U.S. Department of
Transportation

**Federal Railroad
Administration**

Locomotive Emissions Measurements for Various Blends of Biodiesel Fuel

Office of Research
and Development
Washington, DC 20590

DOT/FRA/ORD-14/39

Final Report
December 2014

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE December 2014	3. REPORT TYPE AND DATES COVERED Final Report

4. TITLE AND SUBTITLE Locomotive Emissions Measurements for Various Blends of Biodiesel Fuel	5. FUNDING NUMBERS FR-RRD-12-009
6. AUTHOR(S) John C. Hedrick and Steven G. Fritz	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Southwest Research Institute 6220 Culebra Road San Antonio, Texas 78238	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Railroad Administration Office of Railroad Policy and Development Office of Research and Development Washington, DC 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FRA/ORD-14/39
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public through the FRA Web site at http://www.fra.dot.gov.	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The objective of this project was to assess the effects of various blends of biodiesel on locomotive engine exhaust emissions. The emission tests were conducted on two locomotive models, a Tier 2 EMD SD70ACe and a Tier 1 Plus GE Dash9-44CW, using two baseline fuels: (1) conventional EPA ASTM No. 2-D S15 certification diesel fuel and (2) commercially available California Air Resource Board (CARB) ULSD fuel. A single batch of soy-based B100 was mixed in with the EPA and CARB diesel to yield a 5 percent and 20 percent blend of fuel. A randomized test matrix was used to perform triplicate tests on each of the six test fuels (EPA0, CARB0, EPA5, CARB5, EPA20, and CARB20).

General emissions and fuel economy trends seen in other studies and applications for biodiesel use were also observed in this study. Higher blend levels of biodiesel were associated with lower carbon monoxide and particulate matter, as well as with higher levels of nitrogen oxides and fuel consumption. Use of diesel fuel with 20 percent biodiesel often resulted in statistically significant differences from the fuel with 0 percent or 5 percent biodiesel, while the difference between 0 percent and 5 percent biodiesel was generally not statistically significant.

14. SUBJECT TERMS Locomotive, biodiesel, exhaust emissions	15. NUMBER OF PAGES 47
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

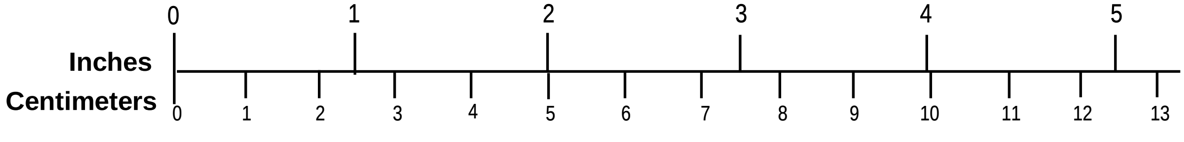
NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

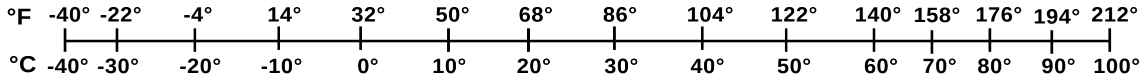
METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC			METRIC TO ENGLISH		
LENGTH (APPROXIMATE)			**LENGTH** (APPROXIMATE)		
1 inch (in)	=	2.5 centimeters (cm)	1 millimeter (mm)	=	0.04 inch (in)
1 foot (ft)	=	30 centimeters (cm)	1 centimeter (cm)	=	0.4 inch (in)
1 yard (yd)	=	0.9 meter (m)	1 meter (m)	=	3.3 feet (ft)
1 mile (mi)	=	1.6 kilometers (km)	1 meter (m)	=	1.1 yards (yd)
			1 kilometer (km)	=	0.6 mile (mi)
AREA (APPROXIMATE)			**AREA** (APPROXIMATE)		
1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)	1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)	1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)	10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)			
MASS - WEIGHT (APPROXIMATE)			**MASS - WEIGHT** (APPROXIMATE)		
1 ounce (oz)	=	28 grams (gm)	1 gram (gm)	=	0.036 ounce (oz)
1 pound (lb)	=	0.45 kilogram (kg)	1 kilogram (kg)	=	2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)	1 tonne (t)	=	1,000 kilograms (kg)
				=	1.1 short tons
VOLUME (APPROXIMATE)			**VOLUME** (APPROXIMATE)		
1 teaspoon (tsp)	=	5 milliliters (ml)	1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	=	15 milliliters (ml)	1 liter (l)	=	2.1 pints (pt)
1 fluid ounce (fl oz)	=	30 milliliters (ml)	1 liter (l)	=	1.06 quarts (qt)
1 cup (c)	=	0.24 liter (l)	1 liter (l)	=	0.26 gallon (gal)
1 pint (pt)	=	0.47 liter (l)			
1 quart (qt)	=	0.96 liter (l)			
1 gallon (gal)	=	3.8 liters (l)			
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)	1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)	1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)			**TEMPERATURE** (EXACT)		
[(x-32)(5/9)] °F	=	y °C	[(9/5) y + 32] °C	=	x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIC



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Acknowledgments

This project was funded by the Federal Railroad Administration (FRA) through FRA Funding Opportunity Number FR-RRD-12-009. FRA implemented a multiphase, multiyear program to assess how the use of biodiesel in locomotives will affect engine performance and durability. This Phase I project also assessed the effects of various blends of biodiesel on locomotive engine exhaust emissions. The FRA technical project manager and grant administrator was Ms. Melissa Shurland.

The National Biodiesel Board provided the B100 fuel used in this project at no cost to FRA or SwRI.

SwRI would like to recognize the support of Richard Nelson, Associate Professor at the Center for Sustainable Energy, Kansas State University. Professor Nelson assisted in the selection and procurement process of the B-100 fuel, as well as with review of the fuel analysis.

The project also benefited from the support of BNSF Railway. BNSF provided the two test locomotives, technical support, and transportation of these two locomotives to Southwest Research Institute’s Locomotive Technology Center (SwRI LTC) in San Antonio, Texas.

Jim Rutherford, consulting statistician at Chevron, provided project planning guidance in the experimental design and test sequence randomization and performed the statistical analysis of the data.

Contents

Illustrations

Tables

Executive Summary

The Federal Railroad Administration (FRA) has implemented a multiphase, multiyear program to assess how biodiesel used as a locomotive fuel affects engine performance and durability, as well as exhaust emissions. FRA is a participant in the SAE International (formerly the Society of Automotive Engineers) Technical Committee 7 (TC7), Biodiesel in Railroad Applications Subcommittee. With the help of the subcommittee, FRA identified several research areas to help develop knowledge about biodiesel use in locomotives.

The objective of this project was to assess the effects of various blends of biodiesel use on locomotive engine exhaust emissions. Emissions tests followed the Federal Test Procedure (FTP) 40 CFR Part 92, as specified by the U.S. Environmental Protection Agency (EPA). The emissions tests were conducted on two locomotive models, a Tier 2 EMD SD70ACe and a Tier 1 Plus GE Dash9-44CW, using two baseline fuels, conventional EPA ASTM No. 2-D S15 (commonly referred to as ultra-low sulfur diesel—ULSD) certification diesel fuel and commercially available California Air Resource Board (CARB) ULSD fuel. A single batch of soy-based B100 was used to blend with the EPA and CARB diesel to yield a 5 percent and 20 percent blend of fuel. A randomized test matrix was used to perform triplicate tests on each of the six test fuels (EPA0, CARB0, EPA5, CARB5, EPA20, and CARB20).

The results of these emissions tests were analyzed to determine the statistical relevance of any difference in exhaust emissions among fuels. General emissions and fuel economy trends seen in other studies and applications for biodiesel were also observed in this study. Higher blend levels of biodiesel were associated with lower carbon monoxide and particulate matter, as well as with higher levels of nitrogen oxides and fuel consumption. Use of diesel fuel with 20 percent biodiesel often resulted in statistically significant differences from the fuel with 0 percent or 5 percent biodiesel, while the difference between 0 percent and 5 percent biodiesel was generally not statistically significant. Different trends between the locomotives could be explained by differences in emissions certification levels and oil consumption.

1. Introduction and Background

On October 16, 2008, the 110th Congress enacted Public Law 110-432. Section 404 of Title IV ("Miscellaneous Provisions") of this Public Law set the stage for FRA to conduct a locomotive biofuel study to determine the extent to which freight railroads, Amtrak, and other passenger rail operators could use biofuel blends.[1]

This Public Law requires FRA to investigate the effects of using various biofuel blends in the railroad environment. The investigations are to focus on the following:

- The environmental benefit (or impact) of using biofuel blends
- The cost of biofuel blends on railroad operations
- Determining if there are sufficient supplies of biofuel for the railroad industry
- Deciding if there are any public benefits to be derived from the use of biofuel in place of traditional diesel fuel
- Determining if the use of biofuel in locomotives will affect performance and or the warranty

FRA has participated in the SAE International TC7 Biodiesel in Railroad Applications Subcommittee. The subcommittee helped FRA identify an approach to meet the objectives specified in Public Law 110-432. The results of this interaction with the TC7 subcommittee allowed FRA to implement a multiphase, multiyear program to assess how biodiesel will affect locomotive engine performance and durability, as well as exhaust emissions.

Southwest Research Institute (SwRI) was awarded a grant by FRA to assess the effects of various blends of biodiesel on locomotive engine exhaust emissions. Emissions tests followed the Federal Test Procedure (FTP) 40 CFR Part 92, as specified by the U.S. Environmental Protection Agency (EPA). The emissions tests were conducted on two locomotive models, a Tier 2 EMD SD70ACe and a Tier 1 Plus GE Dash9-44CW, with two baseline fuels, conventional EPA ultra-low sulfur diesel (ULSD) certification diesel fuel and commercially available California Air Resource Board (CARB) ULSD fuel. A single batch of soy-based B100 was used to blend B5 and B20 biodiesel fuels from both the EPA and CARB baseline fuels. A randomized test matrix was used to perform triplicate tests on each of the six test fuels (EPA0, CARB0, EPA5, CARB5, EPA20, and CARB20). These fuels were tested on two high-horsepower, line-haul locomotive models using triplicate tests over a randomized test matrix, for a total of 36 U.S-EPA Part 92 emissions tests.

---

[1] Rail Safety Improvement Act of 2008, Pub. L. no. 110-432, 122 Stat. 4848 (2008).

