Draft Final Memorandum

Assessment of the Emissions from the Use of California Air Resources Board Qualified Diesel Fuel in Comparison with Federal Diesel Fuels

Prepared for:
Mr. Jim Guthrie
California Air Resources Board
1001 "I" Street
P.O. Box 2815
Sacramento, CA 95812

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Submitted by:
Dr. Thomas D. Durbin
Dr. J. Wayne Miller
Dr. Kent Johnson
Ms. Maryam Hajbabaei
University of California
CE-CERT
Riverside, CA 92521
951-781-5791
951-781-5790 (fax)

Disclaimer

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Abstract

The California Air Resources Board is conducting a comprehensive study to better characterize the emissions impacts of federal diesel fuels and compare the results with the CARB ULSD. The goal of this study is to understand and, to the extent possible, the impacts of emissions from these fuels used in diesel engines. This memorandum summarizes the results from the engine testing under this comprehensive program. The testing described in this memorandum was conducted on a 2007 MBE4000 engine, a 2006 Cummins ISM engine, and a 1991 Detroit Diesel Series 60 engine in CE-CERT's engine dynamometer laboratory. The testing included a baseline CARB ultralow sulfur diesel (ULSD) fuel, two federal diesel feedstocks one referred to as "Federal A", represents an average Federal ultralow sulfur diesel fuel and the second, referred to as "Federal B", a commercially available Federal ultralow sulfur diesel fuel that due to its properties may contribute to higher exhaust emissions. Testing was conducted on two different engine test cycles, the FTP and the 50-mph cruise cycles.

Acronyms and Abbreviations

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

Executive Summary

Improving air quality throughout California is important, as it has a number of unattainment areas for ozone and particulate matter (PM). Diesel engines are one of the main contributors of PM and oxides of nitrogen (NO_x) formation and they have been the target of regulations for years. In California, diesel fuels need to provide emissions equivalent to a specified 10% aromatic reference fuel. As a result of this regulation California diesel fuel has become the cleanest burning fuel in the United States. While studies have shown that diesel fuels with reduced levels of aromatic and higher cetane numbers, such as those needed to meet the California regulation, can provide improved emissions, the actual impact of CARB diesel fuels have not been yet studied in detail, and it is also unknown how these fuels might impact new diesel engines with diesel particulate filters (DPF) or NO_x aftertreatment.

As technology for fuels and diesel engines continue to evolve, there is a need to understand and quantify the continuing impact that CARB diesel fuel will have on controlling diesel emissions into the future. This program provides an evaluation between California and Federal diesel fuels to provide a better understanding of the impact of CARB diesel fuel in-use in the California heavy-duty truck fleet. The program includes engine and chassis dynamometer emissions testing with three different fuels. The testing included a baseline CARB ultralow sulfur diesel (ULSD) fuel, and two federal diesel feedstocks representing an average Federal diesel and a Federal diesel fuel that represents a more extreme in terms of high emissions. This memorandum summarizes the results from the three engines tested under this comprehensive program.

Test Fuels, Engines, and Cycles

A total of three fuels were used for this test program. These test fuels included one representative CARB ultralow sulfur (CARB) diesel fuel and two Federal ultralow sulfur highway (Federal) diesel fuels. One of the Federal diesel fuels, referred to as "Federal A", represents an average Federal ultralow sulfur diesel fuel. The second, referred to as "Federal B", was a commercially available Federal ultralow sulfur diesel fuel that due to its properties may contribute to higher exhaust emissions. The engines were selected from 3 model year categories; 1991-1993, 2002-2006 and 2007+. The 1991-1993 engine was a 1991 Detroit Diesel Series 60 engine. This is the same engine model used for the certification of alternative CARB diesel formulation, and thus it serves as a baseline for comparison for this data to the newer engine technologies. The 2002-2006 engine was a 2006 model year Cummins engine. The engine from the 2007+ model year category was a 2007 Detroit Diesel MBE 4000. Two test cycles were used for this testing including the standard Federal Testing Procedure (FTP) and a cycle based on the 50 miles per hour (mph) CARB heavy heavy-duty diesel truck (HHDDT) cruise cycle.

Engine Testing Results

The emissions changes for all of the emissions and the associated values for the statistical comparisons are provided in Table ES-1 for all of the engines and the test cycles.

The NO_x emissions are shown in Figures ES-1, ES-2, and ES-3, respectively, for the 2007 MBE4000 engine, the 2006 Cummins engine, and the 1991 DDC series 60 engine. NO_x

emissions for the Federal A and Federal B fuels were higher than those for the CARB ULSD for all the engines and cycles. The NO_x increases compared to CARB for the different engines ranged from 4.7 to 10% for the two Federal fuels, were statistically significant for all cases, and were similar between the different test engines. For the 2006 Cummins and the 1991 DDC 60 engines, the emissions for the Federal B fuel were higher than those for the Federal A fuel for most cycle combinations. For 2007 MBE 4000 and 1991 DDC 60, the observed emissions impacts were greater for the FTP than the 50 mph cruise. The opposite trend was seen for the Federal A fuel for 2006 Cummins engine with respect to cycle differences, although this is probably due in part with some stability issues that were seen during the testing for the 50 mph cruise cycle for the Cummins engine.

The PM emissions are shown in Figures ES-4, ES-5, and ES-6, respectively, for the 2007 MBE4000 engine, the 2006 Cummins engine, and the 1991 DDC 60 series engine. The PM emissions showed statistically significant increases on the Federal A and B fuels for the Cummins engine over the FTP, but not over the 50 mph cruise cycle. For the MBE4000, PM emissions did not show any significant differences between fuels on either cycle. For the MBE4000, the values are very low, so the differences were within the measurement error at these levels. For the 1991 DDC 60 engine, the only statistically significant difference seen was for the Federal A on the 50 mph cruise cycle.

THC emissions on 1991 DDC 60 showed statistically significant differences between fuels ranging from a 14.4-29.5% increase using the Federal diesel fuels, while no consistent trends between different fuels for MBE4000 and 2006 Cummins ISM were observed.

CO Emissions for all the three engines showed higher emissions for both Federal diesel blends compared with CARB diesel. The CO emission increases were highest for the FTP cycle for all the three engines. The emissions differences between CARB diesel and the Federal diesels for the 2006 Cummins and the 1991 DDC 60 varied from approximately 3 to 23%.

CO_2 emissions showed slightly higher emissions for both Federal diesel blends and all three engines. The CO_2 emissions increases were relatively consistent between the three engines and ranged from 1-2%, with the Federal B fuel showing slightly higher increases than the Federal A fuel on the Cummins and DDC 60 engines.

Some trends of lower brake specific volumetric fuel consumption were seen for the Federal B fuel. The differences between Federal B and CARB ULSD over the FTP cycle for all three engines were statistically significant. For 1991 DDC 60, the differences between the CARB ULSD and Federal B were also statistically significant over the 50 mph cruise. The lower volumetric fuel consumption for the Federal B fuel is not unexpected, given that this fuel has a higher density than the other test fuels. The CARB and Federal A fuels did not show any significant differences in fuel consumption.

		THC		CO		NO_x		PM		CO_2		BSFC	
	CARB vs.	**% diff**	**P value**	**% diff**	**P value**	**% diff**	**P value**	**% diff**	**P value**	**% diff**	**P value**	**% diff**	**P value**
2007 MBE 4000													
FTP	Federal B	27%	0.135	51%	0.000	7.3%	0.000	53%	0.752	1.4%	0.000	-0.9%	0.000
Cruise	Federal B	-14%	0.270	31%	0.024	4.7%	0.000	109%	0.297	2.0%	0.000	-0.4%	0.255
2006 Cummins ISM													
FTP	Federal A	-1%	0.633	17%	0.000	6.7%	0.000	5%	0.000	1.3%	0.000	-0.1%	0.667
	Federal B	12%	0.000	23%	0.000	7.9%	0.000	8%	0.000	1.3%	0.000	-1.0%	0.002
Cruise	Federal A	-13%	0.000	5%	0.041	9.5%	0.001	0%	0.831	0.9%	0.004	-0.5%	0.080
	Federal B	0%	0.904	9%	0.002	8.1%	0.020	3%	0.278	2.0%	0.000	-0.4%	0.348
1991 DDC													
FTP	Federal A	14%	0.000	9%	0.000	7.5%	0.000	2%	0.425	1.7%	0.003	0.3%	0.524
	Federal B	30%	0.000	12%	0.000	9.3%	0.000	3%	0.341	1.2%	0.013	-1.2%	0.014
Cruise	Federal A	1%	0.756	5%	0.009	5.3%	0.000	7%	0.011	1.4%	0.000	-0.1%	0.589
	Federal B	14%	0.000	3%	0.070	7.3%	0.000	2%	0.330	1.7%	0.000	-0.7%	0.000

Table ES-1. Percentages changes for Federal Diesel blends relative to CARB and associated statistical p values for 2007 MBE 4000, 2006 Cummins ISM and 1991 DDC Engines

