17/06	Base	1,271	John	1,968	nm	0.298	9.72	nm	7.63	630	5.03	87	76
08/17/06	Base	1,272	John	1,973	nm	0.383	8.75	nm	7.62	634	5.00	93	74
Average				**1,969**	**9.78**	**0.373**	**8.95**	**0.6954**	**7.63**	**633**	**5.01**	**88**	**75**
Standard Deviation				*22*	*0.20*	*0.137*	*0.90*	*0.0467*	*0.01*	*8*	*0.06*	*2*	*1*
Coefficient of Variation				1.1%	2.0%	36.6%	10.0%	6.7%	0.2%	1.2%	1.2%	2.5%	1.3%

Table 50. Conventional School Bus – RUCSBC – B20 (2007 Cert Diesel and Agland Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
08/09/06	B20	1,224	John	1,999	10.78	0.179	5.09	0.4875	7.67	657	4.90	87	74
08/09/06	B20	1,225	John	1,968	10.57	0.185	5.68	0.4818	7.60	646	4.98	87	75
08/09/06	B20	1,226	John	1,965	10.28	0.197	5.80	0.4818	7.64	641	5.02	85	78
08/09/06	B20	1,227	John	1,991	10.41	0.206	6.63	0.5317	7.63	654	4.92	82	77
08/11/06	B20	1,247	John	1,928	10.22	0.416	7.85	0.5171	7.62	632	5.10	89	75
08/11/06	B20	1,248	John	1,949	10.35	0.459	8.40	0.5820	7.62	643	5.00	84	75
08/11/06	B20	1,249	John	1,954	10.12	0.455	9.05	0.6172	7.62	642	5.02	91	75
Average				**1965**	**10.39**	**0.300**	**6.93**	**0.5284**	**7.63**	**645**	**4.99**	**86**	**76**
Standard Deviation				*24*	*0.22*	*0.135*	*1.52*	*0.0531*	*0.02*	*8*	*0.07*	*3*	*2*
Coefficient of Variation				1.2%	2.2%	45.2%	21.9%	10.0%	0.3%	1.3%	1.3%	3.6%	2.0%

Table 51. Conventional School Bus – CSHVC – 2007 Cert Diesel

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
08/01/06	Base	1,193	Greg	1,650	10.24	0.338	4.87	0.1954	6.69	533	5.95	96	74
08/01/06	Base	1,194	Greg	1,652	10.22	0.336	4.68	0.2016	6.67	544	5.83	80	75
08/01/06	Base	1,195	Greg	1,644	9.90	0.402	4.89	0.1882	6.69	538	5.90	81	78
08/02/06	Base	1,206	Greg	1,624	9.89	0.603	5.87	0.2114	6.69	543	5.83	77	78
08/02/06	Base	1,207	Greg	1,624	9.76	0.480	6.47	0.2517	6.70	537	5.89	83	79
08/03/06	Base	1,209	Greg	1,634	10.04	0.432	5.24	0.1972	6.70	535	5.93	81	73
08/03/06	Base	1,210	Greg	1,607	9.88	0.463	5.94	0.2371	6.69	528	6.01	86	74
08/03/06	Base	1,211	Greg	1,611	9.85	0.475	6.17	0.2439	6.70	517	6.13	85	74
08/03/06	Base	1,212	Greg	1,618	9.67	0.491	6.31	0.2429	6.70	531	5.97	97	77
08/10/06	Base	1,233	Greg	1,637	9.94	0.433	4.61	0.1436	6.69	535	5.93	86	74
08/10/06	Base	1,234	Greg	1,622	9.85	0.264	4.41	0.1460	6.68	528	6.00	85	73
08/10/06	Base	1,235	Greg	1,615	9.60	0.440	4.52	0.1417	6.69	535	5.92	84	73
08/10/06	Base	1,236	Greg	1,614	9.58	0.487	5.14	0.1624	6.69	539	5.88	84	74
08/10/06	Base	1,237	Greg	1,606	9.73	0.431	4.38	0.1370	6.70	537	5.90	84	73
08/10/06	Base	1,239	Greg	1,610	9.66	0.507	4.76	nm	6.70	537	5.90	85	73
Average				**1,620**	**9.85**	**0.439**	**5.22**	**0.1929**	**6.69**	**534**	**5.93**	**85**	**75**
Standard Deviation				*11*	*0.20*	*0.081*	*0.74*	*0.0414*	*0.01*	*7*	*0.08*	*5*	*2*
Coefficient of Variation				0.7%	2.0%	18.6%	14.1%	21.5%	0.1%	1.2%	1.3%	6.3%	2.8%