2. Technical Approach

Testing for this project was performed by SwRI at the SwRI Locomotive Technology Center (LTC) in San Antonio, Texas. This section provides a brief description of the test fuels, test locomotives, engine power measurements, fuel consumption measurements, and gaseous and particulate exhaust emissions test procedures.

2.1 Test Fuels

The fuels tested during this project were conventional EPA ULSD certification diesel fuel and commercially available CARB ULSD fuel. For each test, a 5 percent and 20 percent biodiesel blend was used. These fuels will be discussed in the following sections.

2.1.1 Biodiesel Background

Biodiesel is derived from vegetable oils, animal fats, and/or used cooking oils or greases which must meet the international fuel specification, ASTM D6751[2].

In December 2007, the Energy Independence and Security Act (EISA) or Renewable Fuel Standard 2 (RFS-2) was signed into law mandating 36 billion gallons of renewable fuel in four separate categories (conventional ethanol, biomass-based diesel, advanced biofuels, and cellulosic-based biofuels) per year by 2022 (Figure 1). Biomass-based diesel (e.g., biodiesel or renewable diesel) was mandated for use at levels of at least 1 billion gallons per year in the transportation sector, including in railroads, beginning in 2012. By comparison, the total annual volume of diesel fuel used in the railroad sector averaged 3.2 billion gallons from 2001–2010 and the biodiesel consumed in the United States in 2011 was slightly greater than 1.1 billion gallons.

Obligated parties, defined as entities that refine or import gasoline or diesel, have a set annual volume of renewable fuel (from one or more of the four categories) they must purchase each year (i.e., their renewable volume obligation or RVO) based on:

1) their percentage of the total gasoline and diesel market, and
2) what is mandated by the RFS-2 in a given year.

The RFS-2 also broadened the market sectors in which biomass-based diesel/biodiesel could be used to help an obligated party meet their annual RVO and now includes locomotives and railroads. In addition, ASTM D975-12a (“Standard Specification for Diesel Fuel Oils”) has allowed biodiesel in concentrations up to 5 percent by volume to be accepted as a fungible component in the U.S. diesel fuel pool. As a part of ASTM D975, fuel users, including railroads, can receive up to B5 fuel without notification.

---

[2] ASTM D6751 - 12, Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels

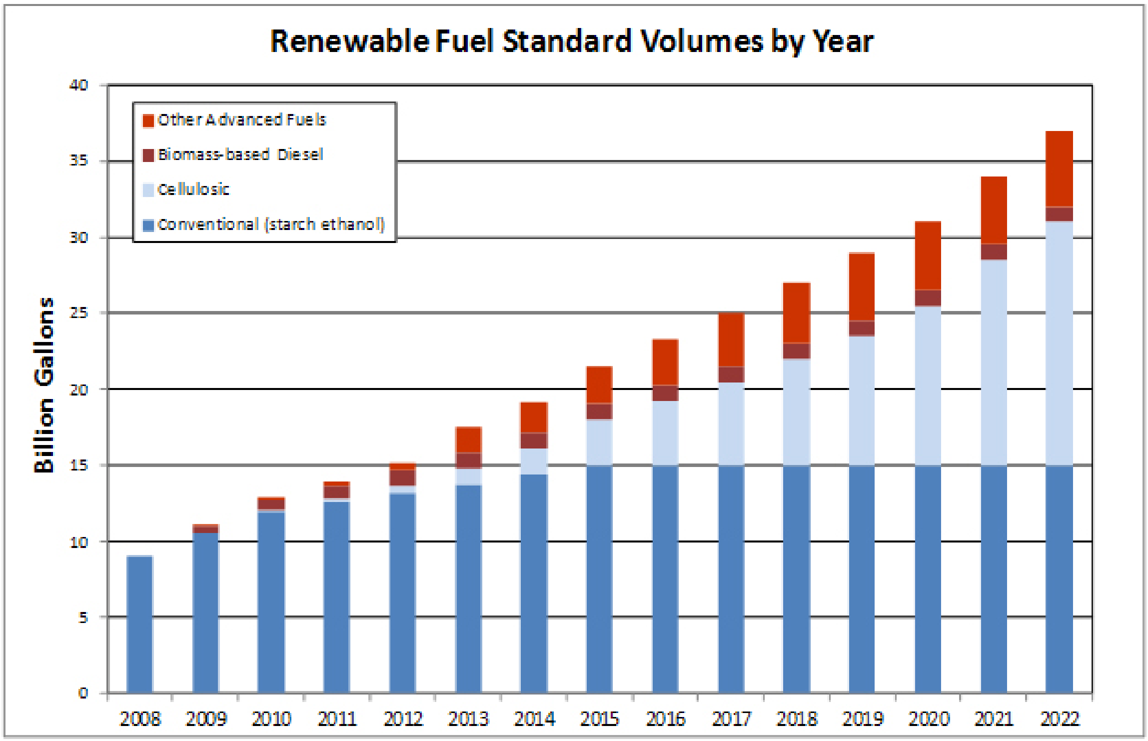


Figure 1. Renewable Fuel Standard with Specific Renewable Fuel "Carve Outs"

For biodiesel to qualify for obligated parties to use in attempting to meet their individual RVO under the RFS-2 mandate, all biodiesel produced must meet the accepted definition of biodiesel:

> *"a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100, and meeting the requirements of ASTM D 6751"*

The definition of biomass-based diesel as specified by RFS-2 is:

- A renewable fuel with lifecycle GHG emissions at least 50 percent less than baseline diesel that
    - is a transportation fuel (motor vehicle, nonroad, locomotive, marine), transportation fuel additive, heating oil, or jet fuel,
    - is biodiesel (mono-alkyl ester that meets ASTM D 6751) or nonester renewable diesel,
    - is registered as a motor vehicle fuel or fuel additive under 40 CFR Part 79 if intended for use in a motor vehicle, and
    - DOES NOT include renewable fuel where renewable biomass is "simultaneously" coprocessed with petroleum.

Since 2001, ASTM D 6751 has been the approved standard for B100 for blending up to B20. It is performance-based, feedstock and process neutral, and 48 States have now legislatively adopted the ASTM D6751 specifications for biodiesel. ASTM D7467 covers blends containing 6 percent to 20 percent biodiesel for on or off road engines, and the B100 blend stock must meet ASTM D 6751.

All candidate B100 fuels for consideration met ASTM D6751 standards, and the blended biodiesel fuels (B5 and B20) met ASTM D975 and ASTM D7467 standards, respectively. The project B100 procurement also stipulated that once the biodiesel was received by SwRI, the blended fuels would be sampled per ASTM D4057, and the biodiesel content would be determined by ASTM D7371 to ensure that blend levels for testing were reached. Further conditions posed to all potential suppliers were as follows:

1) The selected biodiesel fuel must be procured from a fuel manufacturer/producer that participates in the BQ-9000 accreditation program;
2) The original biodiesel feedstock must be unsaturated and must be qualified under the RFS-2 program with respect to life-cycle greenhouse gas emissions.

In addition, all fuel procured were to be accompanied by a Certificate of Analysis (COA) verifying quality specifications were met or exceeded at the time of receipt at the testing site in San Antonio, Texas.

A Request for Quote (RFQ) concerning the requirements for supplying biodiesel to this FRA project was developed by the National Biodiesel Board (Appendix A) and sent to all current BQ-9000 companies. Three BQ-9000 companies responded to the RFQ and one of them proposed using a feedstock that currently does not qualify under the RFS-2 program. Between the final two companies, AGP was selected as the vendor—they were the most cost-effective (lowest cost per gallon delivered). The National Biodiesel Board provided the B100 test fuel at no cost to FRA or SwRI. Appendix B shows the COA that accompanied the biodiesel chosen for this project, and Table 1 shows the results of the B100 fuel analysis.

TABLE 1. B100 FUEL ANALYSIS

ASTM Method	Test Property	Units	PPRD Test Results
D240	Heat of Combustion		
	GROSS	BTU / lb	17091
	GROSS	MJ / kg	39.753
D240	Heat of Combustion		
	NET	BTU / lb	16012
	NET	MJ / kg	37.243
D4052	API Gravity	--	28.4
	Specific Gravity	--	0.8852
	Density at 15°C	grams / L	884.8
D445	Viscosity at 40°C	cSt	4.016
D5291	Elemental Analysis		
	Carbon Content	weight %	76.93
	Hydrogen Content	weight %	11.83
D5453	Sulfur Content	ppm	2.8
D613	Cetane Number	--	52.5
EN14078	FAME Content by FTIR	volume %	99.9

2.1.2 CARB Diesel

CARB diesel fuel was designed to reduce diesel engine emissions by limiting the aromatics to a maximum of 10 percent. CARB regulations also allow fuel refiners to produce an alternative CARB diesel fuel with more than 10 percent aromatic hydrocarbons. However, before a fuel can be sold as a CARB diesel, the refiner must demonstrate, through independent testing, that the alternative diesel formulation provides comparable emission benefits to a standard CARB diesel fuel.

For this project, a single batch of CARB diesel was procured by SwRI from Southern California and stored in a clean storage tank at SwRI's LTC. A sample of the fuel was then taken and analyzed before blending. Results of the CARB diesel analysis are shown in Table 2 and the results "are within the certification limits for production," so the fuel was determined to be a legal California diesel fuel.

TABLE 2. CARB DIESEL ANALYSIS RESULTS

ASTM Method	Test Property	Units	PPRD Test Results
D240	Heat of Combustion		
	GROSS	BTU / lb	19663
	GROSS	MJ / kg	45.736
D240	Heat of Combustion		
	NET	BTU / lb	18438
	GROSS	MJ / kg	42.888
D4052	API Gravity	--	37.7
	Specific Gravity	--	0.8364
	Density at 15°C	grams / L	836
D2500	Cloud Point	deg. C	-13
D4052	API Gravity	--	34.9
	Specific Gravity	--	0.8504
	Density at 15°C	grams / L	850
D445	Viscosity at 40°C	cSt	3.334
D4629	Nitrogen Content	ppm	32.7
D4737	Cetane Index	calculated	49.6
D5186	Total Aromatics by SFC		
	Total Aromatics	mass %	22.1
	Mono-Aromatics	mass %	19.6
	Polynuclear Aromatics (PNA)	mass %	2.5
D5291	Elemental Analysis		
	Carbon Content	weight %	86.49
	Hydrogen Content	weight %	13.42
D5453	Sulfur Content	ppm	8.5
D613	Cetane Number	--	51.3
D86 **	Distillation		
	IBP	degF	337
	10%	degF	435
	50%	degF	539
	90%	degF	620
	FBP	degF	654
	Recovered	mL	97.9
	Residue	mL	1.5
	Loss	mL	0.6
D93	Flash Point	deg. F	157
D97	Pour Point	deg. C	-21
D976	Cetane Index	calculated	50.2
EN14078	FAME Content by FTIR	volume %	<0.5

2.1.3 EPA S15 (ULSD)

The U.S.-EPA ULSD fuel was purchased as a single batch and the fuel meets the properties listed in Title 40: Protection of Environment, Part 1065, Subpart H standards[3]. Table 3 shows a list of limits that allows a fuel to meet the EPA specifications and the results of the analysis of the batch of fuel purchased for this project.