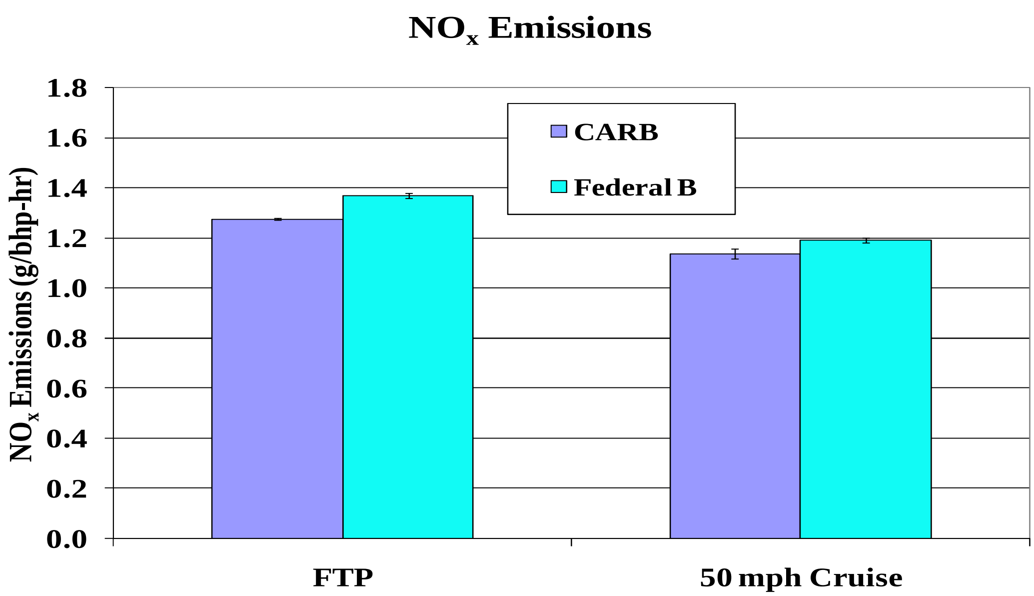


Figure ES-1. Average NO_x Emission Results for the 2007 MBE4000

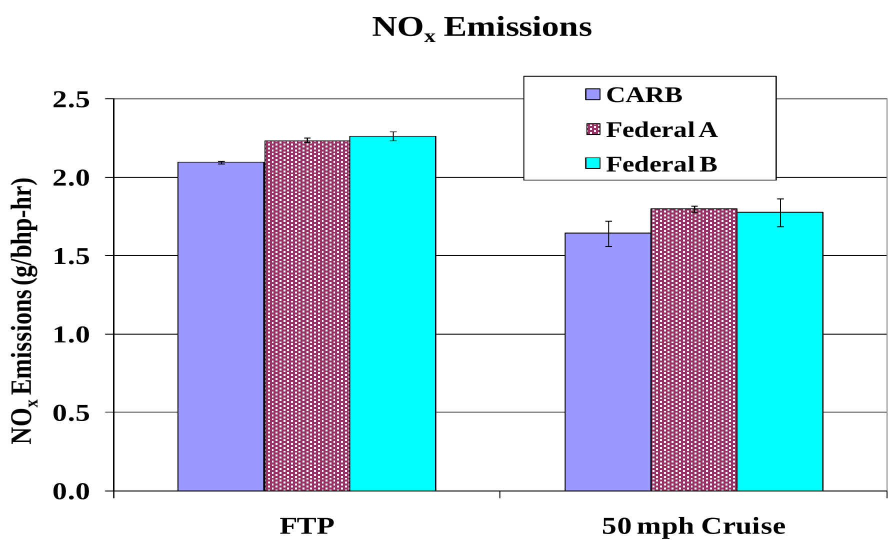


Figure ES-2. Average NO_x Emission Results for the 2006 Cummins ISM

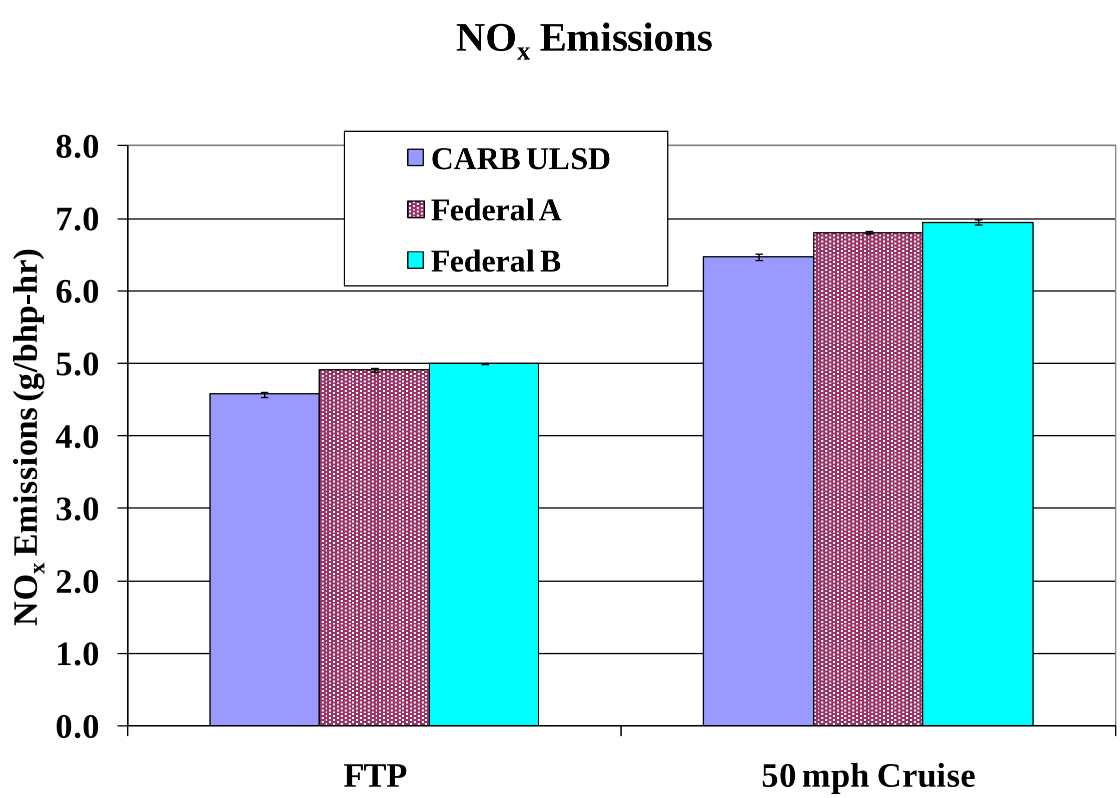


Figure ES-3. Average NO_x Emission Results for the 1991 Detroit Diesel Series 60

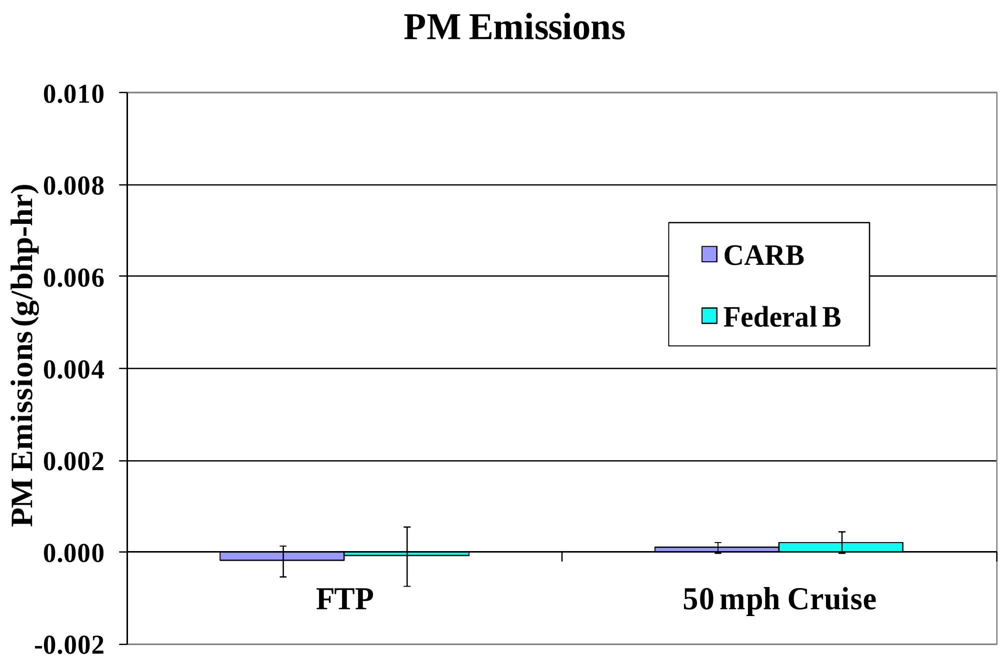


Figure ES-4. Average PM Emission Results for the 2007 MBE4000

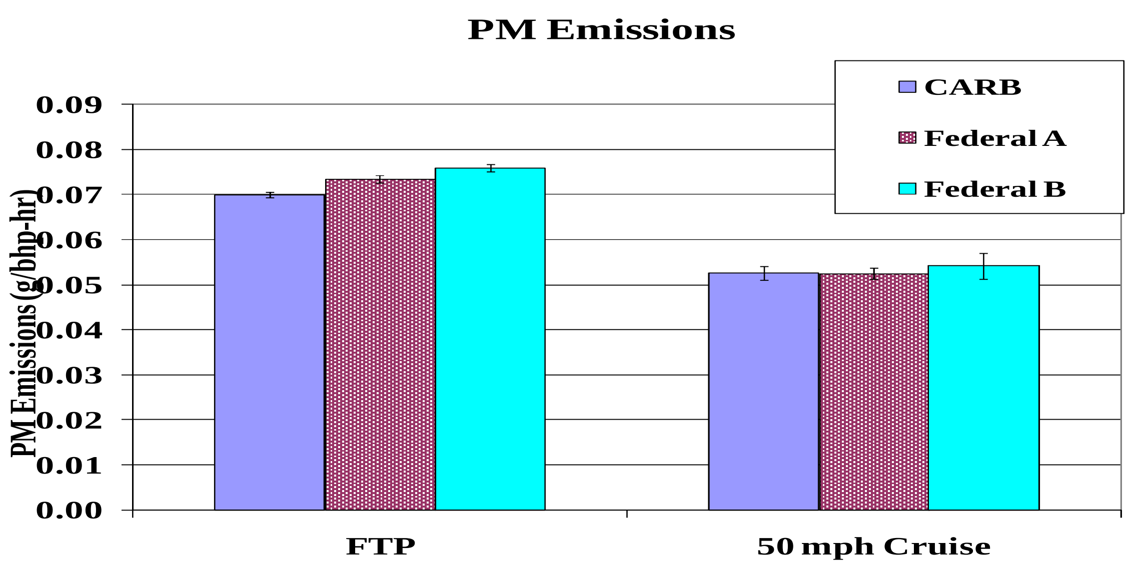


Figure ES-5. Average PM Emission Results for the 2006 Cummins ISM

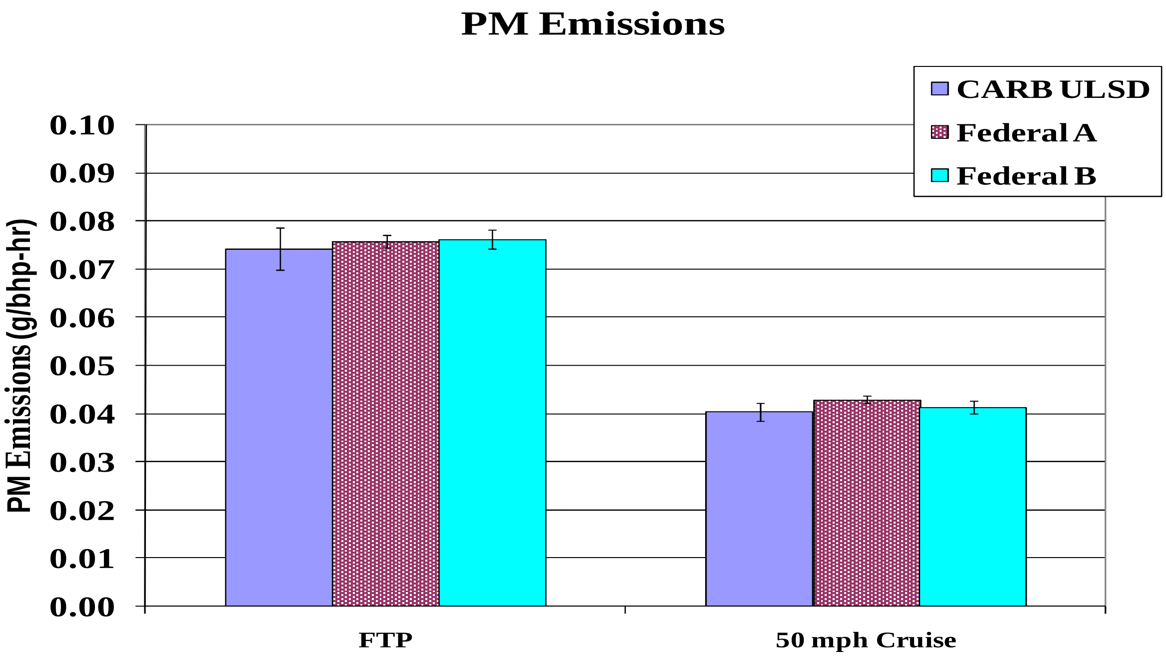


Figure ES-6. Average PM Emission Results for the 1991 Detroit Diesel Series 60

1.0 Introduction

The importance of improving air quality throughout California is well documented and California has a number of metropolitan areas that remain in unattainment status for ozone and particulate matter. Diesel engines are primary contributors to the emissions inventory for both particulate matter (PM) and oxides of nitrogen (NO_x) and have been the target of regulations for a number of years. NO_x can have direct health impacts, can contribute to ozone formation, and can contribute to secondary PM formation. Associations between ambient PM and adverse health effects have also been well documented in numerous studies and the California Air Resources Board (CARB) designated PM emitted from diesel engines as a Toxic Air Contaminant (TAC) in 1998.

Regulations to control diesel emissions have target both the engine technology as well as the diesel fuels used in the engines. In California, diesel fuel regulations mandate that fuels sold in the state must meet the requirement of 10% or less aromatic hydrocarbon content, or show emissions that are equivalent to a 10% aromatic reference fuel. The development of the California diesel fuel regulations are based on numerous studies that have shown that certain fuel parameters such as aromatics, cetane number, and sulfur can have an important impact on diesel emission levels. The California diesel fuel regulations have provided the State with a diesel fuel that is the cleanest burning in the United States and in important element of the State's plan to improve air quality.

While numerous studies have shown that diesel fuels with reduced levels of aromatic and higher cetane numbers can provide improved emissions, the actual impact of CARB diesel fuels on in-use diesel emissions has not been extensively studied. Diesel engine technology has also evolved considerably over the past decade and the newest technology engines are equipped with diesel particulate filters (DPFs) to control PM. As of 2010, diesel engines will be equipped with additional aftertreatment to further control NO_x emissions. Additionally, Federal diesel fuels have also evolved as ultralow sulfur levels have now been implemented nationwide to facility the use of these aftertreatment devices. As technology for fuels and diesel engines continue to evolve, it is important to understand and quantify the continuing impact that CARB diesel fuel has on controlling diesel emissions as we move into the future.

This program provides an evaluation between California and Federal diesel fuels to provide a better understanding of the impact of CARB diesel fuel in-use in the California heavy-duty truck fleet. The test program includes both heavy-duty chassis dynamometer testing and more controlled engine dynamometer testing. The engine dynamometer testing provides a comparison between the different fuels under more controlled conditions. The heavy-duty chassis dynamometer testing will include a wider range of engine technologies from the latest technologies with aftertreatment for either PM and/or NO_x to older technologies where the fuel benefits will likely be more significant. The vehicles will be tested over a standard cycle to provide a comparison of emissions differences between fuels under conditions representative of real-world driving. A total of 3 fuels are being tested, including a CARB-certified diesel fuel and 2 Federal diesel fuels. This memorandum describes the results of the engine dynamometer portion of the program.

2.0 Experimental Procedures

2.1 Test Fuels

A total of three fuels were used for this test program. These test fuels included one representative CARB ultralow sulfur (CARB) diesel fuel and two Federal ultralow sulfur highway (Federal) diesel fuels. One of the Federal diesel fuels, referred to as "Federal A", represents an average Federal ultralow sulfur diesel fuel. The second, referred to as "Federal B", was a commercially available Federal ultralow sulfur diesel fuel that due to its properties may contribute to higher exhaust emissions.

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

The Federal A fuel is a federal certification fuel and it was obtained directly from a specialty fuel provider. This fuel was also selected because it has properties that represent an average federal diesel fuel, especially for aromatics, API gravity, and cetane number.

The Federal B fuel was obtained from a commercial retailer outside of California. It is heavier than the Federal A fuel, having a lower API gravity, higher aromatic hydrocarbon content, and lower cetane number than the Federal A fuel.

The fuel property ranges targeted for the three test fuels were based on CARB's Fuels Enforcement data, a California Energy Commission (CEC) refinery survey, Alliance of Automobile Manufacturers' North American Fuel Surveys, a Northrop Grumman Diesel Fuel Oil Survey, and additional proprietary fuel survey data. The fuel property ranges were discussed and approved by the Advisory Panel.

Fuel analyses for the six targeted fuel properties along with ASTM D975-specified properties have been conducted on the CARB and the two Federal diesel fuels. The analyses were conducted in triplicate. The majority of the analyses were conducted by CARB in their fuel laboratory in El Monte, CA. The cetane number analyses were conducted at the Southwest Research Institute (SwRI) in San Antonio, TX. A summary of the averaged results of the analyses for the selected properties of the test fuels is provided in Table 2-1.

Table 2-1. Selected Fuel properties

	CARB ULSD	Federal A Diesel	Federal B Diesel
API gravity (@ 60ºF)	36.8	35.2	34.0
Aromatics, vol. %	19.1	30.6	36.0
Cetane number,	50.4	45.5	44.1
Distillation, IBP			
T50,ºF	477	487	493
T90, ºF	606	581	618
Sulfur, ppm	7	13	5

2.2 Engine Selection

The engines were selected from three model year categories; 2007+, 2002-2006 and 1991-1993. The 2007 engine model year represents the latest technology that is available at present. The 2002-2006 engines are estimated to represent an important contribution to the emissions inventory from the present through 2017. The 1991 -1993 engine category was included since this is the engine model category that is used as the basis of comparison for CARB's diesel fuel certification program.

The engine selected from the 2007+ model year category was a 2007 Detroit Diesel MBE 4000. This engine was pulled from a truck purchased specifically for this project and a complementary CARB program on biodiesel emissions. The Detroit Diesel MBE 4000 is a 12.8 liter diesel engine that also employs cooled EGR and a passive/active diesel oxidation catalyst (DOC)/DPF combination. The specifications of the engine are provided in Table 2-2.

Table 2-2.Test Engine Properties

Engine Manufacturer	Detroit Diesel Corp.
Engine Model	MBE4000
Model Year	2007
Engine Family Name	7DDXH12.8DJA
Engine Type	In-line 6 cylinder, 4 stroke
Displacement (liter)	12.8
Power Rating (hp)	Varies, 350-450 hp @ 1900 rpm
Fuel Type	Diesel
Induction	Turbocharger with after cooler

The 2002-2006 engine was a 2006 model year Cummins engine. This engine was also pulled from a truck purchased specifically for this project and a complementary CARB program on biodiesel emissions. The specifications of the engine are provided in Table 2-3.

Table 2-3. Test Engine Properties

Engine Manufacturer	Cummins, Inc.
Engine Model	ISM 370
Model Year	2006
Engine Family Name	6CEXH0661MAT
Engine Type	In-line 6 cylinder, 4 stroke
Displacement (liter)	10.8
Power Rating (hp)	385 @ 1800 rpm
Fuel Type	Diesel
Induction	Turbocharger with charge air cooler

CE-CERT's in-house 1991 Detroit Diesel series 60 engine was used for the 1991-1993 model year category. This is the same engine platform that has formed the basis of CARB's diesel fuel certification program. The specifications for this engine are provided in Table 2-4.

Table 2-4.Test Engine Properties

Engine Manufacturer	Detroit Diesel Corp.
Engine Model	Series 60
Model Year	1991
Engine Family Name	MDD11.1FZA2
Engine Type	In-line 6 cylinder, 4 stroke
Displacement (liter)	11.1
Power Rating (hp)	360 @ 1800 rpm
Fuel Type	Diesel
Induction	Turbocharger with after cooler

2.3 Test Cycles

Two test cycles were used for this testing including the standard Federal Testing Procedure (FTP) and a cycle based on the 50 miles per hour (mph) CARB heavy heavy-duty diesel truck (HHDDT) cruise cycle.

The 50 mph Cruise cycle was developed separately for the three engines. For the 2007 the 50 mph Cruise cycle was developed based on engine parameters downloaded during chassis dynamometer testing that was conducted before the engine was removed from the truck. The vehicle with the 2007 MBE4000 engine was operated over the 50 mph Cruise cycle approximately 7 times. Since the 50 mph Cruise cycle represented a heavier load cycle and was based on the vehicle being run at its fully loaded weight. The J1939 signal with the engine parameters was collected from the test vehicle while it was driven on the chassis dynamometer.