Table 52. Conventional School Bus – CSHVC – B20 (2007 Cert Diesel and Agland Biodiesel)

Date	Fuel	Run	Driver	CO_2 (g/mile)	NOx (g/mile)	THC (g/mile)	CO (g/mile)	PM (g/mile)	Distance (miles)	Fuel Cons (g/mile)	Fuel Econ (mpg)	Humidity (grain/lb)	Temp (F)
08/01/06	B20	1,198	Greg	1,624	9.83	0.419	6.22	0.2211	6.69	554	5.81	102	77
08/01/06	B20	1,199	Greg	1,623	9.65	0.473	7.06	0.2494	6.68	554	5.80	104	78
08/01/06	B20	1,200	Greg	1,608	9.51	0.439	6.90	0.2464	6.69	551	5.83	104	78
08/02/06	B20	1,202	Greg	1,641	10.21	0.346	4.69	0.1685	6.69	544	5.91	77	75
08/02/06	B20	1,203	Greg	1,622	9.73	0.386	5.46	0.1978	6.70	538	5.97	77	75
08/02/06	B20	1,204	Greg	1,615	9.63	0.336	5.60	0.2004	6.69	546	5.89	77	75
08/02/06	B20	1,205	Greg	1,624	9.60	0.447	6.48	0.2260	6.69	548	5.87	78	76
08/03/06	B20	1,214	Greg	1,616	9.95	0.383	6.18	0.2328	6.69	545	5.90	78	80
08/03/06	B20	1,215	Greg	1,602	9.67	0.395	5.94	0.2266	6.69	543	5.92	77	76
08/03/06	B20	1,216	Greg	1,592	9.82	0.407	6.11	0.2218	6.69	538	5.98	102	75
08/04/06	B20	1,218	Greg	1,641	9.96	0.515	5.96	0.2029	6.69	544	5.92	75	79
08/04/06	B20	1,219	Greg	1,620	9.61	0.473	5.92	0.1856	6.68	548	5.87	93	74
08/04/06	B20	1,220	Greg	1,626	9.71	0.531	5.98	0.1938	6.69	554	5.80	76	77
08/04/06	B20	1,221	Greg	1,620	9.77	0.756	6.81	0.2119	6.69	556	5.78	91	74
08/04/06	B20	1,222	Greg	1,612	9.53	0.562	6.59	0.2125	6.69	553	5.82	92	75
08/15/06	B20	1,251	Greg	1,673	9.55	0.352	4.96	0.1724	6.69	553	5.83	90	75
08/15/06	B20	1,252	Greg	1,656	9.55	0.355	4.50	0.1647	6.69	549	5.87	88	79
08/15/06	B20	1,254	Greg	1,655	10.43	0.326	3.58	0.1096	6.69	555	5.81	86	80
08/15/06	B20	1,255	Greg	1,645	10.24	0.342	3.68	0.1113	6.69	555	5.81	86	81
Average				**1,627**	**9.79**	**0.434**	**5.72**	**0.1977**	**6.69**	**549**	**5.86**	**87**	**77**
Standard Deviation				*20*	*0.26*	*0.105*	*1.01*	*0.0391*	*0.00*	*6*	*0.06*	*11*	*2*
Coefficient of Variation				1.2%	2.7%	24.1%	17.7%	19.8%	0.1%	1.0%	1.0%	12.1%	2.9%

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14. ABSTRACT *(Maximum 200 Words)*
The objective of this study was to determine if testing entire vehicles, vs. just the engines, on a heavy-duty chassis dynamometer provides a better, more realistic measurement of the impact of B20 on regulated pollutant emissions. This report also documents completion of the National Renewable Energy Laboratory's Fiscal Year 2006 Annual Operating Plan Milestone 10.4. This milestone supports the U.S. Department of Energy, Fuels Technologies Program Multiyear Program Plan Goal of identifying fuels that can displace 5% of petroleum diesel by 2010. Considering all of the data available, we conclude that B20 has no net impact on NOx.

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