---

[3] Title 40: Protection of Environment, PART 1065—ENGINE-TESTING PROCEDURES, Subpart H—Engine Fluids, Test Fuels, Analytical Gases and Other Calibration Standards

TABLE 3. EPA CERTIFICATION ULSD SPECIFICATIONS AND ANALYSIS RESULTS

ASTM Method	Test Property	Units	Title 40: Protection of Environment PART 1065—ENGINE-TESTING PROCEDURES	PPRD Test Results
D240	Heat of Combustion			
	GROSS	BTU / lb	--	19474
	GROSS	MJ / kg	--	45.296
D240	Heat of Combustion			
	NET	BTU / lb	--	18298
	NET	MJ / kg	--	42.561
D4052	API Gravity	--	--	33.0
	Specific Gravity	--	--	0.8603
	Density at 15°C	grams / L	--	859.8
D2500	Cloud Point	deg. C	--	-13
D4052	API Gravity	--	32 to 37	33
	Specific Gravity	--	--	0.8603
	Density at 15°C	grams / L	--	859.8
D445	Viscosity at 40°C	cSt	2.0 to 3.52	2.934
D4629	Nitrogen Content	ppm	--	4.1
D4737	Cetane Index	calculated	--	43.9
D5186	Total Aromatics by SFC			
	Total Aromatics	mass %	> 10	33.0
	Mono-Aromatics	mass %	--	28.9
	Polynuclear Aromatics (PNA)	mass %	--	4.0
D5291	Elemental Analysis			
	Carbon Content	weight %	--	87.00
	Hydrogen Content	weight %	--	12.89
D5453	Sulfur Content	ppm	7 to 15	11.6
D613	Cetane Number	--	40 to 50	43.9
D86 **	Distillation			
	IBP	degF	339.8 to 399.2	349
	10%	degF	399.2 to 460.4	408
	50%	degF	469.4 to 539.6	528
	90%	degF	559.4 to 629.6	629
	FBP	degF	609.8 to 690.8	668
	Recovered	mL	--	98
	Residue	mL	--	1.3
	Loss	mL	--	0.7
D93	Flash Point	deg. F	> 129	155
D97	Pour Point	deg. C	--	-27
D976	Cetane Index	calculated	--	45.8
EN14078	FAME Content by FTIR	volume %	--	<0.5

2.1.4 Fuel Blends

After the three different base fuels (CARB0, EPA0, and B100) were delivered, analyzed, had their results reviewed, and were approved for testing, the base fuels were then blended in separate storage tanks (shown in Figure 2) to create CARB5, CARB20, EPA5, and EPA20 fuel blends. The results of the fuel analysis for these fuel blends are provided in Appendix C.

Figure 2. Fuel Storage Tanks and Fuel Totes

2.2 Test Sequence

With two locomotives (one GE and one EMD), six fuels, and triplicate tests (for each fuel on each locomotive), a total of thirty six FTP tests were performed. For each locomotive, the six fuels were each run in a random sequence. The second pass on the set of six fuels was in reverse order from the first pass. The third pass for each locomotive was a new random sequence for the six fuels. The sequence for testing the six fuels in the two locomotives is shown in Table 4. With replication and randomization in the design of this study, we were able to statistically evaluate fuel effects within each locomotive and assess interactions between locomotives and fuel effects.

TABLE 4. TEST SEQUENCE

Test	Fuel Sequence Locomotive #1	Fuel Sequence Locomotive #2
1	EPA20	CARB0
2	CARB0	CARB20
3	EPA0	CARB5
4	CARB20	EPA20
5	EPA5	EPA5
6	CARB5	EPA0
7	CARB5	EPA0
8	EPA5	EPA5
9	CARB20	EPA20
10	EPA0	CARB5
11	CARB0	CARB20
12	EPA20	CARB0
13	EPA20	CARB0
14	CARB5	EPA0
15	EPA5	EPA20
16	CARB20	CARB20
17	EPA0	EPA5
18	CARB0	CARB5

2.3 Test Fuel Delivery System and Procedures

For each individual FTP test, the applicable test fuel was delivered to the locomotive in a dedicated 550-gallon stainless steel tote. Each of the six test fuels had its own tote and associated fuel transfer pump to fill the tote from the bulk storage tank. To eliminate the possibility of cross contamination between the test fuels, the project used six totes (one for each of the six test fuels). The totes were labeled and color coded to further reduce the possibility that test fuel was not correctly dispensed and tested. Figure 3 shows the CARB0 label (white color code) on the side of the stainless steel tote.

Figure 3. Example of Fuel Label on the CARB0 Fuel Tote

Multiple steps were taken to verify that no fuels were cross contaminated during testing. The steps focused on making sure that the test cell and the locomotive engine fuel system were adequately purged of a tested fuel before conducting the emissions test with another fuel. The process followed these steps:

1. Verify that the tote label name and color code match the label on fuel storage tank.
2. Fill tote with appropriate test fuel from fuel storage tank.
3. Deliver full tote to test cell and hook up to the test cell fuel system.
4. Purge test cell fuel system (including fuel lines, primary fuel filters, pump, and day tank) of test fuel.
5. Fill day tank.
6. Operate the locomotive fuel pump (engine off) for a minimum of 6 minutes and purge all return fuel from the locomotive.
7. Verify fuel tote label matched the test to be run (final check).
8. Start and warm up engine.
9. Operate the engine at notch 8 for 20 minutes.
10. Conduct FTP test.
11. Take fuel sample from test cell day tank and label sample bottle.
12. Drain the remaining test fuel in day tank (back into the test fuel tote to minimize the amount of fuel that needs to be purged).

Figure 4 shows the test fuel and purge totes next to the test cell fuel system, along with the secondary containment for the totes. The test fuel tote was placed as close as possible to the test cell fuel system to minimize the amount of fuel in the supply fuel lines.

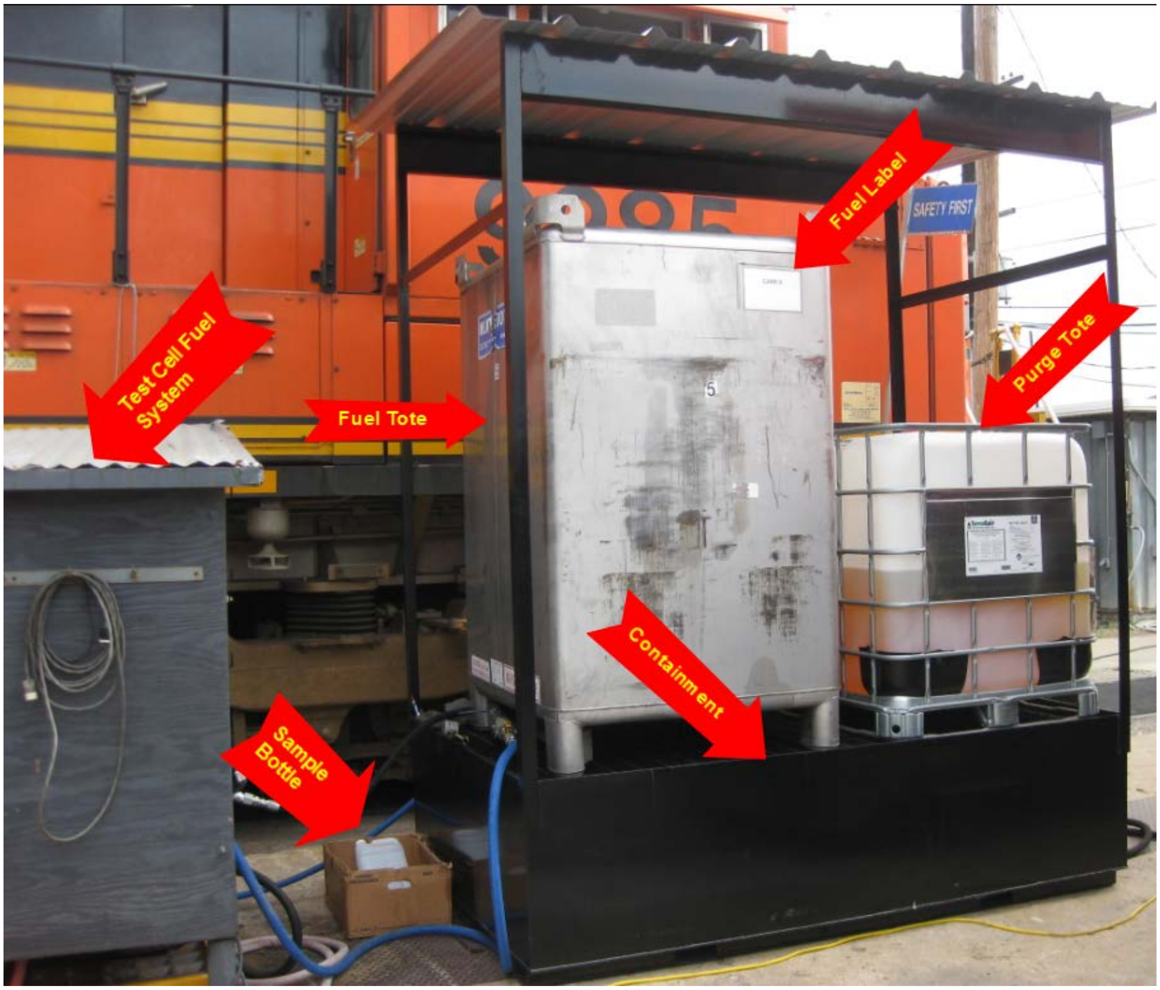


Figure 4. Test Fuel and Purge Totes

2.4 Test Locomotives

Two locomotive types were used for this project, one manufactured by EMD and one by GE. The EMD locomotive selected was a Tier 2 EMD SD70ACe and the GE locomotive was a Tier 1 Plus GE DASH9-44CW.