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

For the 2006 Cummins engine, engine parameter data for the 50 mph Cruise cycle were not collected from the vehicle prior to when the engine was removed. Similarly for the 1991 DDC series 60 engine, this engine was not taken from a vehicle, so the corresponding parameter data for the 50 mph Cruise cycle was not available. For these engines, an engine dynamometer test cycle version of this cycle that was developed for the ACES program was utilized (Clark et al., 2007). This cycle was developed from data collected through the E55/59 chassis dynamometer study of heavy-duty trucks.

2.4 Test Matrix

The test matrix was developed to provide a sufficient number of replicates and a randomization of the test matrix. The sequence of the testing for each engine was the same. This general sequence is shown in Table 2-5.

Table 2-5. Engine Dynamometer Test Matrix for each Test Engine

Test Day				
Heavy-Duty FTP Test Cycle				
Day 1	CCC	AAA	AAA	BBB
Day 2	BBB	CCC		
ARB HHDDT Cruise Test Cycle				
Day 2			CCC	AAA
Day 3	AAA	BBB	BBB	CCC

C = CARB diesel fuel, A = Federal A diesel fuel, B = Federal B diesel fuel

2.5 Emissions Testing

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

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

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

3.0 Engine Testing Results

3.1 NO_x Emissions

The NO_x emission results for the testing on the three test engines are presented in Figure 3-1, Figure 3-2, and Figure 3-3, respectively, on a gram per brake horsepower hour (g/bhp-hr) basis. The results for each test cycle/fuel combination represent the average of all test runs done on that particular combination. The error bars represent one standard deviation on the average value.

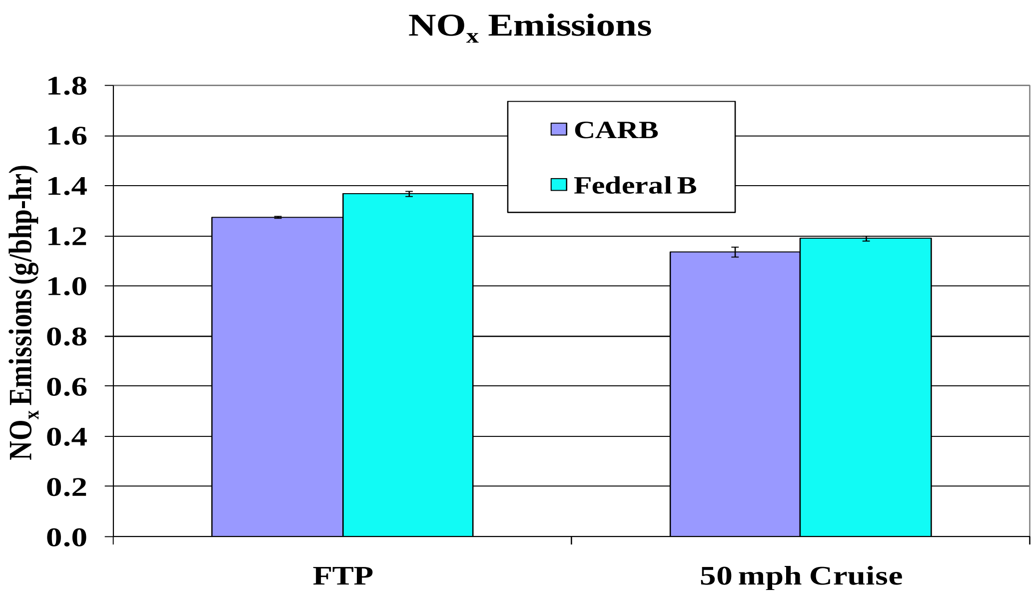


Figure 3-1.Average NO_x Emission Results for the 2007 MBE4000

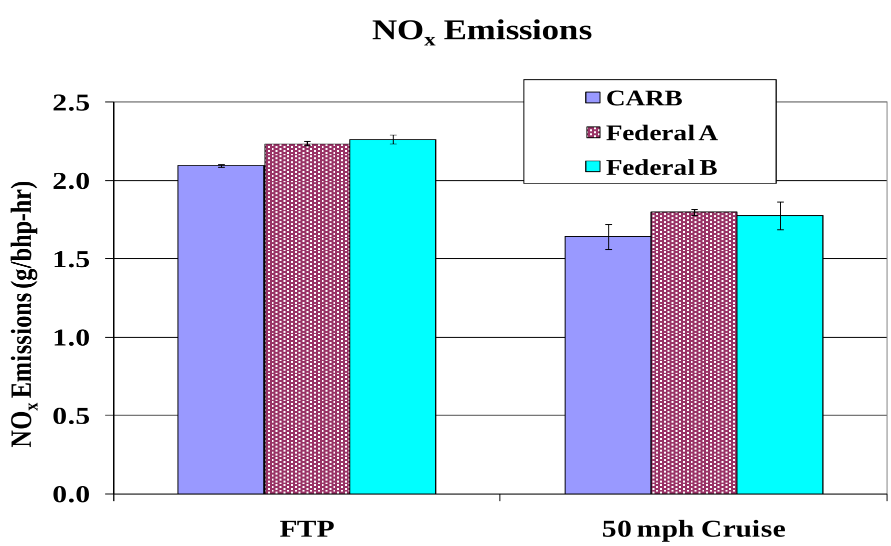


Figure 3-2.Average NO_x Emission Results for the 2006 Cummins ISM

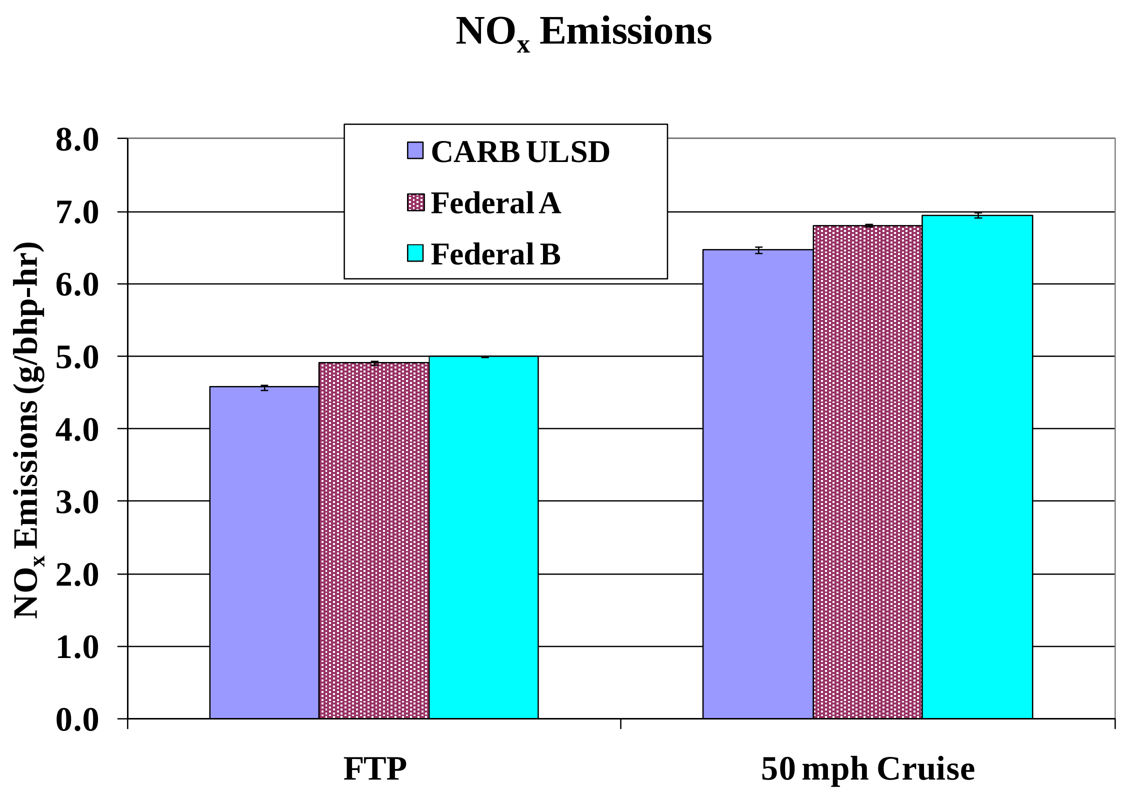


Figure 3-3. Average NO_x Emission Results for the 1991 Detroit Diesel Series 60

The average NO_x emissions for the Federal A and Federal B fuels were higher than those of the CARB baseline fuel. Table 3-1 shows the percentage differences for the different fuels on the different engines and different test cycles, along with the associated p-values for statistical comparisons using a 2-tailed, 2 sample equal variance t-test. These statistical analyses provide information on the statistical significance of the different findings. For the discussion in this memorandum, results are considered to be statistically significant for p values $\leq$0.05.

NO_x emissions for the Federal A and Federal B fuels were higher than those for the CARB ULSD for all the engines and cycles. The NO_x increases compared to CARB for the different engines ranged from 4.7 to 10% for the two Federal fuels, were statistically significant for all cases, and were similar between the different test engines. For the 2006 Cummins and the 1991 DDC 60 engines, the emissions for the Federal B fuel were higher than those for the Federal A fuel for most cycle combinations. For the Cummins engine, a marginally statistically significant difference (p=0.073) was found between the NO_x emissions for the FTP for the Federal A and Federal B fuels, with the emissions for the Federal B fuel being approximately 1.2% higher. The differences between the NO_x emissions for the Federal A and B fuels over the 50 mph cruise was not statistically significant (p=0.523), however. For the 1991 DDC 60, the NO_x emissions were about 1.8-2% higher for the Federal B diesel fuel compared with Federal A diesel fuel over the two cycles, with all the differences being statistically significant. The impacts of test cycle on the emissions differences between fuels over the three engines can be evaluated. For 2007 MBE 4000 and 1991 DDC 60, the observed emissions impacts were greater for the FTP than the 50 mph cruise, while the opposite trend was seen for the Federal A fuel for 2006 Cummins engine.

		2007 MBE4000			2006 Cummins ISM			1991 DDC 60		
	CARB vs.	**Ave.**	**% Diff**	**P-values**	**Ave.**	**% Diff**	**P-values**	**Ave.**	**% Diff**	**P-values**
FTP	**CARB**	1.2748			2.0962			4.5723		
	Federal A	-	-	-	2.2357	6.7%	0.000	4.9132	7.5%	0.000
	Federal B	1.3678	7.3%	0.000	2.2625	7.9%	0.000	4.9972	9.3%	0.000
50 mph Cruise	**CARB**	1.1365			1.6427			6.4697		
	Federal A		-	-	1.7988	9.5%	0.001	6.8097	5.3%	0.000
	Federal B	1.1898	4.7%	0.000	1.7750	8.1%	0.020	6.9450	7.3%	0.000

Table 3-1. NO_x Percentage Differences Between the Federal Diesel Fuel and the CARB ULSD base fuel for each Cycle [g/bhp-hr basis].

For the 2006 Cummins Engine, there were some issues with the stability of the NO_x emissions on the 50 mph cruise. In particular, for some few tests with the Federal B and CARB fuels NO_x emissions were approximately 0.1-0.2 g/bhp-hr lower than comparable earlier tests. These differences were found for the last two tests on the Federal B diesel fuel and the last 3 tests on the CARB diesel for the cruise cycle. These can be attributed to differences in operation that were observed between approximately 300 to 450 seconds into the cycle, as shown in Figure 3-4, and were not fuel related. Although these changes did not impact the fact that there are statistically significant differences between the Federal A and B and CARB fuels, they did impact the magnitude of these differences. For example, the percentage difference for the Federal A fuel (10%) is higher than that for the Federal B fuel (8.1%) for the Cummins 50 mph cruise because the conditions for the lower test results were not found for any of the Federal A tests. It should be noted that some additional FTPs were run following the completion of the testing on the 50 mph cruise cycle. The FTP emissions were found to be stable and essentially the same as those measured earlier in the program, indicating that the engine was running properly and stably for the FTP.

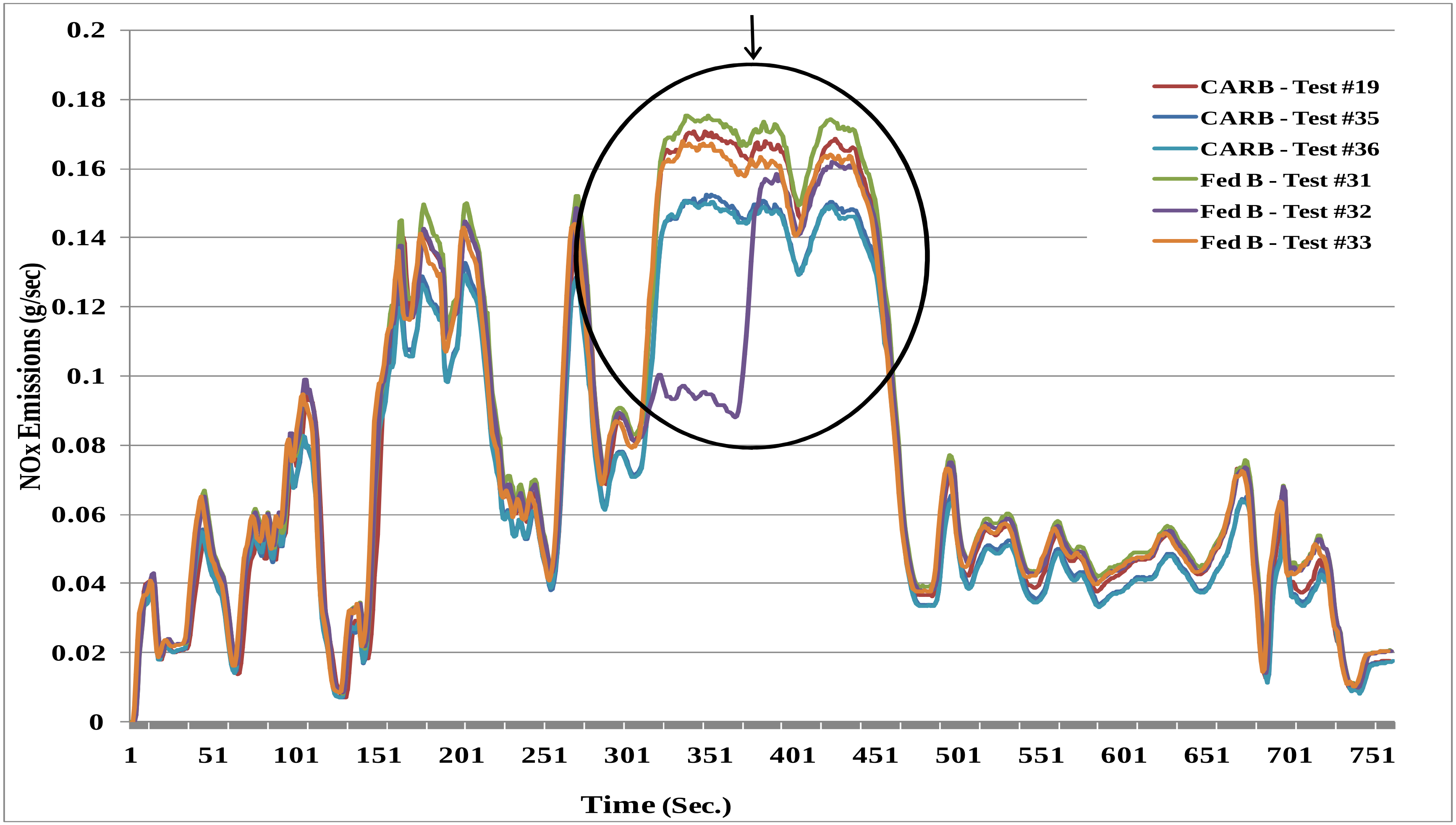


Figure 3-4. Real-Time NO_x Emission Traces for the 50 MPH CARB Cruise Cycle for the CARB and Federal B diesel blend.

3.2 PM Emissions

The PM emission results for the testing on the three test engines are presented in Figure 3-5, Figure 3-6, and Figure 3-7, respectively, on a g/bhp-hr basis. Table 3-2 shows the percentage differences for the different fuels for the different test cycles for both test engines, along with the associated p-values for statistical comparisons using a t-test.

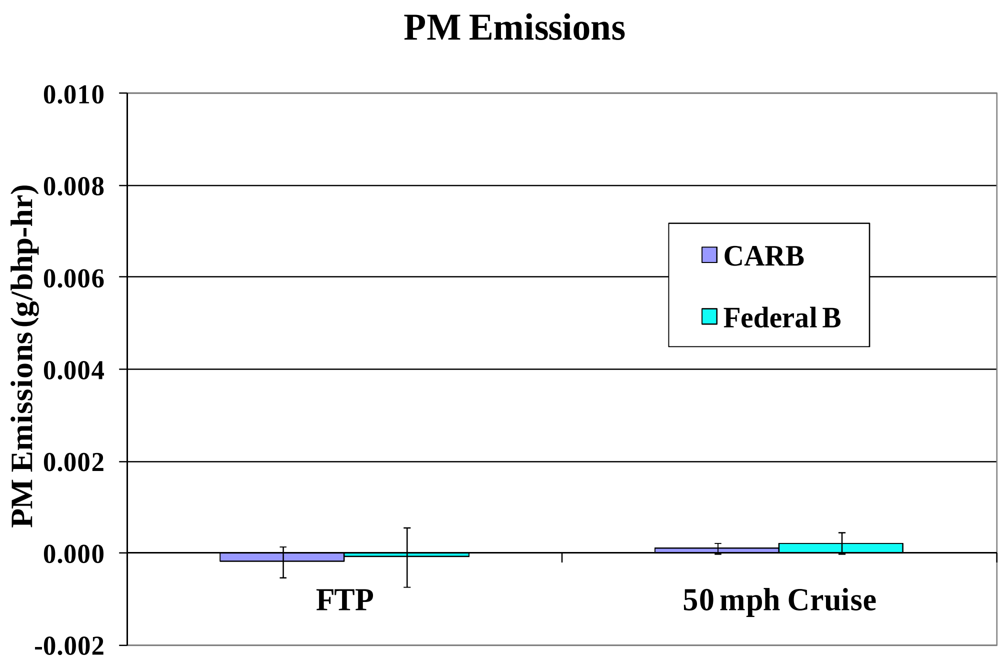


Figure 3-5. Average PM Emission Results for the 2007 MBE4000

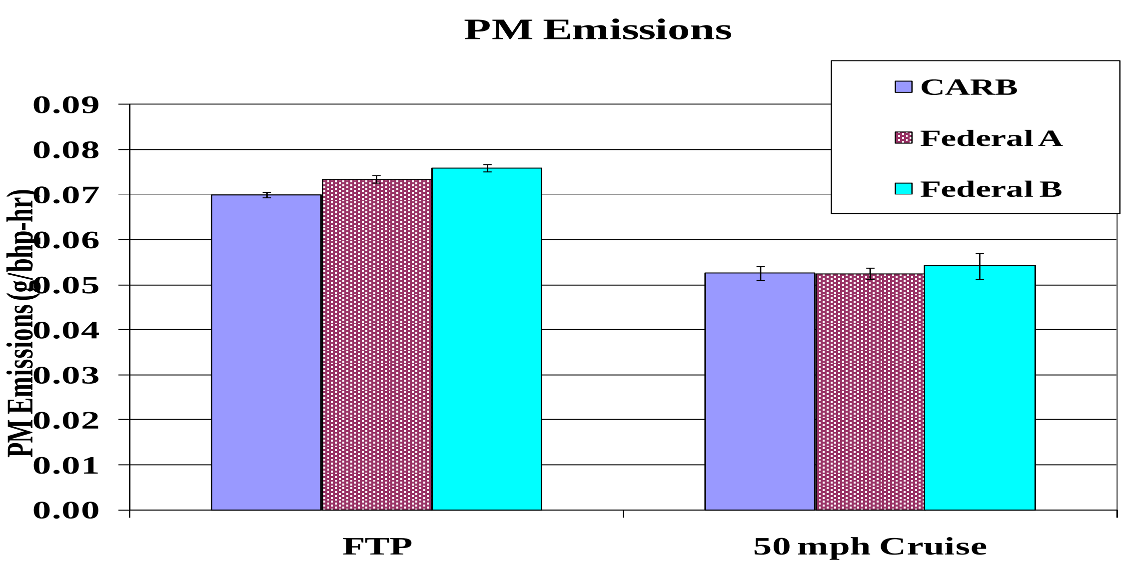


Figure 3-6. Average PM Emission Results for the 2006 Cummins ISM

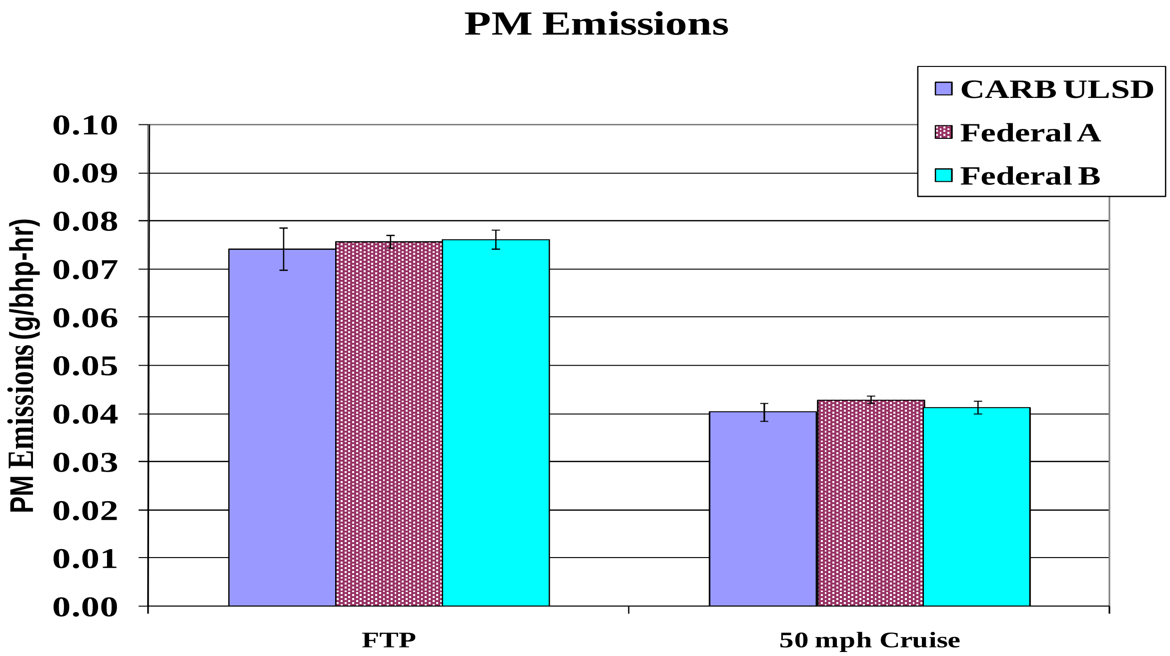


Figure 3-7. Average PM Emission Results for the 1991 Detroit Diesel Series 60

The PM emissions showed statistically significant increases on the Federal A and B fuels for the Cummins engine over the FTP, but not over the 50 mph cruise cycle or for the MBE4000. For the MBE4000, the values are very low, so the differences are within the measurement error at these levels.

		2007 MBE4000			2006 Cummins ISM			1991 DDC 60		
	CARB vs.	**Ave.**	**% Diff**	**P-values**	**Ave.**	**% Diff**	**P-values**	**Ave.**	**% Diff**	**P-values**
FTP	**CARB**	0.000			0.070			0.074		
	Federal A	-	-	-	0.073	5%	0.000	0.076	2%	0.425
	Federal B	0.000	53%	0.752	0.076	8%	0.000	0.076	3%	0.341
50 mph Cruise	**CARB**	0.000			0.053			0.040		
	Federal A	-	-	-	0.052	0%	0.831	0.043	7%	0.011
	Federal B	0.000	109%	0.297	0.054	3%	0.278	0.041	2%	0.330

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

3.3 THC Emissions

The THC emission results for the testing with the Federal Diesel feedstock on the three different test engines are presented in Figure 3-8, Figure 3-9, and Figure 3-10 respectively, on a g/bhp-hr basis. Table 3-3 shows the percentage differences for the different fuels for the different test cycles for both test engines, along with the associated p-values for statistical comparisons using a t-test.