The EMD SD70ACe test locomotive was BNSF9285 and is shown in Figure 5. This locomotive was powered by a turbocharged, 16-cylinder, EMD 710 engine that meets U.S.-EPA locomotive Tier 2 emissions standards. The locomotive emissions tag is shown in Figure 6 and details about the engine are provided in Table 5[4].

---

[4] http://www.emdiesels.com/emdweb/international/india_710.jsp

Figure 5. BNSF9285, a Tier 2 EMD SD70ACe

ELECTRO MOTIVE

Manufactured in: ☐ Canada ☐ U.S.A. ☒ Mexico

Assembled in: ☐ Canada ☐ U.S.A. ☒ Mexico

Model : SD70ACe
Serial : 20066862-156
Date : 08-2008

Electro-Motive
9301 W. 55th Street
P.O. Box 10381
LaGrange, Illinois 60525

Electro-Motive Canada
P.O. Box 5160
London, Ontario N6A 4N5

Original Locomotive Emission Control Information

This locomotive conforms to EPA regulations applicable to locomotives originally manufactured on or after January 1, 2005

Engine Family: 8EMDG0710ES4

Locomotive Useful Life per 40 CFR Part 92 32,250 MW-hrs.
Emission Standards: This engine family has been certified as conforming to EPA Tier 2 Standards
Engine Maintenance: See MI 20002 and Running Maintenance Manual

Figure 6. BNSF9285 Locomotive Emissions Sticker

TABLE 5. EMD 710 ENGINE DETAILS

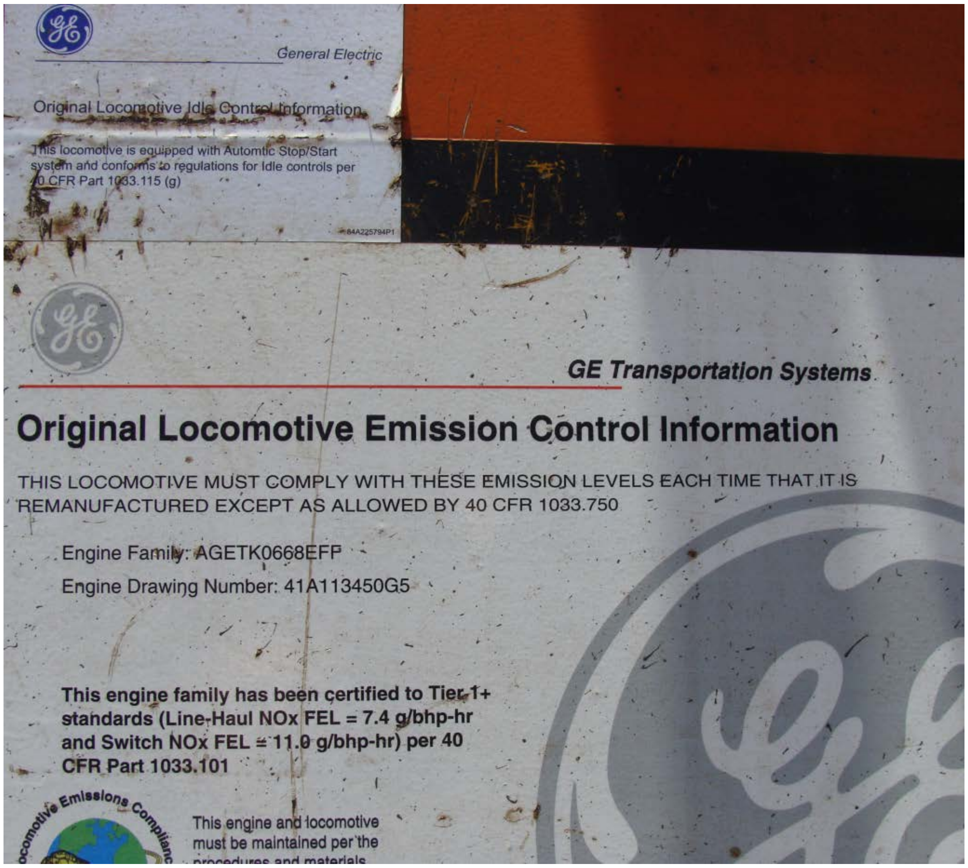
Engine Model	16-710G3B–T2
Engine Type	Two-Cycle Diesel
Engine Configuration	V-16
Displacement	710 Cubic Inch per Cylinder (11.63 liter) 11,360 Cubic Inch Total Displacement (186.2 liter)
Bore	9.0625 Inch (230.19 mm)
Stroke	11 Inch (279.4 mm)
Compression Ratio	18:1
Fuel Injection System	Electronic Unit Injector (EUI)
Rated Speed and Load	4,500 HP (3,356 kW) at 950 RPM
Idle Speed	200 RPM

The GE test locomotive was BNSF5014 and is shown in Figure 7. This U.S.-EPA Tier 1 Plus GE DASH9-44CW locomotive was originally built in 2004. However, the turbocharged, 16-cylinder, GE 7FDL engine was rebuilt in August 2010, and the engine was upgraded to the applicable U.S.-EPA Locomotive Tier 1 Plus. The locomotive emissions sticker is shown in Figure 8 and details of the GE 7FDL engine are shown in Table 6[5].

Figure 7. BNSF5014, a Tier 1 Plus GE Dash9-44CW

---

[5] http://www.getransportation.com/resources/cat_view/8-rail-resources/9-brochures.html



General Electric

Original Locomotive Idle Control Information

This locomotive is equipped with Automtic Stop/Start system and conforms to regulations for Idle controls per 40 CFR Part 1033.115 (g)

84A225794P1

GE Transportation Systems

Original Locomotive Emission Control Information

THIS LOCOMOTIVE MUST COMPLY WITH THESE EMISSION LEVELS EACH TIME THAT IT IS REMANUFACTURED EXCEPT AS ALLOWED BY 40 CFR 1033.750

Engine Family: AGETK0668EFP

Engine Drawing Number: 41A113450G5

This engine family has been certified to Tier 1+ standards (Line-Haul NOx FEL = 7.4 g/bhp-hr and Switch NOx FEL = 11.0 g/bhp-hr) per 40 CFR Part 1033.101

This engine and locomotive must be maintained per the procedures and materials

Figure 8. BNSF5014 Locomotive Emissions Sticker

TABLE 6. GE 7FDL ENGINE DETAILS

Engine Model	GE 7FDL16AE1
Engine Type	Four-Cycle Diesel
Engine Configuration	V-16
Displacement	668 Cubic Inch per Cylinder (10.93 liter) 10,675 Cubic Inch Total Displacement (174.9 liter)
Bore	9 Inch (228.6 mm)
Stroke	10.5 Inch (266.7 mm)
Compression Ratio	15.7:1
Fuel Injection System	Electronic Fuel Injection (EFI)
Rated Speed and Load	4,500 hp (3355 kW) at 1050 RPM
Idle Speed	335 RPM

2.5 Power Measurements

Power measurement for the EMD SD70ACe locomotive required the use of three power meters, as shown schematically in Figure 9. A Voltech PM3000A Universal Power Analyzer measured the two load grid paths with the use of two shunts with the capacity of 0 to 1,000 amps and the corresponding differential voltage output of 0 to 100 mV. Precision voltage dividers of 1000:1, manufactured by Zimmer Electronic Systems (ZES), were required due to the voltage input limitations of 1,400 volts for the Voltech PM3000A Universal Power Analyzer.

Accessory power of the EMD companion alternator was measured using an Ohio Semitronics P-153X5S wattmeter, a pair of current transducers, and direct voltage measurements. A second Ohio Semitronics P-150X5S wattmeter measured the auxiliary power converter, which powers the battery charging and the low voltage DC systems, as shown in Figure 9.

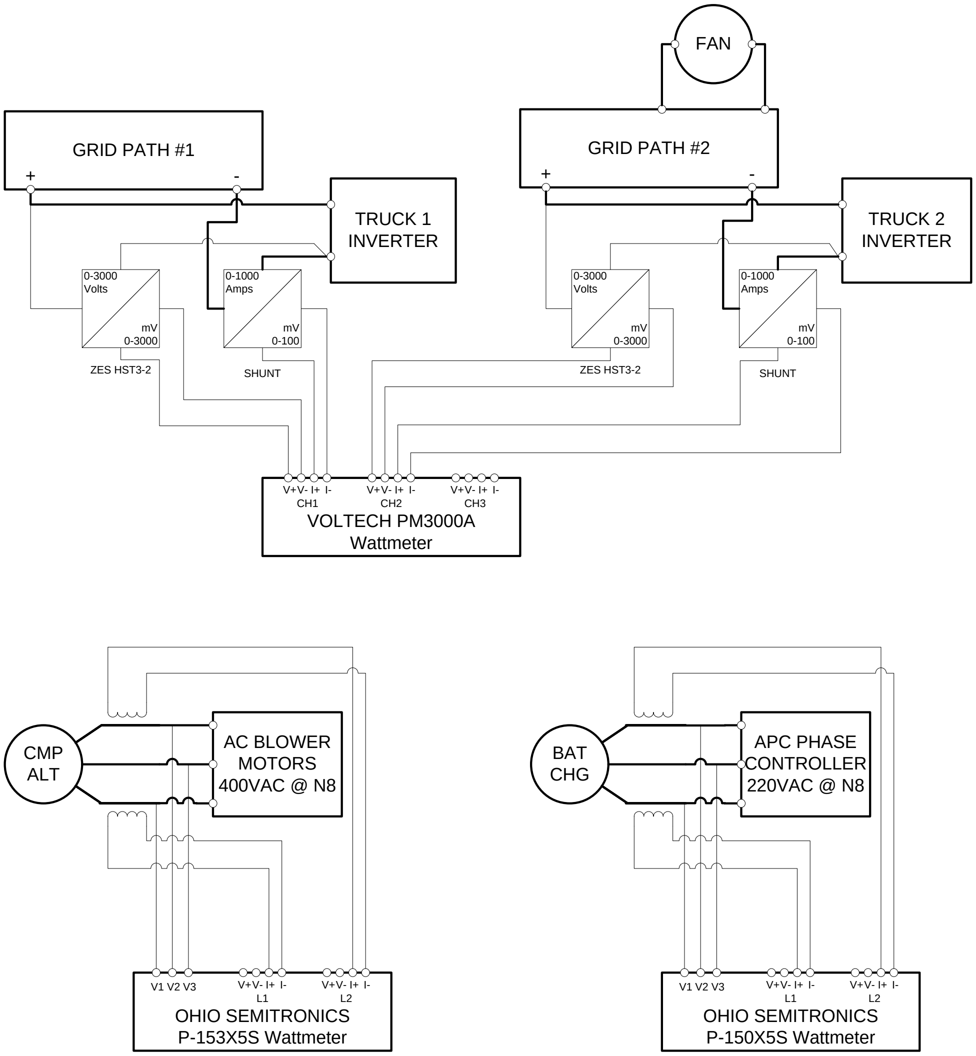


Figure 9. EMD SD70Ace Power Measurement Schematic

Power measurements on BNSF 5014, the Tier 1 Plus GE Dash9-44CW locomotive, were made using a Voltech PM3000A Universal Power Analyzer. A single external current shunt was used for the main alternator current measurements. The shunt had a capacity of 0 to 4,000 amps and a corresponding differential voltage output of 0 to 100mV. The power measurement schematic is shown in Figure 10.