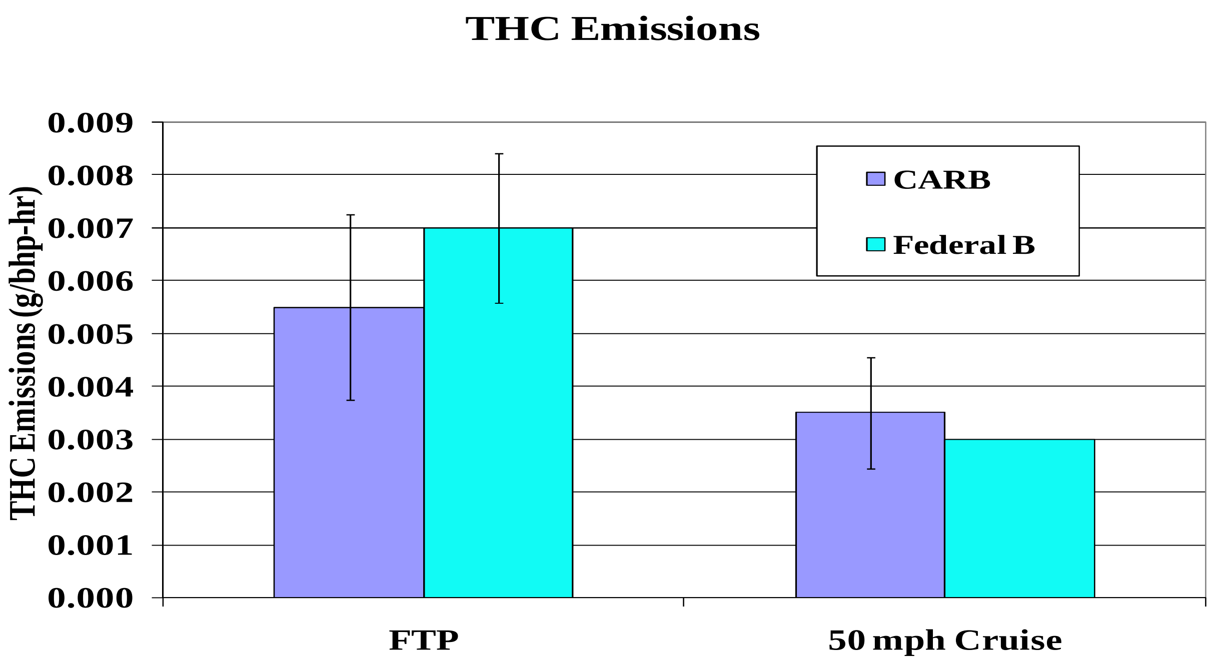


Figure 3-8. Average THC Emission Results for the 2007 MBE4000

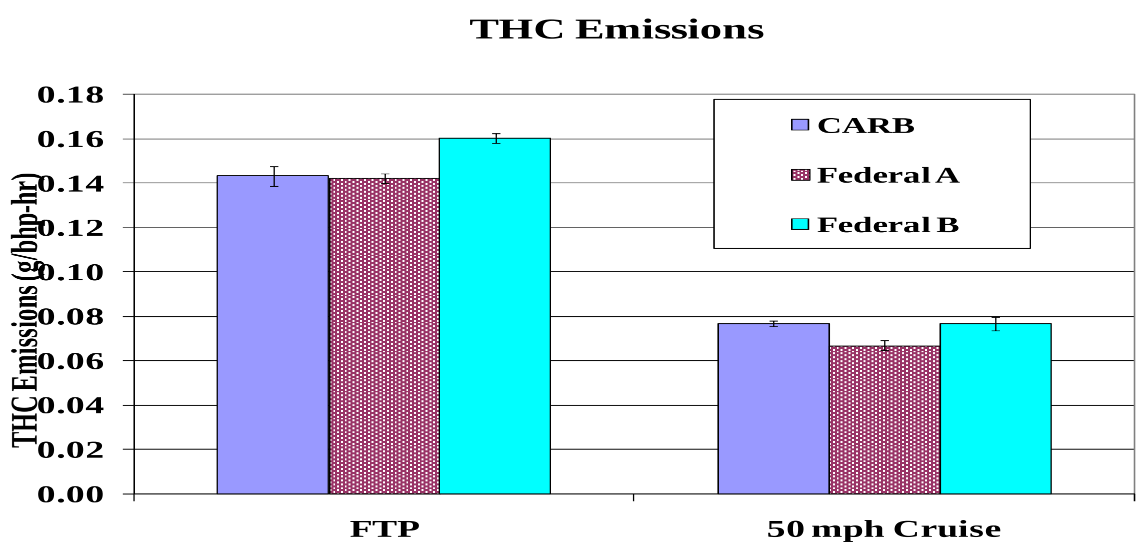


Figure 3-9. Average THC Emission Results for the 2006 Cummins ISM

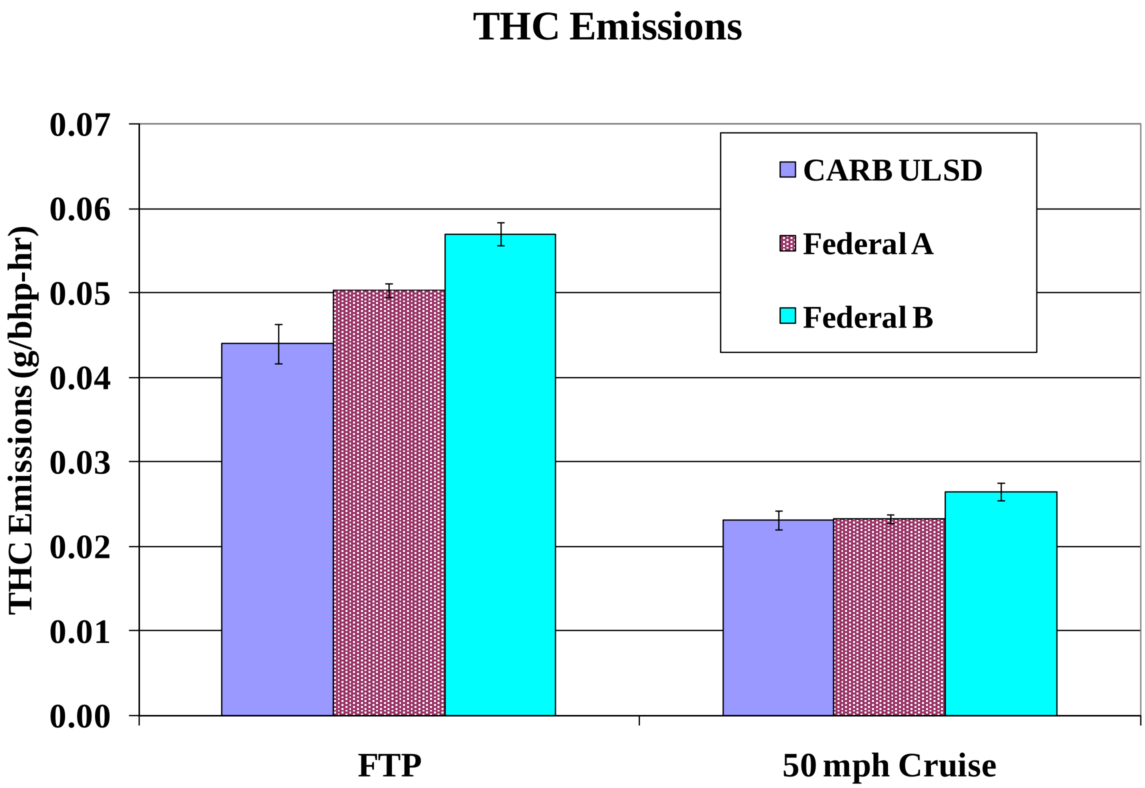


Figure 3-10. Average THC Emission Results for the 1991 Detroit Diesel Series 60

		2007 MBE4000			2006 Cummins ISM			1991 DDC 60		
	CARB vs.	**Ave.**	**% Diff**	**P-values**	**Ave.**	**% Diff**	**P-values**	**Ave.**	**% Diff**	**P-values**
FTP	**CARB**	0.006			0.143			0.044		
	Federal A		-	-	0.142	-1%	0.633	0.050	14%	0.000
	Federal B	0.007	27%	0.135	0.160	12%	0.000	0.057	30%	0.000
50 mph Cruise	**CARB**	0.004			0.077			0.023		
	Federal A		-	-	0.067	-13%	0.000	0.023	1%	0.756
	Federal B	0.003	-14%	0.270	0.077	0%	0.904	0.027	14%	0.000

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

THC emissions on 1991 DDC 60 showed statistically significant differences between fuels, while no consistent trends between different fuels for MBE4000 and 2006 Cummins ISM were observed. The 1991 DDC 60 showed higher emissions in comparison with CARB ULSD over FTP cycle for both Federal diesel blends. The same trend was also seen over the 50 cruise for the Federal B, but not for the Federal A fuel. For the MBE4000, the emissions levels were very low and near the measurement threshold. The Cummins engine showed some unusual trends in that, for the FTP, the Federal B fuel showed the highest emissions with the emissions from the

Federal A and CARB fuels being similar, whereas for the 50 mph cruise cycle, the emissions for the Federal A fuel were lowest with the emissions of the Federal B and CARB fuel being similar.

3.4 CO Emissions

The CO emission results for the testing with the three test engines are presented in Figure 3-11, Figure 3-12, and Figure 3-13 , respectively, on a g/bhp-hr basis. Table 3-4 shows the percentage differences for the different fuels for the different test cycles for both test engines, along with the associated p-values for statistical comparisons using a t-test.

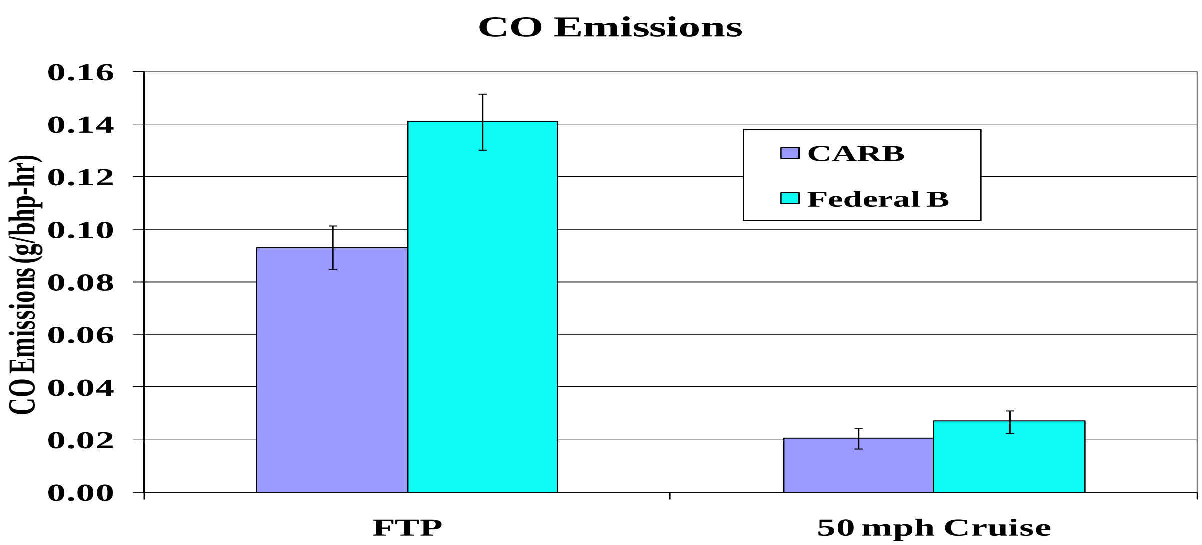


Figure 3-11. Average CO Emission Results for the 2007 MBE4000

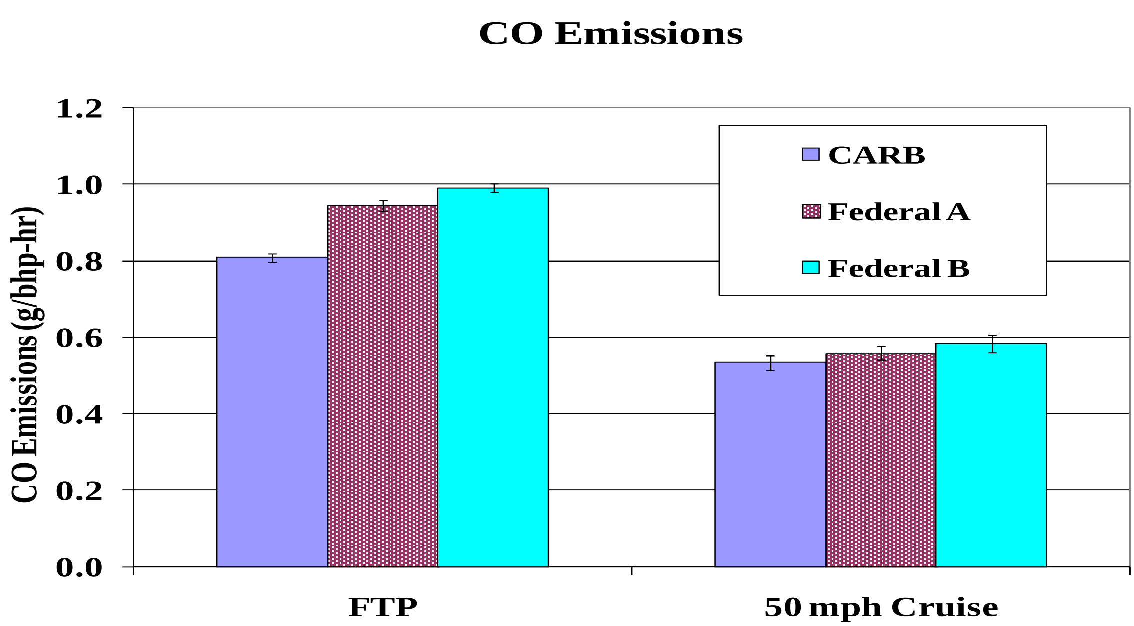


Figure 3-12. Average CO Emission Results for the 2006 Cummins ISM

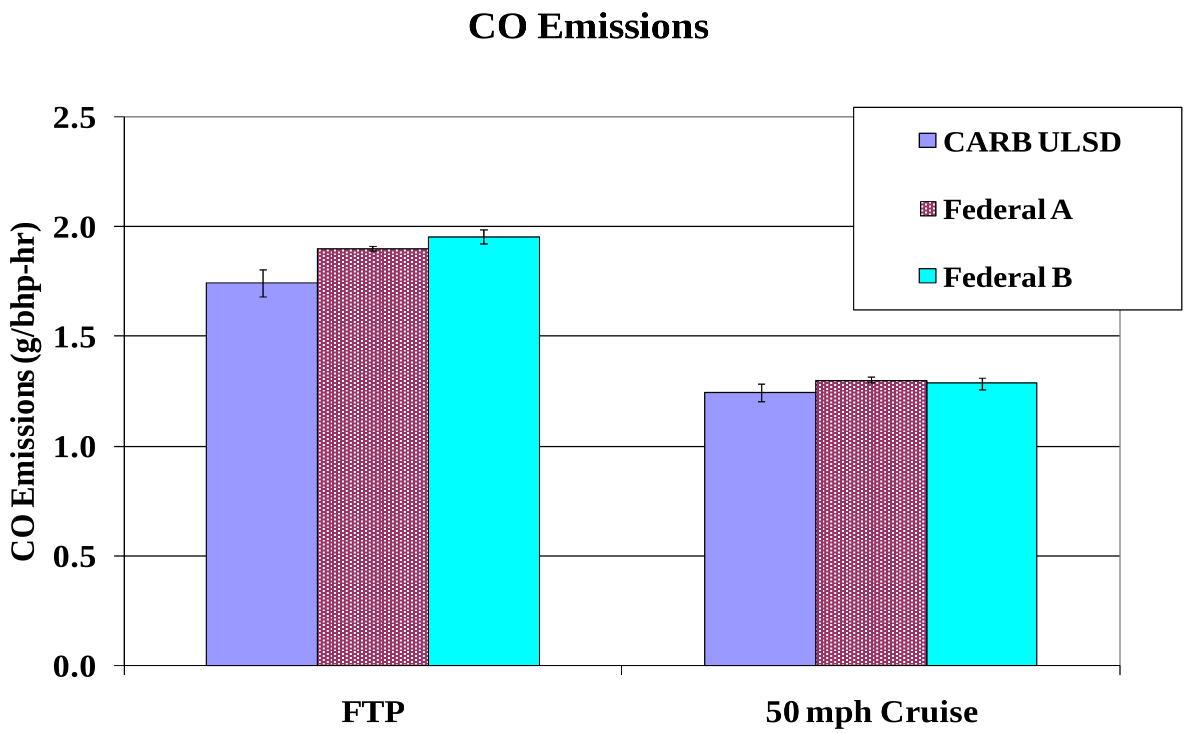


Figure 3-13. Average CO Emission Results for the 1991 Detroit Diesel Series 60

CO Emissions for all the three engines showed higher emissions for both Federal diesel blends compared with CARB diesel. The CO emissions increases were highest for the FTP cycle for all the three engines. The emissions differences between CARB diesel and the Federal diesels for the 2006 Cummins and the 1991 DDC 60 varied from approximately 3 to 23%. The CO emissions increases were higher for the 2007 MBE4000 engine, but the CO emissions for this engine were at very low levels.

		2007 MBE4000			2006 Cummins ISM			1991 DDC 60		
	CARB vs.	Ave.	% Diff	P-values	Ave.	% Diff	P-values	Ave.	% Diff	P-values
FTP	CARB	0.093			0.809			1.742		
	Federal A		-	-	0.945	17%	0.000	1.901	9%	0.000
	Federal B	0.021	51%	0.000	0.991	23%	0.000	1.955	12%	0.000
50 mph Cruise	CARB	0.141			0.534			1.247		
	Federal A		-	-	0.559	5%	0.041	1.303	5%	0.009
	Federal B	0.027	31%	0.024	0.585	9%	0.002	1.287	3%	0.070

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

3.5 CO_2 Emissions

The CO_2 emission results for the testing on the test engines are presented in Figure 3-14, Figure 3-15, and Figure 3-16, respectively, on a g/bhp-hr basis. Table 3-5 shows the percentage differences for the different fuels for the different test cycles for both test engines, along with the associated p-values for statistical comparisons using a t-test.