Accessory power of the GE auxiliary alternator was measured at each test point using a pair of current transducers, direct voltage measurements, and the Voltech PM3000A Universal Power Analyzer, as shown in Figure 10. The accessory power of the locomotive is the power supplied to subsystems via an auxiliary or companion alternator. These auxiliary loads include radiator cooling fans, traction motor and inertial filter blowers, and other parasitic items needed to run the locomotive.

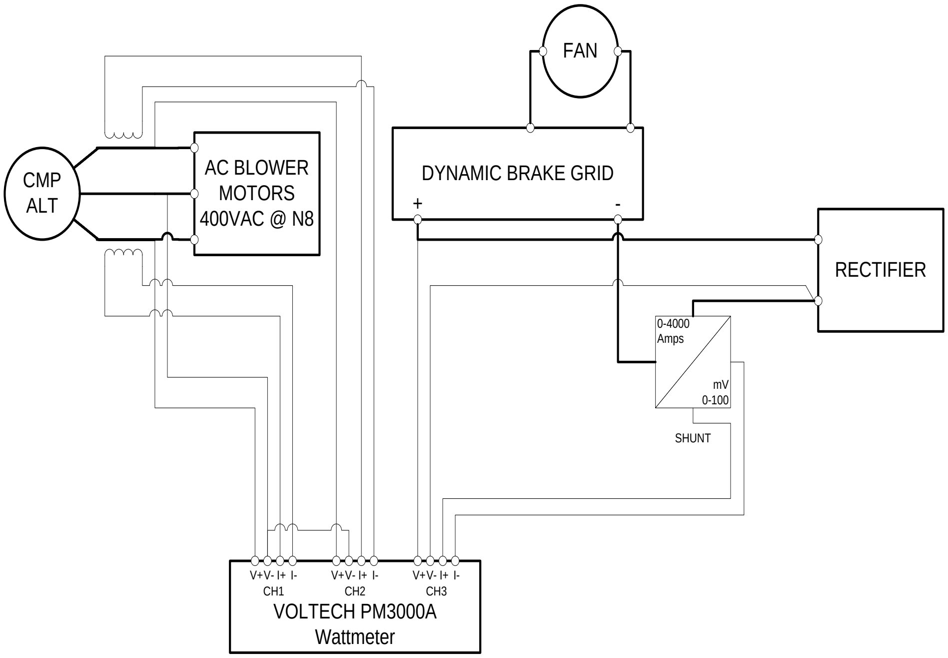


Figure 10. GE DASH9-44CW Power Measurement Schematic

2.6 Fuel Consumption Measurements

Diesel fuel consumption was measured on a mass flow basis using a Micro Motion® mass flow meter. The fuel measurement system was equipped with a heat exchanger to control engine fuel supply temperature. Hot fuel, normally returned to the locomotive fuel tank, was cooled before returning to the fuel measurement reservoir (“make-up tank”) to assure a consistent fuel supply temperature at the engine.

2.7 Exhaust Emissions Test Procedures

SwRI performed exhaust emission tests using the FTP for locomotives, as detailed in 40 CFR Part 92, Subpart B. In accordance with the FTP, emissions of hydrocarbons (HC), carbon dioxide (CO_2), oxides of nitrogen (NO_X), oxygen (O_2) and particulate matter (PM) emissions were measured for each throttle notch. This data was used to calculate the U.S.-EPA line-haul and switch cycle weighted composite emission for each pollutant. Smoke opacity was also measured during the testing, as mandated by the FTP.

2.7.1 Gaseous Emission Sampling

A heated sample line was used to transfer the raw exhaust sample from the probe mounted on the exhaust stack extension to the emission instruments used to measure the raw exhaust concentrations of HC, CO, CO_2, O_2, and NOx at each operating mode.

Hydrocarbon concentrations were determined using a California Analytical Instruments Model 300 heated flame ionization detector (HFID) calibrated on propane. NOx concentrations were measured using a California Analytical Instruments Model 400 heated chemiluminescent detector (HCLD). NOx correction factors for engine intake air humidity were applied as specified by EPA in 40 CFR §1065.670. Concentrations of CO and CO_2 were determined by nondispersive infrared (NDIR) instruments and O_2 concentrations were measured using a magneto-pneumatic analyzer.

Gaseous mass emission rates were computed using the measured concentrations, the observed (measured) fuel consumption rate, and calculated engine airflow. Engine airflow was not directly measured in this test program. Instead, engine airflow was determined according to FTP guidelines by using the carbon balance, the fuel carbon content, and knowledge of the concentrations of the carbon-containing constituents in the exhaust (CO_2, CO, and HC) to compute the fuel/air ratio (f/a). Engine airflow rate was then computed using the measured fuel consumption rate and the computed f/a ratio. The sum of measured fuel and computed intake air was taken as the mass flow of exhaust.

2.7.2 Particulate Emission Sampling

PM emissions were measured at each test mode using a “split then dilute” technique in which a portion of the raw exhaust was “split” from the total flow and mixed with filtered air in an 8-inch diameter dilution tunnel. The raw split sample was transferred from a particulate sample probe, mounted on the exhaust stack extension (shown on the roof of BNSF5014 in Figure 7) to the dilution tunnel via a short insulated pipe between the exhaust stack extension and the entry of the particulate dilution tunnel.

After adequate dilution, a particulate sample was extracted from the dilution tunnel with a sample probe and transferred to the filter holder. Particulate was accumulated on two 90 mm fluorocarbon-coated glass fiber filters (Pallflex T60A20) in series at a target filter face velocity of 70 cm/s. The filters were mounted in a stainless steel filter holder connected to the sample probe. Particulate filters were preconditioned and weighed before and after testing, following the FTP. The particulate mass emission rate was computed using the mass collected on the filters, the volume of dilute exhaust drawn through the filters, and dilution air and raw exhaust flow parameters.

2.7.3 Cycle Weighted Emission Calculations and Standards

HC, CO, NO_X, and PM were sampled at each locomotive notch and the switch and line-haul cycles were calculated using the U.S.-EPA weighting factors[6]. The U.S.-EPA test cycle and weighting factors applied to each notch are shown in Table 7.

TABLE 7. U.S.-EPA LOCOMOTIVE TEST CYCLE WEIGHT FACTORS

Notch	**Switch Cycle WF**	**Line-haul Cycle WF**
LI	29.9%	19.0%
Idle	29.9%	19.0%
DB2	0.0%	12.5%
1	12.4%	6.5%
2	12.3%	6.5%
3	5.8%	5.2%
4	3.6%	4.4%
5	3.6%	3.8%
6	1.5%	3.9%
7	0.2%	3.0%
8	0.8%	16.2%
sum =	100.0%	100.0%

The U.S.-EPA locomotive exhaust emissions standards are shown in Table 8. BNSF5014 was designed to meet Tier 1 Plus, and BNSF9285 was designed to meet Tier 2 standards.

TABLE 8. U.S.-EPA EMISSIONS STANDARDS

Year Manufactured	Tier	Line-Haul Cycle				Switch Cycle			
		NOx	PM	HC	CO	NOx	PM	HC	CO
1973–1992	0 Plus	8.0	0.22	1.00	5.0	11.8	0.26	2.10	8.0
1993–2004	1 Plus	7.4	0.22	0.55	2.2	11.0	0.26	1.20	2.5
2005–2011	2	5.5	0.20	0.30	1.5	8.1	0.24	0.60	2.4
2012 or later	2 Plus	5.5	0.10	0.30	1.5	8.1	0.13	0.60	2.4
2012–2014	3	5.5	0.10	0.30	1.5	5.0	0.10	0.60	2.4
2015 or later	4	1.3	0.03	0.14	1.5	1.3	0.03	0.14	2.4

---

[6] CFR Title 40: Protection of Environment, CONTROL OF AIR POLUTION FROM LOCOMOTIVES AND LOCOMOTIVE ENGINES; PART 92, Section 92.132.

3. Test Results

With replication and randomization in the design of this study, we were able to statistically evaluate fuel effects within each locomotive and assess interactions between locomotives and fuel effects. For many of the results and cycles, the interactions were significant. For the purposes of these analyses, we use "significant" to indicate statistically significant with alpha equal to 0.05 (α=0.05). We used a statistical model that included locomotive, fuel, and interactions between locomotive and fuel to define 12 means (2 locomotives (9285 and 5014) X 2 base fuels (EPA and CARB) X 3 biodiesel levels (0, 5, and 20 percent)) for each of the cycles and each of the test results. We created comparison intervals around each of these 12 means such that when the intervals do not overlap for a pair of fuels within a locomotive, we can say the difference between the two fuels is statistically significantly different with α=0.05, using Tukey's multiple comparison procedure. These intervals are shown in the attached Figures 11–27. The following discussion is based on comparisons using these figures.

General trends for biodiesel seen in other studies and in other applications were seen in this study. Higher levels of biodiesel were associated with lower CO and PM and higher levels of NO_X and fuel usage. Biodiesel at 20 percent often resulted in statistically significant differences from 0 or 5 percent biodiesel, while the difference between 0 and 5 percent biodiesel was generally not statistically significant. Different trends between the locomotives could be explained by differences in emissions certification levels and oil consumption.

Carbon Monoxide (CO):

Within each locomotive, the EPA and CARB base fuels did not have significantly different CO emissions. In locomotive 9285, the only significant effect of biodiesel was that CARB0 had significantly higher emissions than CARB20 or EPA20. In locomotive 5014, CARB20 and EPA20 both had significantly lower emissions than the other fuels, while the B5 fuels were not significantly different from their base fuels.