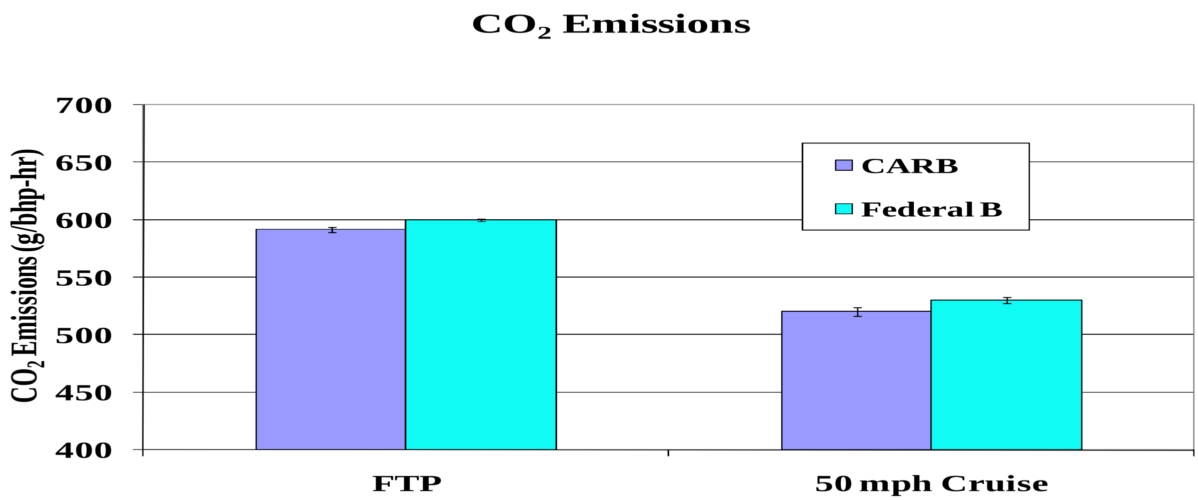


Figure 3-14. Average CO_2 Emission Results for the 2007 MBE4000

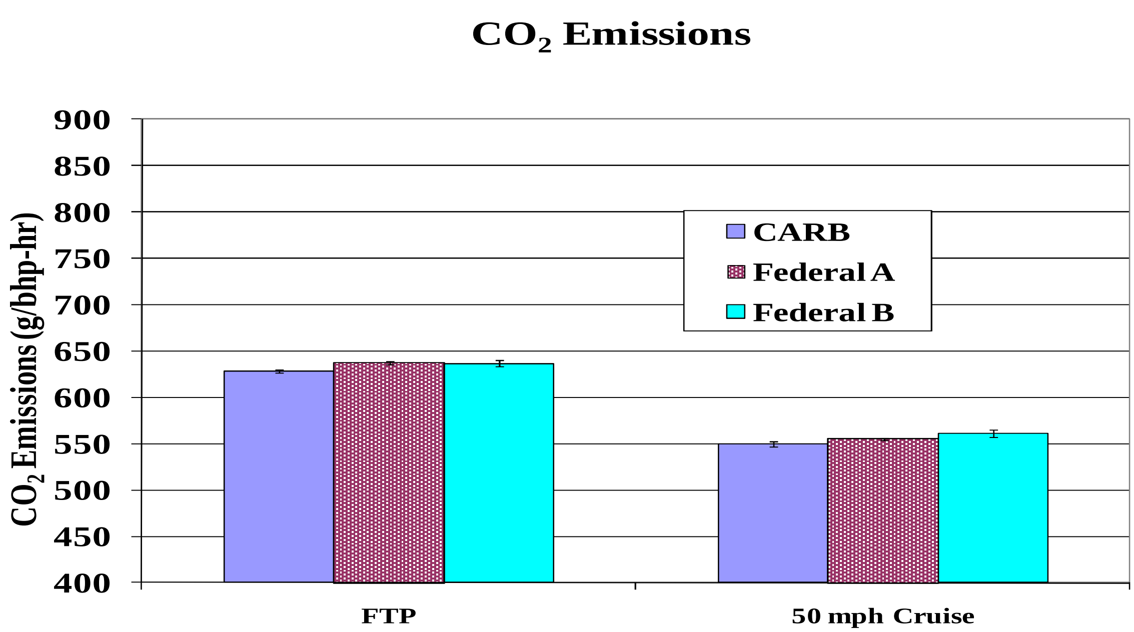


Figure 3-15. Average CO_2 Emission Results for the 2006 Cummins ISM

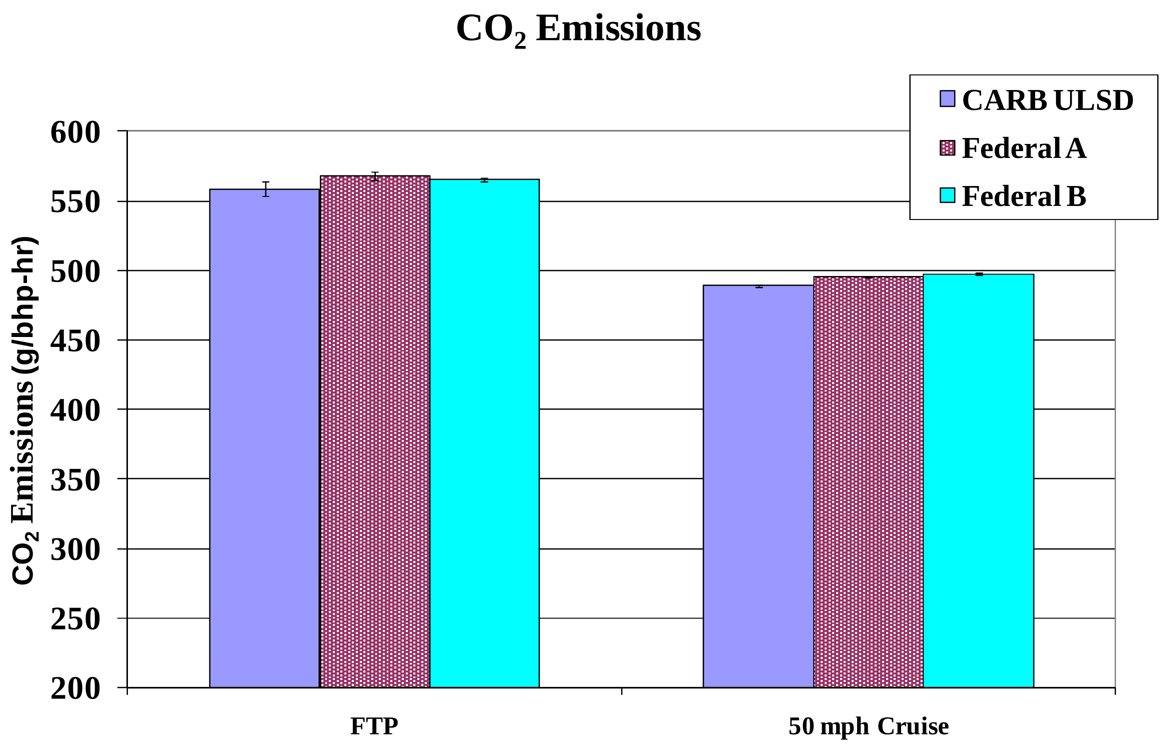


Figure 3-16. Average CO_2 Emission Results for the 1991 Detroit Diesel Series 60

CO_2 emissions showed slightly higher emissions for both Federal diesel blends and all three engines. The CO_2 emissions increases were relatively consistent between the three engines and ranged from 1-2%, with the Federal B fuel showing slightly higher increases than the Federal A fuel on the Cummins and DDC 60 engines for the 50 mph cruise cycle. The increases were statistically significant in all cases.

		2007 MBE4000			2006 Cummins ISM			1991 DDC 60		
	CARB vs.	**Ave.**	**% Diff**	**P-values**	**Ave.**	**% Diff**	**P-values**	**Ave.**	**% Diff**	**P-values**
FTP	**CARB**	591.62			628.57			558.58		
	Federal A		-	-	636.98	1.3%	0.000	568.08	1.7%	0.003
	Federal B	600.15	1.4%	0.000	636.86	1.3%	0.000	565.05	1.2%	0.013
50 mph Cruise	**CARB**	520.34			549.94			489.02		
	Federal A		-	-	555.10	0.9%	0.004	495.74	1.4%	0.000
	Federal B	530.55	2.0%	0.000	561.11	2.0%	0.000	497.29	1.7%	0.000

Table 3-5. CO_2 Percentage Differences Between the Federal Diesel Blends and the CARB ULSD base fuel for each Cycle.

3.6 Brake Specific Fuel Consumption

The brake specific fuel consumption results for the testing with the three different test engines are presented in Figure 3-17, Figure 3-18, and Figure 3-19 respectively, on a gallons per brake horsepower hour (gal./bhp-hr) basis. Table 3-6 shows the percentage differences for the different fuels for the different test cycles, along with the associated p-values for statistical comparisons using a t-test.

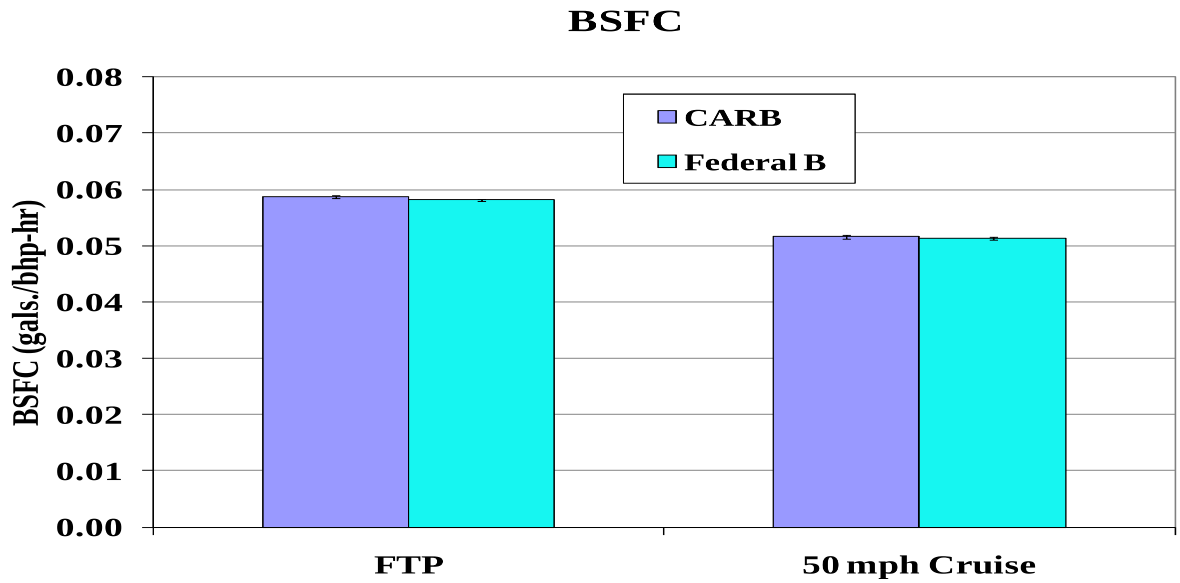


Figure 3-17. Average Brake Specific Fuel Consumption Results for the 2007 MBE4000

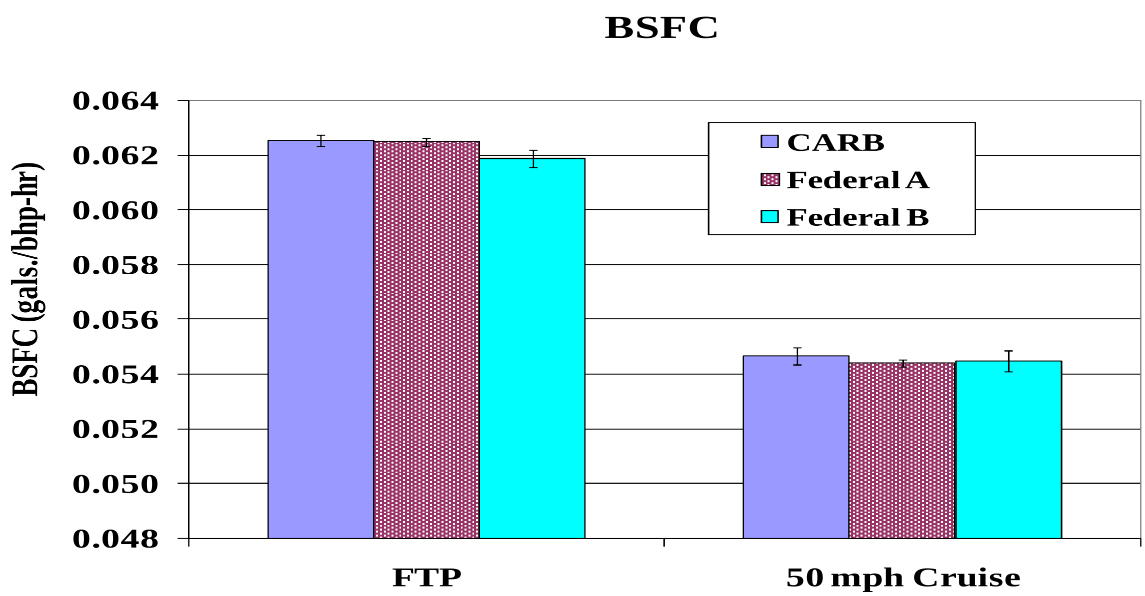


Figure 3-18. Average Brake Specific Fuel Consumption Results for the 2006 Cummins ISM

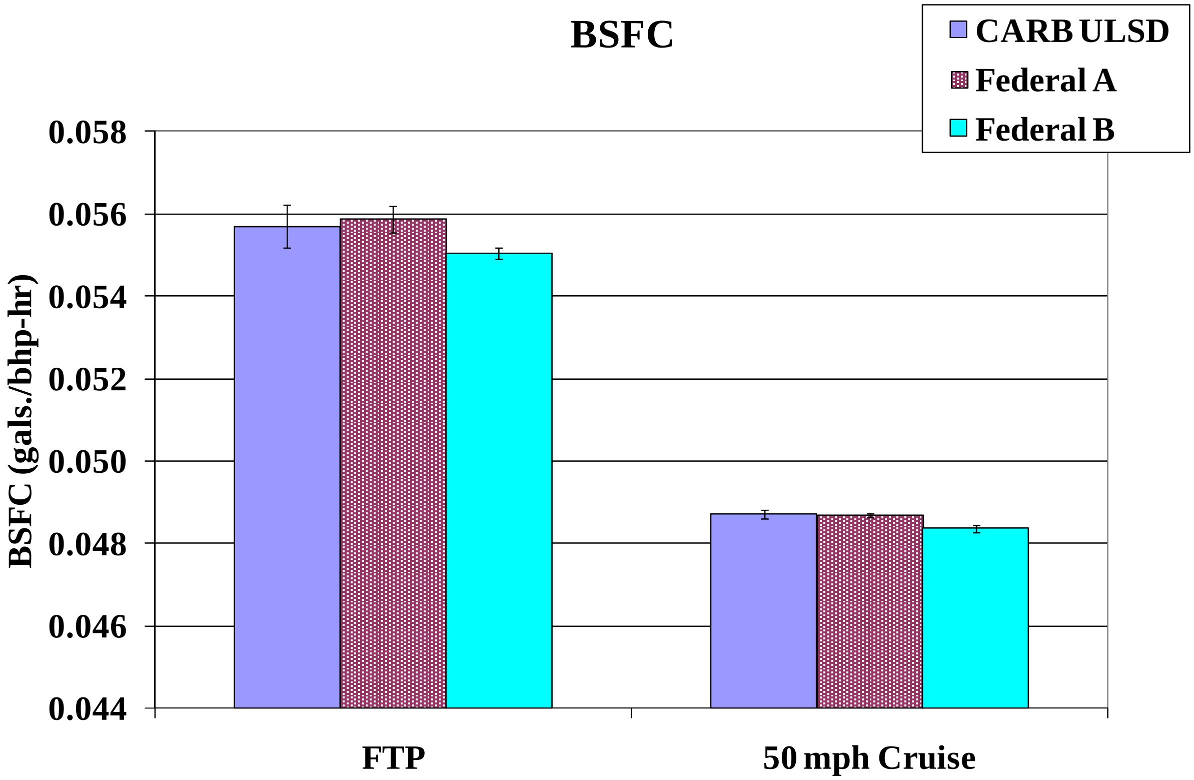


Figure 3-19. Average Brake Specific Fuel Consumption Results for the 1991 Detroit Diesel Series 60

Some trends of lower brake specific fuel consumption were seen for the Federal B fuel. The differences between Federal B and CARB ULSD over the FTP cycle for all three engines were statistically significant, and ranged from -0.9 to -1.2%. For 1991 DDC 60 the differences between the CARB ULSD and Federal B were also statistically significant over the 50 mph cruise. The lower fuel consumption for the Federal B fuel is not unexpected, given that this fuel has a higher density than the other test fuels. The CARB and Federal A fuels did not show any statistically differences in fuel consumption for any of the engines or test cycles.

		2007 MBE4000			2006 Cummins ISM			1991 DDC 60		
	CARB vs.	Ave.	**% Diff**	**P-values**	**Ave.**	**% Diff**	**P-values**	**Ave.**	**% Diff**	**P-values**
FTP	**CARB**	0.0587			0.0625			0.0557		
	Federal A		-	-	0.0625	-0.1%	0.667	0.0559	0.3%	0.524
	Federal B	0.0582	-0.9%	0.000	0.0619	-1.0%	0.002	0.0550	-1.2%	0.014
50 mph Cruise	**CARB**	0.0516			0.0547			0.0487		
	Federal A		-	-	0.0544	-0.5%	0.080	0.0487	-0.1%	0.589
	Federal B	0.0514	-0.4%	0.255	0.0545	-0.4%	0.348	0.0484	-0.7%	0.000

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

4.0 Summary

The California Air Resources Board is conducting a comprehensive study to better characterize the potential emissions benefits of CARB ULSD compared to other federal diesel fuels. The goal of this study is to understand the impacts of emissions from these different fuels in diesel engines. The program includes engine dynamometer and chassis dynamometer emissions testing with three different fuels. The testing included a baseline CARB ultralow sulfur diesel (ULSD) fuel and two federal diesel fuels. One Federal fuel, referred to as "Federal A", represents an average Federal ultralow sulfur diesel fuel and the second, referred to as "Federal B", is commercially available Federal ultralow sulfur diesel fuel that due to its properties may contribute to higher exhaust emissions. This memorandum summarizes the results from three engines tested under this comprehensive program. The testing described in this memorandum was conducted on a 2007 MBE4000 engine, a 2006 Cummins ISM engine and a 1991 Detroit Diesel Series 60 engine in CE-CERT's engine dynamometer laboratory. Testing was also conducted on two different engine test cycles, the FTP and 50 mph CARB cruise cycles.

A summary of the results is as follows:

Engine Testing Results:

- NO_x emissions for the Federal A and Federal B fuels were higher than those for the CARB ULSD for all the engines and cycles. The NO_x increases compared to CARB for the different engines ranged from 4.7 to 10% for the two Federal fuels, were statistically significant for all cases, and were similar between the different test engines. For the 2006 Cummins and the 1991 DDC 60 engines, the emissions for the Federal B fuel were higher than those for the Federal A fuel for most cycle combinations. For 2007 MBE 4000 and 1991 DDC 60, the observed emissions impacts were greater for the FTP than the 50 mph cruise. The opposite trend was seen for the Federal A fuel for 2006 Cummins engine with respect to cycle differences, although this is probably due in part with some stability issues that were seen during the testing for the 50 mph cruise cycle for the Cummins engine.
- The PM emissions showed statistically significant increases on the Federal A and B fuels for the Cummins engine over the FTP, but not over the 50 mph cruise cycle or for the MBE4000 on either cycle. For the MBE4000, the values are very low, so the differences were within the measurement error at these levels.
- THC emissions on 1991 DDC 60 showed statistically significant differences between fuels ranging from a 14.4-29.5% increase using Federal diesel blend fuels, while no consistent trends between different fuels for MBE4000 and 2006 Cummins ISM were observed for the 50-mph cruise cycle.
- CO Emissions for all the three engines showed higher emissions for both Federal diesel blends compared with CARB diesel. The CO emissions increases were highest for the FTP cycle for all the three engines. The emissions differences between CARB diesel and the Federal diesels for the 2006 Cummins and the 1991 DDC 60 varied from approximately 3 to 23%.

- CO_2 emissions showed slightly higher emissions for both Federal diesel blends and all three engines. The CO_2 emissions increases were relatively consistent between the three engines and ranged from 1-2%, with the Federal B fuel showing slightly higher increases than the Federal A fuel on the Cummins and DDC 60 engines for the 50 mph cruise cycle.
- Some trends of lower brake specific fuel consumption were seen for the Federal B fuel. The differences between Federal B and CARB ULSD over the FTP cycle for all three engines were statistically significant. For 1991 DDC 60 the differences between the CARB ULSD and Federal B were also statistically significant over the 50 mph cruise. The lower fuel consumption for the Federal B fuel is not unexpected, given that this fuel has a higher density than the other test fuels. The CARB and Federal A fuels did not show any differences in fuel consumption for the Cummins engine.

5.0 References

Clark, N.N., Gautam, M., Wayne, W.S., Thompson, G., Lyons, D.W., Zhen, F., Bedick, C., Atkinson, R.J., and McKain, D.L. (2007) Creation of the Heavy-Duty Diesel Engine Test Schedule for Representative Measurement of Heavy-Duty Engine Emissions. Report by the Center for Alternative Fuels, Engines & Emissions West Virginia University to the Coordinating Research Council, Inc., CRC Report No. ACES-1, July.

Cocker, D.R., Shah, S.D., Johnson, K.C., Miller, J.W., and Norbeck, J.M. (2004a) Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 1. Regulated Gaseous Emissions. Environ. Sci. Technol. 38, 2182.

Cocker, D.R., Shah, S.D., Johnson, K.C., Zhu, X., Miller, J.W., and Norbeck, J.M. (2004b) Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 2. Sampling and Toxics and Particulate Matter. Environ. Sci. Technol. 38, 6809.

Appendix A – Full Fuel Properties

Table A-1 Diesel Fuel D975 Specifications

	Units	Test Method	CARB ULSD	Federal A	Federal B
Sulfur Content	Mass ppm	D5453-93	7.4	13.3	5.3
Total Aromatic Content	mass%	D5186-96	19.4	32.0	37.8
PAH	mass%	D5186-96	1.6	11.6	5.8
Nitrogen Content	Mass ppm	D4629-96	115	4	84
Cetane No.	Rating	D613-94	50.4	45.5	44.1
Density	g/mL	D4052	0.8407	0.8488	0.8552
Carbon Mass fraction	%	D3343	86.56	86.97	87.15
Distillation		D86-96			
10%	°F		384	411	395
50%	°F		477	486	493
90%	°F		606	618	618

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

Collection of Data on Engine Operating Parameters

The heavily loaded 50 mph CARB heavy heavy-duty diesel truck (HHDDT) cruise cycle for the MBE4000 was developed from engine operating parameters. The engine operating parameters were obtained by operating the test vehicle with the specific engine installed on a chassis dynamometer while recording the J1939 signal from the engine ECM. This allowed the development on an engine dynamometer test cycle that had a direct correspondence to the loads the engine would experience when operated on a chassis dynamometer.

The 2007, 12.8 liter MBE4000 was equipped in an International truck chassis. This truck had an empty weight of 13,200 lbs. and a fully loaded capacity of 66,000 lbs.

The chassis dynamometer test cycles were run at CARB's Heavy-Duty Vehicle Emissions Testing Laboratory in Los Angeles, CA. The vehicle was operated over the 50 mph CARB cruise cycles while the J1939 signal was collected to obtain the engine parameters. For the 50 mph CARB cruise cycle, the truck was loaded on the dynamometer to its fully loaded capacity.

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

The CARB Heavy Heavy-Duty Diesel Truck (HHDDT) 50 mph Cruise schedule was developed for chassis dynamometer testing by the California Air Resources Board with the cooperation of West Virginia University. This cycle covers a distance of 10.5 miles with an average speed of 48.9 mph and maximum speed of 66.9 mph. The speed/time traces for the 50 mph CARB cruise cycle is provided below in Figure B-1.

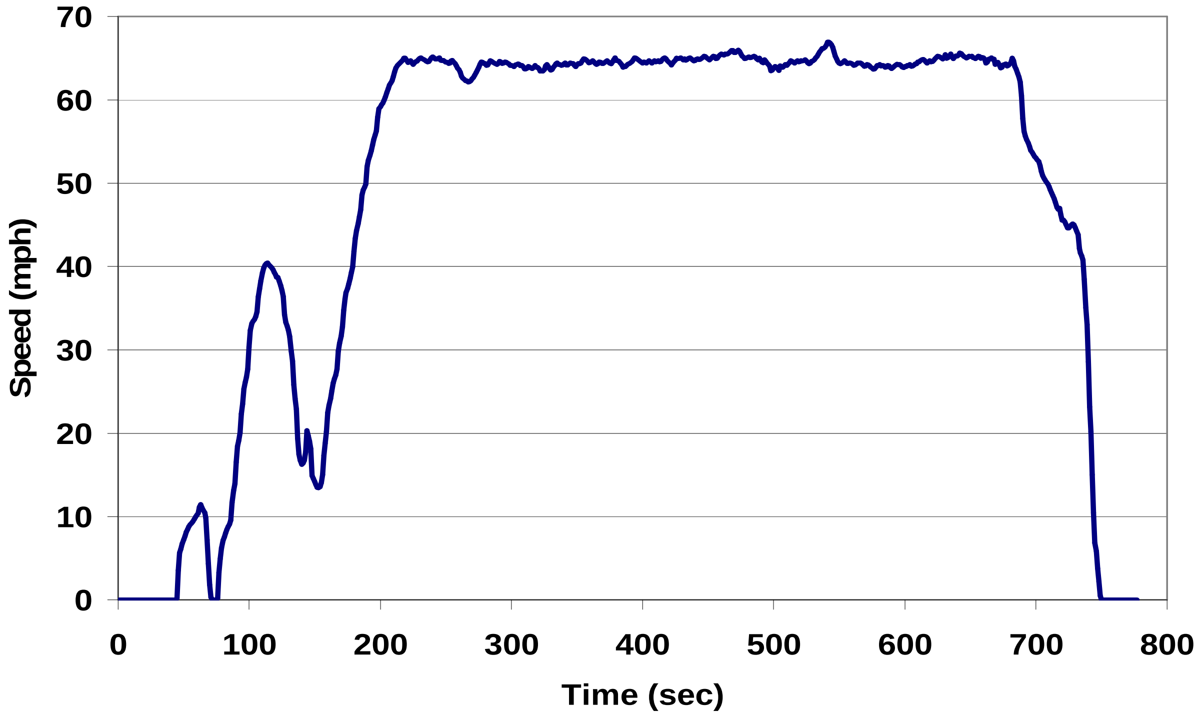


Figure B-1. Speed/Time Trace for the 50 mph CARB Cruise chassis dynamometer cycle.

Initial Development of the Engine Dynamometer Test Cycles

The 50 mph cruise cycles for the MBE4000 was developed from the engine speed and torque values from the J1939 data stream. Initially, the engine speed and torque were averaged over all of the test iterations. It was found that slight differences in time alignment between different test iterations resulted in differences in the exact location of the peaks in torque and engine speed. Specifically, the engine parameters would be near a peak in load for one cycle, while the loads for other test cycles would be lower at the same point. As such, the peaks in engine speed and torque could not be adequately represented with a cycle based solely on averaging.

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

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

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

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

Testing and Final Development of Engine Dynamometer Test Cycles

The 50 mph cruise cycle for the MBE4000 was initially run on the dynamometer without any modification to evaluate how well the cycle could be followed on the engine dynamometer and to provide a comparison with the regression parameters currently used for the FTP. In an effort to optimize the performance of the cycle on the engine dynamometer, additional tests were conducted with varying settings of the dynamometer controls, such as throttle response. Similar development work was used for the cycles for the ACES program to address any issues that could be attributed to the use of a clutch in the actual vehicle that removes the inertia load from the engine during gearshifting. Since the engine driveshaft is directly coupled to the dynamometer, this decoupling of the engine driveline cannot be simulated on the engine dynamometer. As such, these events were considered to be representative of the behavior that can be expected when translating engine parameters between a vehicle chassis and an engine dynamometer.
To improve the operation of the cycles on the engine dynamometer, the cycles were modified slightly after the initial runs. Specifically, the rpm and torque values were set to zero for period of the cycle where the engine was in an idling segment. This eliminated small variations in rpm that occur near the idle point in real operation and small torque values that would likely be associated with auxiliary equipment when the engine was operating in the chassis. The normalized cycles in their final form are presented in Figures B-2.

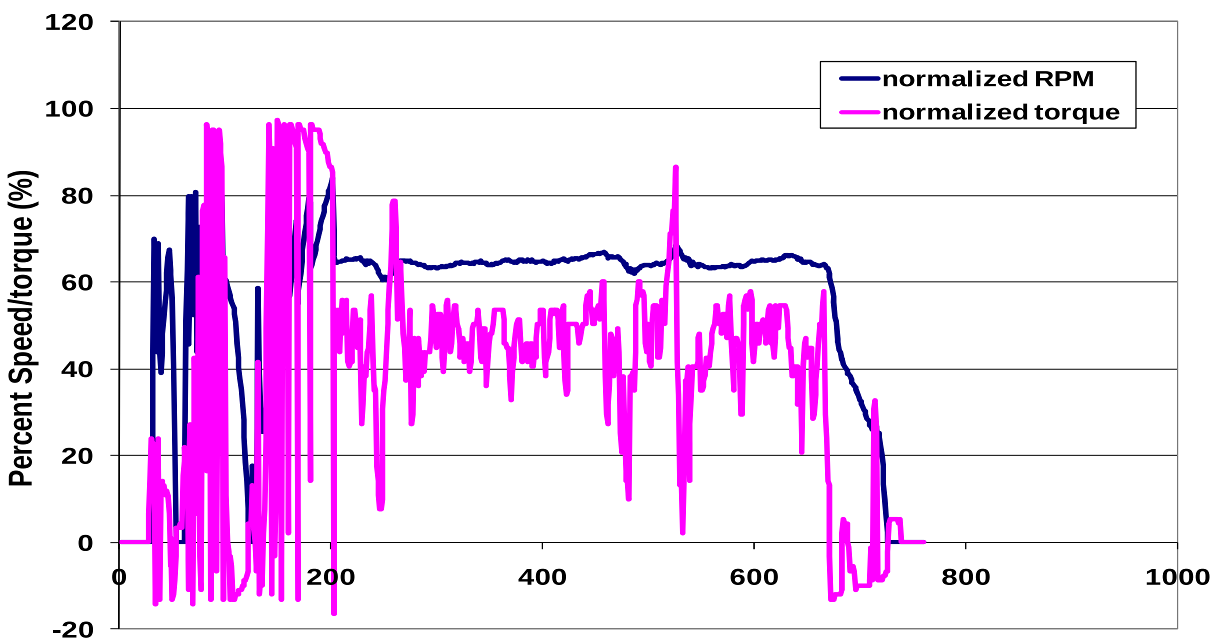


Figure B-2. 50 mph CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Cruise for the 2007 MBE4000

For the 2006 Cummins and 1991 Detroit Diesel engines, the 50 mph cruise cycle used in this test program was based on engine dynamometer test cycle version of this cycle that was developed for the ACES program was utilized (Clark et al., 2007). This was due to the fact that corresponding chassis dynamometer data was not available for this cycle for these engines. The ACES 50 mph cruise cycle was developed from data collected through the E55/59 chassis dynamometer study of heavy-duty trucks. The engine rpm/torque profile for the 50 cruise engine dynamometer test cycle that was used is provided in Figure B-3.