Oxides of Nitrogen (NOx):

Within each locomotive, EPA0 had significantly higher NOx emissions than CARB0 for the line-haul and switch cycle. While the differences were directionally the same for notch 8, they were not significant for either locomotive. For some of the cycle and locomotive combinations, the 20 percent biodiesel fuel had significantly higher NOx than their respective base fuels or 5 percent biodiesels. For none of the combinations was the 5 percent biodiesel significantly different from its base fuel.

Particulate Matter (PM):

With locomotive 5014 for line-haul, EPA0 had significantly higher PM emissions than CARB0. Also with locomotive 5014 for line-haul and notch 8, EPA20 had significantly lower PM than EPA5 or EPA0 and CARB20 had significantly lower PM emissions than CARB0.

Hydrocarbons (HC):

There were no significant differences among the six fuels' hydrocarbon emissions within a locomotive in this cycle.

Notch 8 Brake Horse Power (BHP):

There were no significant differences among the six fuels BHP within a locomotive.

Notch 8 Observed Fuel Mass Flow Rate:

CARB20 used significantly more fuel (mass flow rate) than CARB0 and CARB5 in both locomotives. EPA20 used significantly more fuel (mass flow rate) than EPA0 and EPA5 in locomotive 9285. EPA20 used significantly more fuel (mass flow rate) than EPA0 in locomotive 5014.

Corrected Brake Specific Fuel Consumption (cBSFC):

For the line-haul cycle, the cBSFC was significantly higher for CARB0 than for EPA20 for locomotive 9285. For locomotive 5014 with this cycle, cBSFC was significantly higher for CARB0, CARB5, and EPA20 than for EPA20. For the switch cycle, there were no significant differences among fuels for either locomotive. For notch 8, 20 percent biodiesel had significantly higher cBSFC than 0 percent and 5 percent biodiesel in both locomotives and both base fuels.