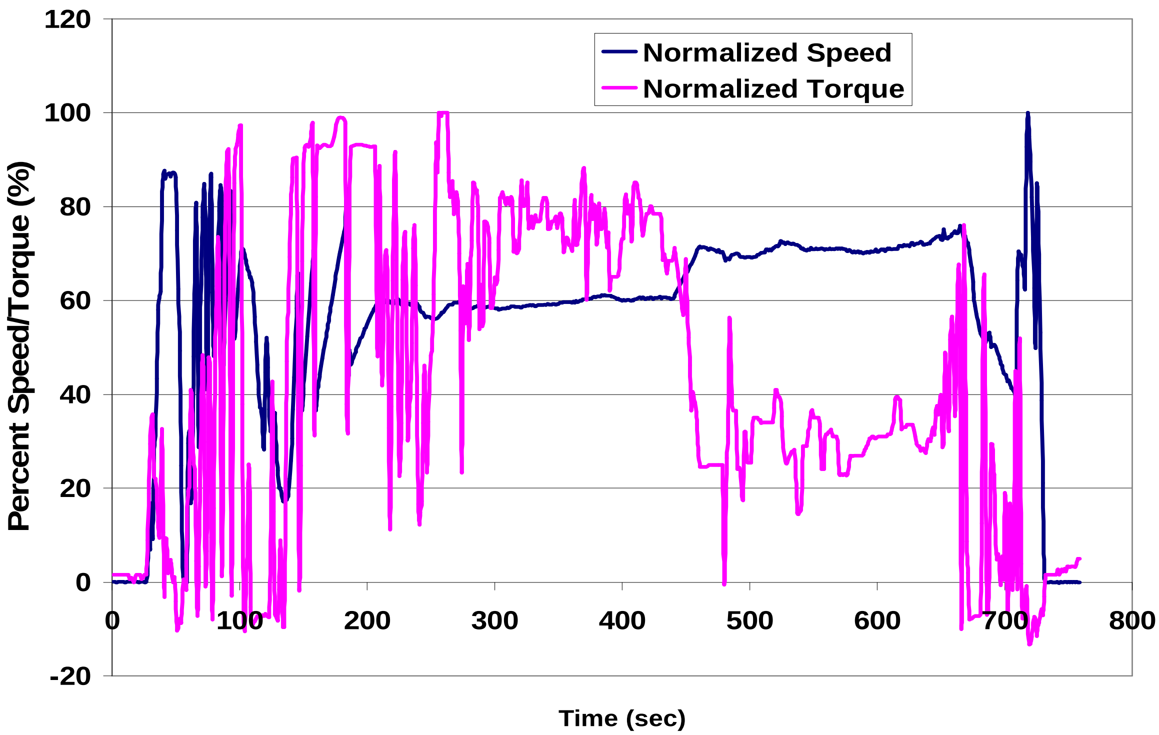


Figure B-3. 50 mph CARB Heavy Heavy-Duty Diesel Truck (HHDDT) Cruise for the 2006 Cummins ISM and 1991 DDC Series 60

Regression Statistics

Since the 50 mph cruise cycle is inherently different from the FTP, new regression statistics were developed for the 50 mph cruise cycle for each engine. The new regression statistics were developed based on replicate runs of the cycle and comparisons between the regression runs for this cycle and those used for the FTP.

The techniques used for the development of the new regression statistics were similar to those used in the ACES program cycle development. The new regression statistics were scaled to comparable values for the FTP based on the tolerance, or how closely the parameter was met for the standard FTP. The equations utilized for these comparisons were the same as those utilized in the ACES programs, as provided below. In essence, these equations provide the same margin of error on a percentage basis for the new cycle, as is typically utilized in the FTP. These were utilized in cases where greater tolerance was needed for the statistics than is typically given in the FTP. In cases where the FTP regression statistics could be readily met without modification, the standard FTP criteria were maintained. In the cases where the tolerances were greater than those used for the FTP, the validation criteria were expanded for the 50 mph cruise. A comparison of the FTP regression statistic criteria with the values obtained for the developed cycles is provided in Table B-1 to Table B-3 for the three engines.

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

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

		Speed				Torque				Power			
		Slope:	Intercept:	SteYX:	Rsq:	Slope:	Intercept:	SteYX:	Rsq:	Slope:	Intercept:	SteYX:	Rsq:
FTP	upper	1.03	50	100	1	1.03	15	188.5	1	1.03	5	30.95	1
	lower	0.97	-50	0	0.97	0.83	-15	0	0.88	0.89	-5	0	0.91
Cruise	upper	1.03	38.2	75.3	1.00	1.00	62.3	165.9	0.99	1.02	35.5	26.8	0.99
	lower	0.97	-38.2	0.0	0.97	0.81	-62.3	0.0	0.87	0.88	-35.5	0.0	0.90
										valued doubled			

Table B-1. Comparison of regression statistics criteria for the FTP with values obtained for the Cruise for 2007 MBE4000 Engine. Shaded areas indicate criteria where the values were greater than those for the FTP and were modified for the regression criteria

		Speed				Torque				Power			
		Slope	Intercept	SteYX	Rsq	Slope	Intercept	SteYX	Rsq	Slope	Intercept	SteYX	Rsq
FTP	upper	1.03	50	100	1	1.03	15	188.5	1	1.03	5	30.95	1
	lower	0.97	-50	0	0.97	0.83	-15	0	0.88	0.89	-5	0	0.91
Cruise	upper	1.03	-7.9	44.1	1.00	1.05	22.2	153.8	1.01	1.02	26.6	21.7	0.99
	lower	0.97	7.9	0.0	0.97	0.84	-22.2	0.0	0.89	0.88	-26.6	0.0	0.90
										value doubled			

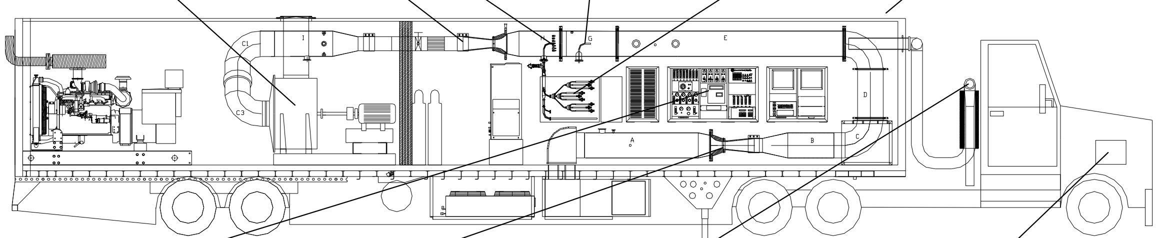
Table B-2. Comparison of regression statistics criteria for the FTP with values obtained for the Cruise for 2006 Cummins ISM Engine. Shaded areas indicate criteria where the values were greater than those for the FTP and were modified for the regression criteria

		Speed				Torque				Power			
		Slope:	Intercept:	SteYX:	Rsq:	Slope:	Intercept:	SteYX:	Rsq:	Slope:	Intercept:	SteYX:	Rsq:
FTP	upper	1.03	50	100	1	1.03	15	188.5	1	1.03	5	31.0	1
	lower	0.97	-50	0	0.97	0.83	-15	0	0.88	0.89	-5	0.0	0.91
Cruise	upper	1.03	30.08	86.83	1.00	1.05	19.45	140.73	1.02	1.03	57.22	24.68	1.00
	lower	0.97	-30.08	0.00	0.97	0.85	-19.45	0.00	0.90	0.89	-57.22	0.00	0.91
											valued doubled		

Table B-3. Comparison of regression statistics criteria for the FTP with values obtained for the Cruise for 1991 DDC Engine. Shaded areas indicate criteria where the values were greater than those for the FTP and were modified for the regression criteria

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

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



Major Systems within the Mobile Emission Lab

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

The mobile laboratory contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical instruments measure NO_x, methane (CH_4), total hydrocarbons (THC), CO, and CO_2 at a frequency of 10 Hz and were selected based on optimum response time and on road stability. The 200-L Tedlar bags are used to collect tunnel and dilution air samples over a complete test cycle. A total of eight bags are suspended in the MEL allowing four test cycles to be performed between analyses. Filling of the bags is automated with Lab View 7.0 software (National Instruments, Austin, TX). A summary of the analytical instrumentation used, their ranges, and principles of operation is provided in the table below. Each modal analyzer is time-corrected for tunnel, sample line, and analyzer delay time.

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

Summary of gas-phase instrumentation in MEL

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Appendix D – Quality Assurance/Quality Control

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

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

Table D-1. Summary of Routine Calibrations

EQUIPMENT	FREQUENCY	VERIFICATION PERFORMED	CALIBRATION PERFORMED
CVS	Daily Daily Weekly Monthly Per Set-up Second by second	Differential Pressure Absolute Pressure Propane Injection CO_2 Injection CVS Leak Check Back pressure tolerance ±5 inH_20	Electronic Cal Electronic Cal
Cal system MFCs	Annual Monthly	Primary Standard Audit bottle check	MFCs: Drycal Bios Meter
Analyzers	Pre/Post Test Daily Monthly	Zero span drifts Linearity Check	Zero Span
Secondary System Integrity and MFCs	Semi-Annual Semi-Annual	Propane Injection: 6 point primary vs. secondary check	MFCs: Drycal Bios Meter & TSI Mass Meter
Data Validation	Variable Per test	Integrated Modal Mass vs. Bag Mass Visual review	
PM Sample Media	Weekly Monthly	Trip Tunnel Banks Static and Dynamic Blanks	
Temperature	Daily	Psychrometer	Performed if verification fails
Barometric Pressure	Daily	Aneroid barometer ATIS	Performed if verification fails
Dewpoint Sensors	Daily	Psychrometer Chilled mirror	Performed if verification fails

Appendix E – Average Emissions Results for Each Fuel/Cycle Combination Federal Diesel blend Testing-2007 MBE4000

Fuel	Cycle		THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2 g/bhp-hr	BSFC gals/bhp-hr
CARB ULSD	FTP	Ave.	0.006	0.093	1.275	-0.00018	591.62	0.059
		St. Dev.	0.002	0.008	0.0045	0.00034	1.97	0.000
		COV	32.01%	8.78%	89.89%	----	0.33%	0.33%
		Replicates	6	6	6	6	6	6
CARB ULSD	50 mph Cruise	Ave.	0.004	0.021	1.137	0.00011	520.339	0.052
		St. Dev.	0.001	0.004	0.019	0.000	3.982	0.000
		COV	29.97%	19.03%	0.00%	118.18%	0.77%	0.76%
		Replicates	6	6	6	6	6	6
Federal B	FTP	Ave.	0.007	0.141	1.368	-0.00009	600.145	0.058
		St. Dev.	0.001	0.011	0.01083	0.00066	1.22	0.000
		COV	20.20%	7.49%	0.00%	----	0.20%	0.20%
		Replicates	6	6	6	6	6	6
Federal B	50 mph Cruise	Ave.	0.003	0.027	1.190	0.00022	530.551	0.051
		St. Dev.	0.000	0.004	0.011	0.000	2.527	0.000
		COV	0.00%	15.89%	0.00%	101.55%	0.48%	0.48%
		Replicates	6	6	6	6	6	6

Appendix F – Average Emissions Results for Each Fuel/Cycle Combination Federal Diesel blend Testing-2006 Cummins ISM

Fuel	Cycle		THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2 g/bhp-hr	BSFC gals/bhp-hr
CARB ULSD	FTP	Ave.	0.143	0.809	2.096	0.070	628.574	0.063
		St. Dev.	0.004	0.011	0.010	0.001	2.004	0.000
		COV	3.11%	1.40%	0.47%	0.88%	0.32%	0.32%
		Replicates	8	8	8	8	8	8
CARB ULSD	50 mph Cruise	Ave.	0.077	0.534	1.643	0.053	549.941	0.055
		St. Dev.	0.001	0.019	0.079	0.002	3.192	0.000
		COV	1.73%	3.50%	4.83%	2.85%	0.58%	0.58%
		Replicates	6	6	6	6	6	6
Federal A	FTP	Ave.	0.142	0.945	2.236	0.073	636.977	0.062
		St. Dev.	0.002	0.014	0.014	0.001	1.645	0.000
		COV	1.57%	1.52%	0.64%	1.09%	0.26%	0.26%
		Replicates	6	6	6	6	6	6
Federal A	50 mph Cruise	Ave.	0.067	0.559	1.799	0.052	555.102	0.054
		St. Dev.	0.002	0.017	0.020	0.001	1.261	0.000
		COV	3.47%	3.13%	1.11%	2.35%	0.23%	0.23%
		Replicates	6	6	6	6	6	6
Federal B	FTP	Ave.	0.160	0.991	2.263	0.076	636.855	0.062
		St. Dev.	0.002	0.011	0.029	0.001	3.146	0.000
		COV	1.46%	1.09%	1.30%	1.08%	0.49%	0.50%
		Replicates	6	6	6	6	6	6
Federal B	50 mph Cruise	Ave.	0.077	0.585	1.775	0.054	561.112	0.054
		St. Dev.	0.003	0.023	0.086	0.003	3.960	0.000
		COV	3.93%	3.88%	4.84%	5.26%	0.71%	0.71%
		Replicates	6	6	6	6	6	6

Appendix G – Average Emissions Results for Each Fuel/Cycle Combination Federal Diesel blend Testing-1991 DDC60 Engine

Fuel	Cycle		THC g/bhp-hr	CO g/bhp-hr	NO_x g/bhp-hr	PM g/bhp-hr	CO_2 g/bhp-hr	BSFC gals/bhp-hr
CARB ULSD	FTP	Ave.	0.044	1.742	4.572	0.074	558.584	0.0557
		St. Dev.	0.002	0.061	0.032	0.004	5.110	0.001
		COV	5.18%	3.53%	0.70%	5.90%	0.91%	0.93%
		Replicates	6	6	6	6	6	6
CARB ULSD	50 mph Cruise	Ave.	0.023	1.247	6.470	0.040	489.017	0.049
		St. Dev.	0.001	0.040	0.045	0.002	1.007	0.000
		COV	5.05%	3.22%	0.70%	4.84%	0.21%	0.21%
		Replicates	6	6	6	6	6	6
Federal A	FTP	Ave.	0.050	1.901	4.913	0.076	568.080	0.0559
		St. Dev.	0.001	0.010	0.027	0.001	3.249	0.000
		COV	1.62%	0.51%	0.54%	1.75%	0.57%	0.57%
		Replicates	6	6	6	6	6	6
Federal A	50 mph Cruise	Ave.	0.023	1.303	6.810	0.043	495.740	0.049
		St. Dev.	0.001	0.015	0.017	0.001	0.507	0.000
		COV	2.21%	1.13%	0.25%	1.68%	0.10%	0.10%
		Replicates	6	6	6	6	6	6
Federal B	FTP	Ave.	0.057	1.955	4.997	0.076	565.055	0.055
		St. Dev.	0.001	0.033	0.012	0.002	1.359	0.000
		COV	2.48%	1.71%	0.25%	2.61%	0.24%	0.25%
		Replicates	6	6	6	6	6	6
Federal B	50 mph Cruise	Ave.	0.027	1.287	6.945	0.041	497.295	0.048
		St. Dev.	0.001	0.027	0.030	0.001	0.919	0.000
		COV	3.96%	2.10%	0.44%	3.18%	0.18%	0.18%
		Replicates	6	6	6	6	6	6