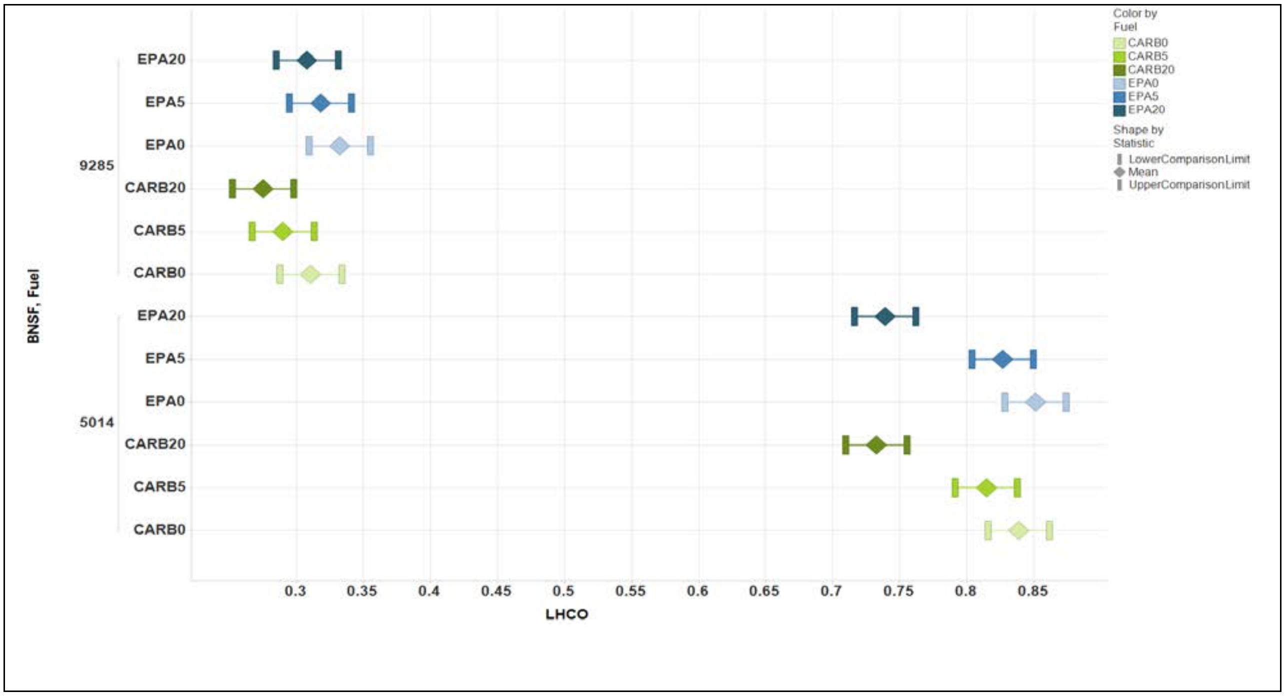


Figure 11. EPA Line-Haul Cycle CO Emissions Summary

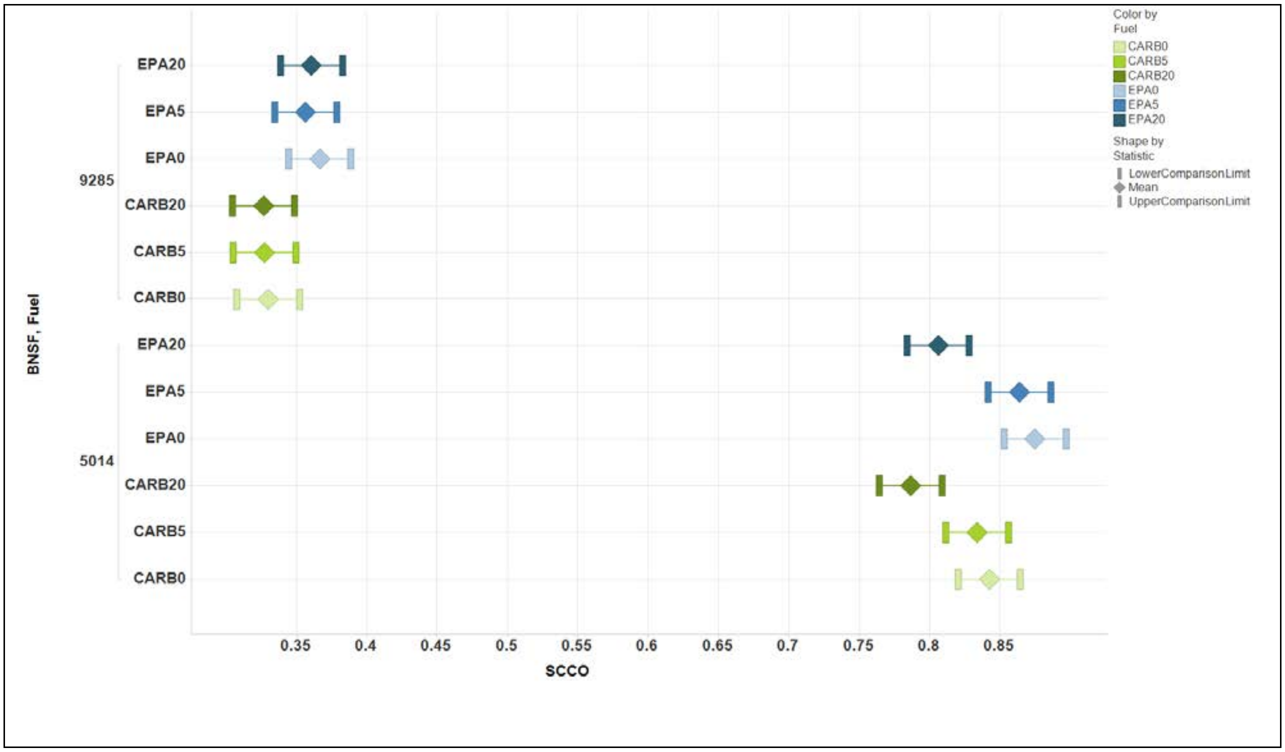


Figure 12. EPA Switch Cycle CO Emissions Summary

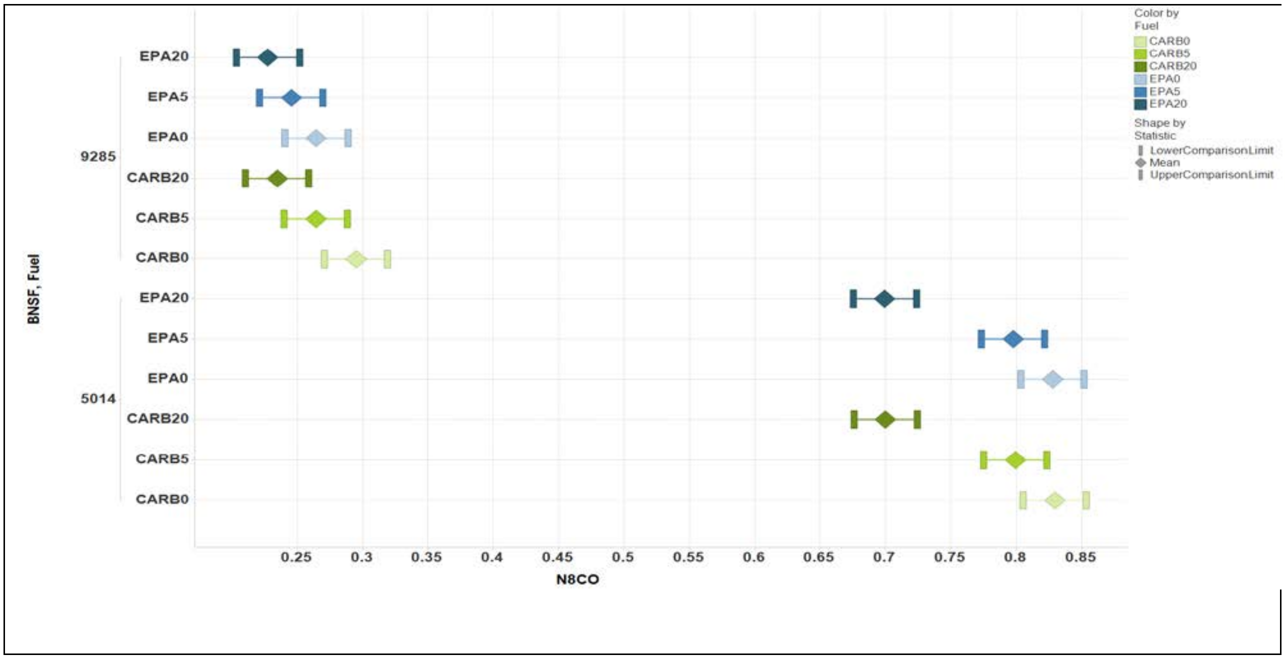


Figure 13. EPA Notch 8 CO Emissions Summary

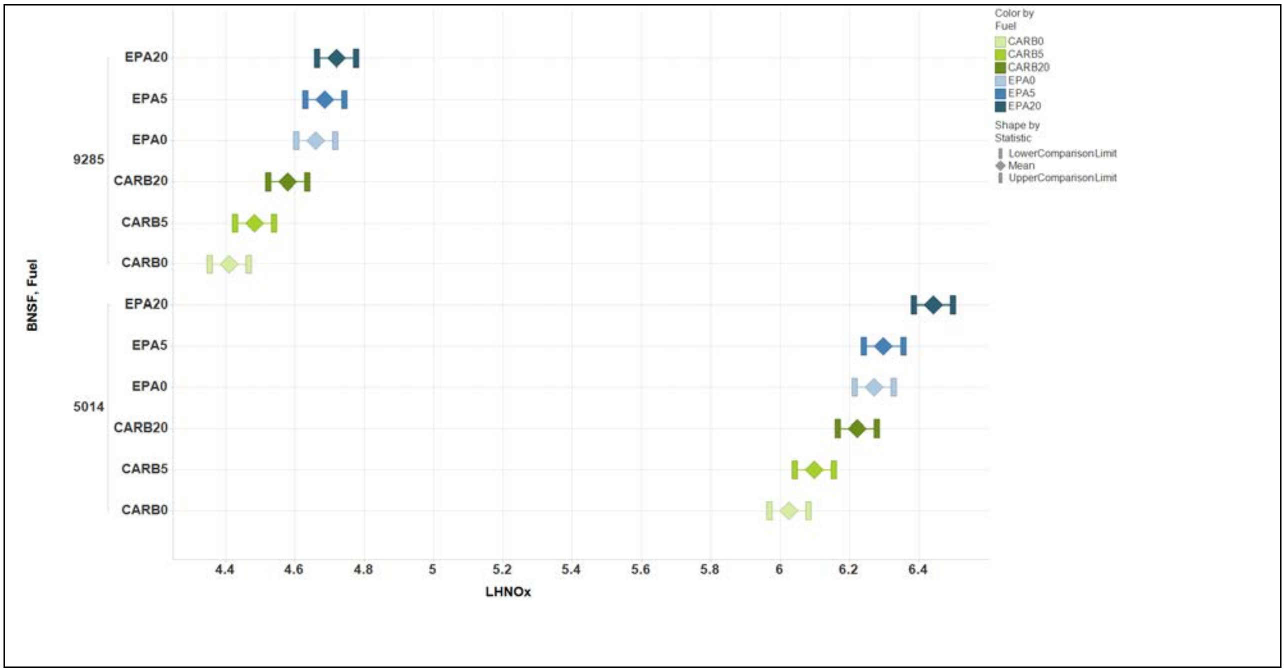


Figure 14. EPA Line-Haul Cycle NOX Emissions Summary

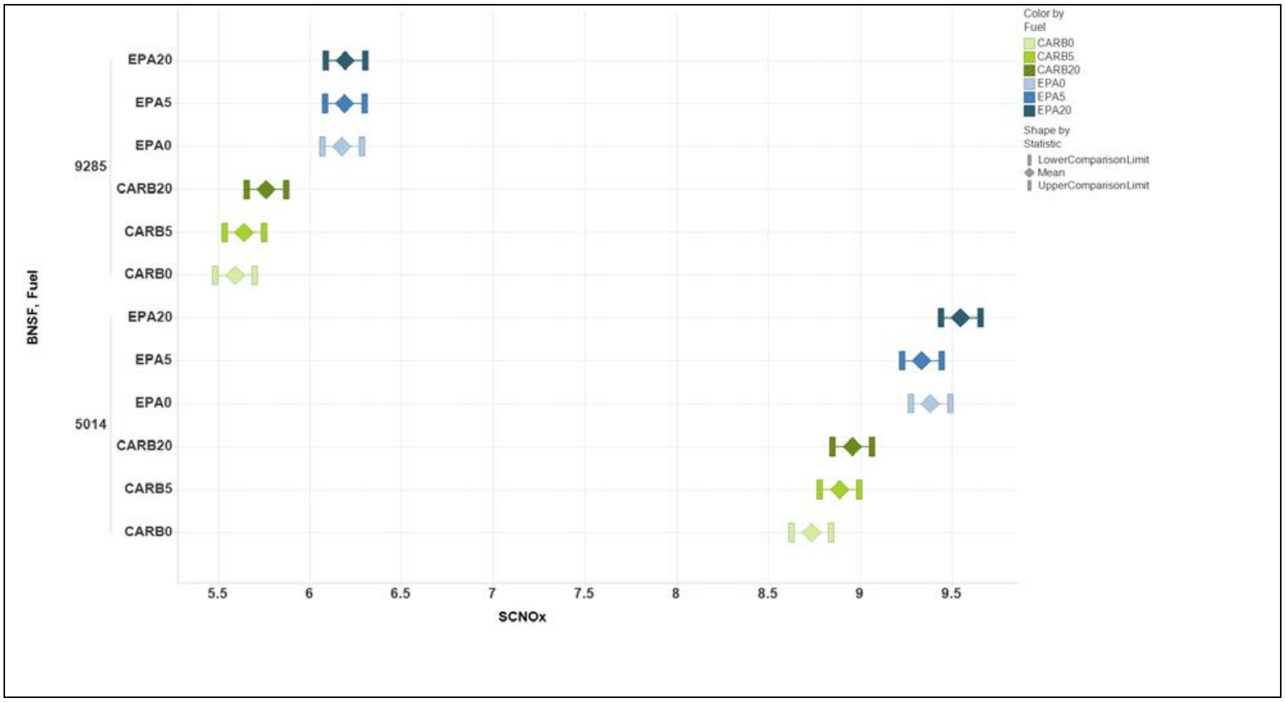


Figure 15. EPA Switch Cycle NOX Emissions Summary

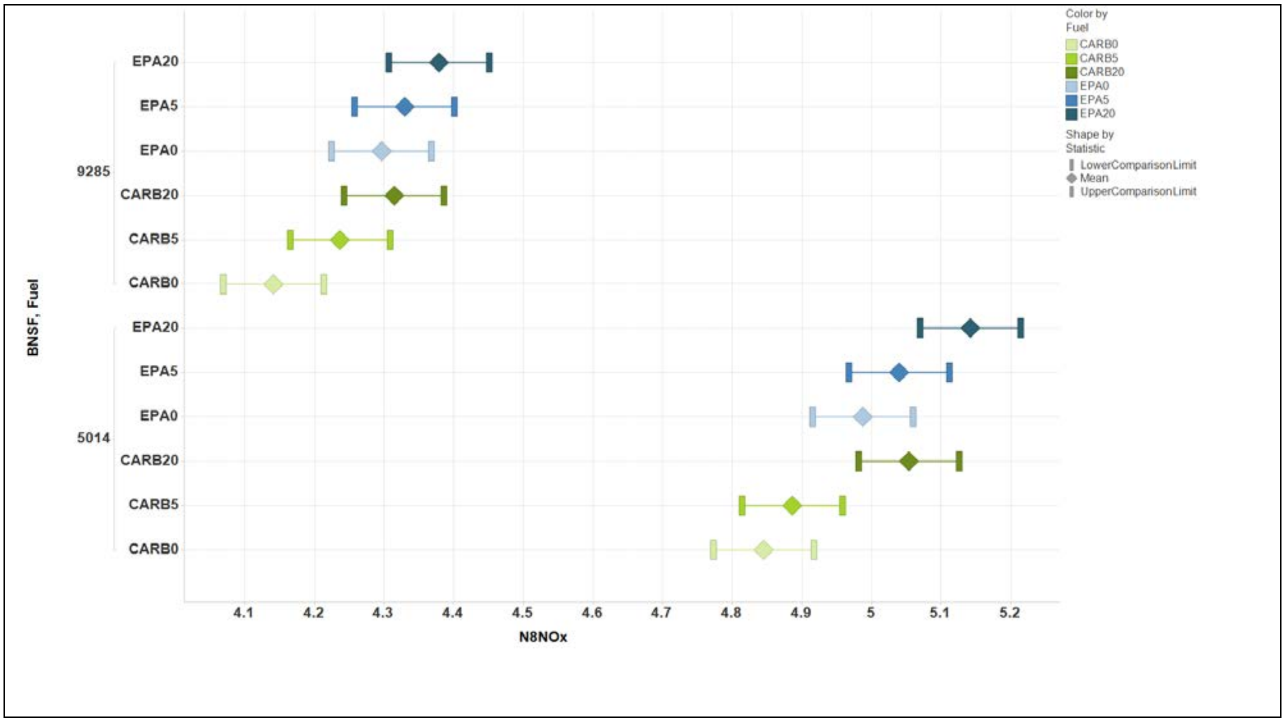


Figure 16. EPA Notch 8 NOX Emissions Summary

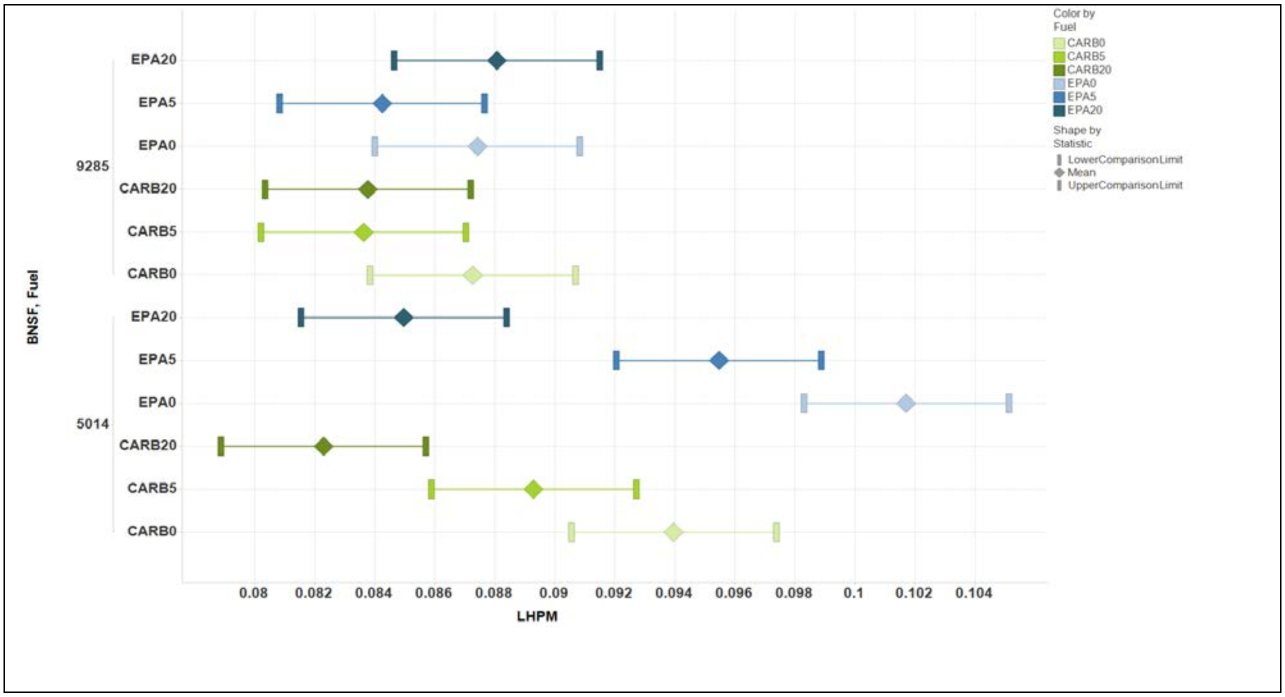


Figure 17. EPA Line-Haul Cycle PM Emissions Summary

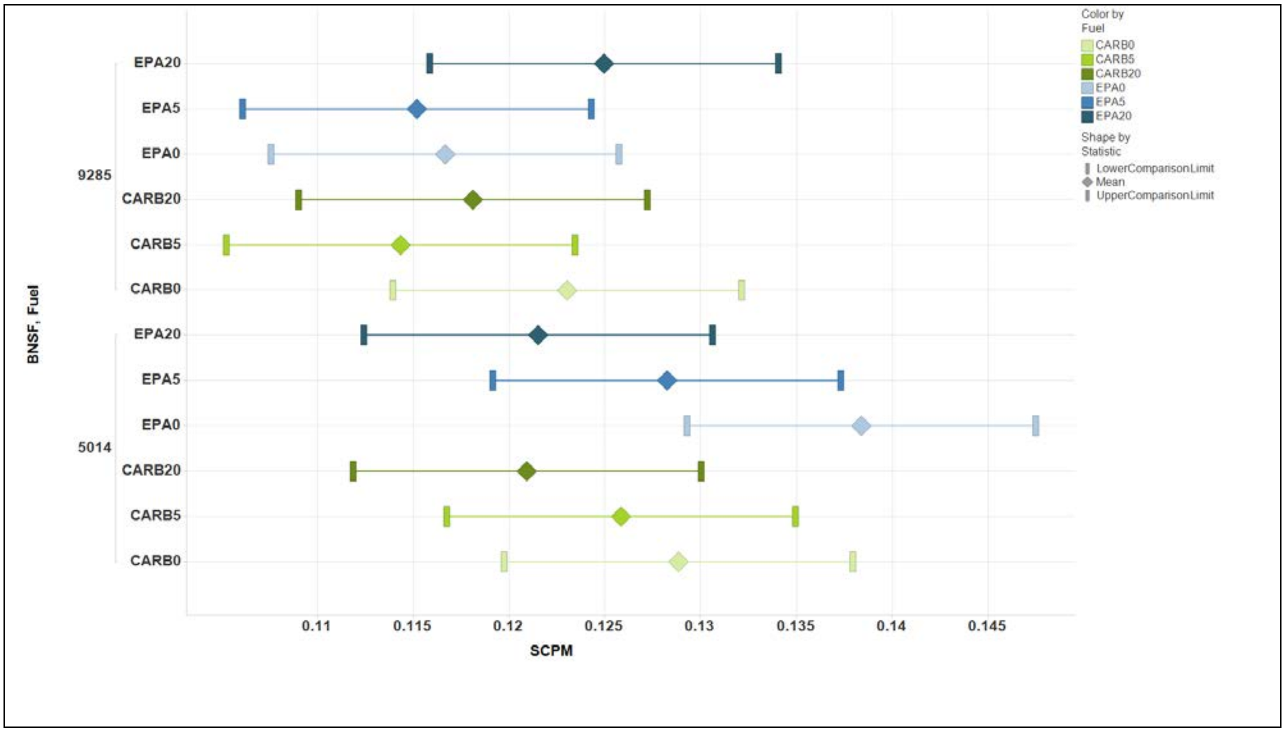


Figure 18. EPA Switch Cycle PM Emissions Summary

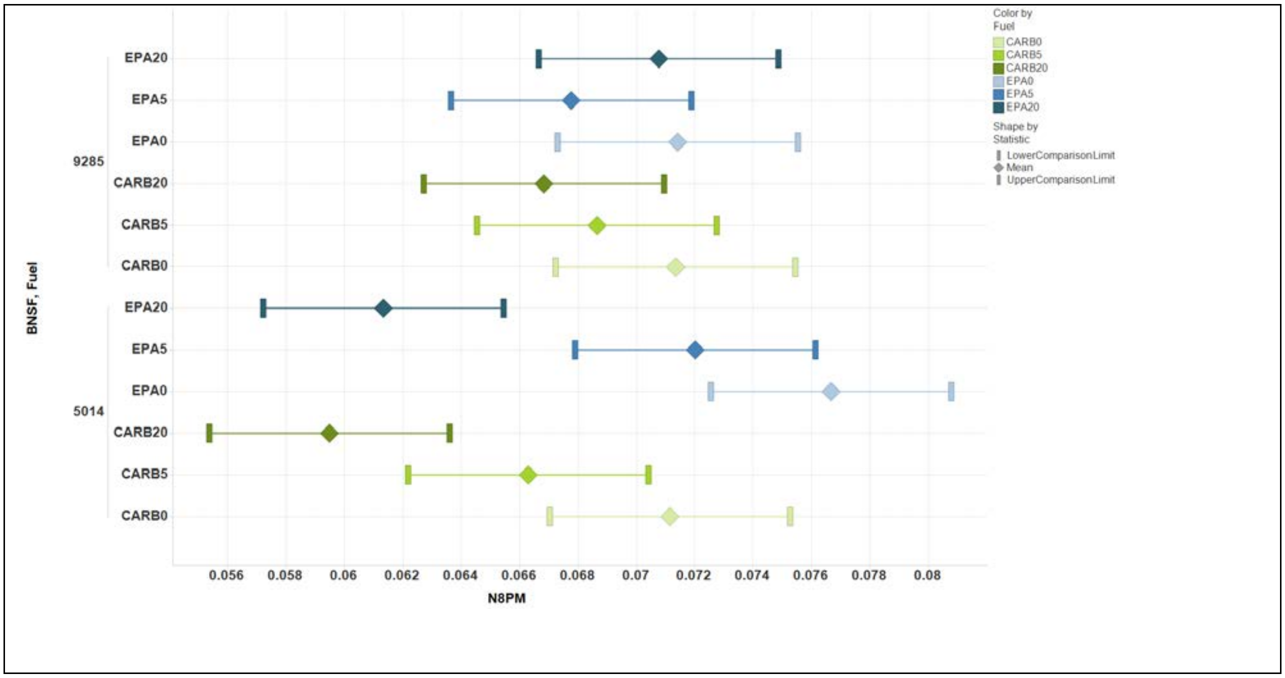


Figure 19. EPA Notch 8 PM Emissions Summary

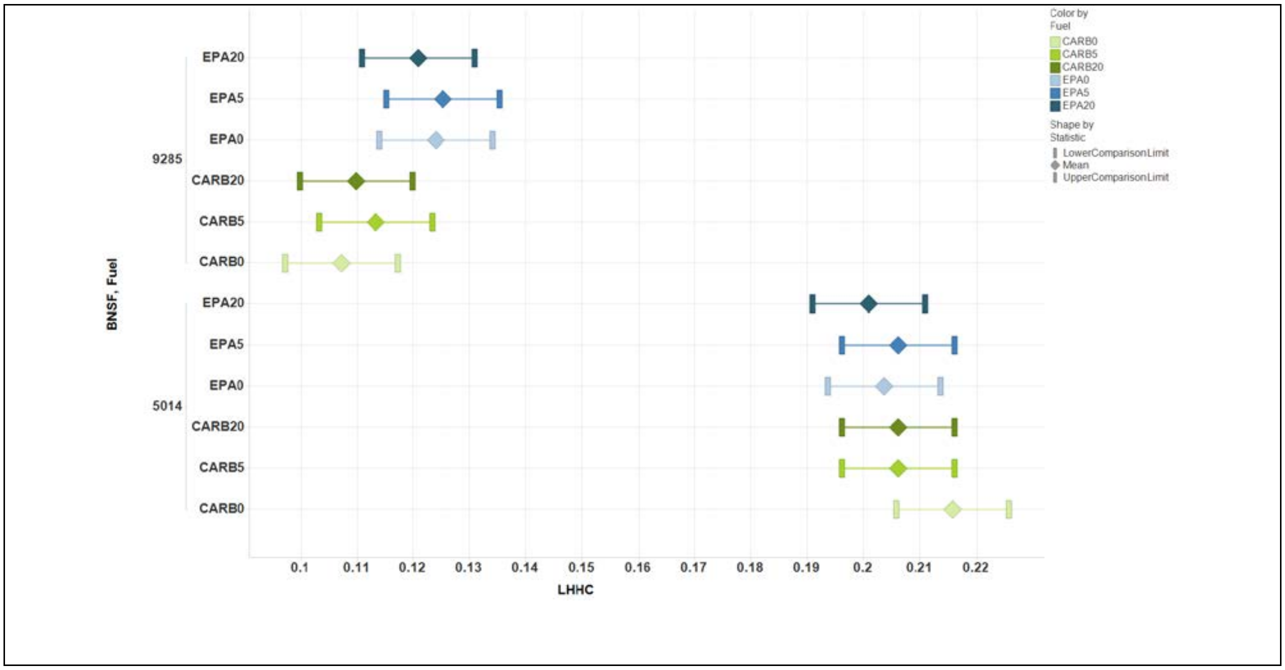


Figure 20. EPA Line-Haul Cycle HC Emissions Summary

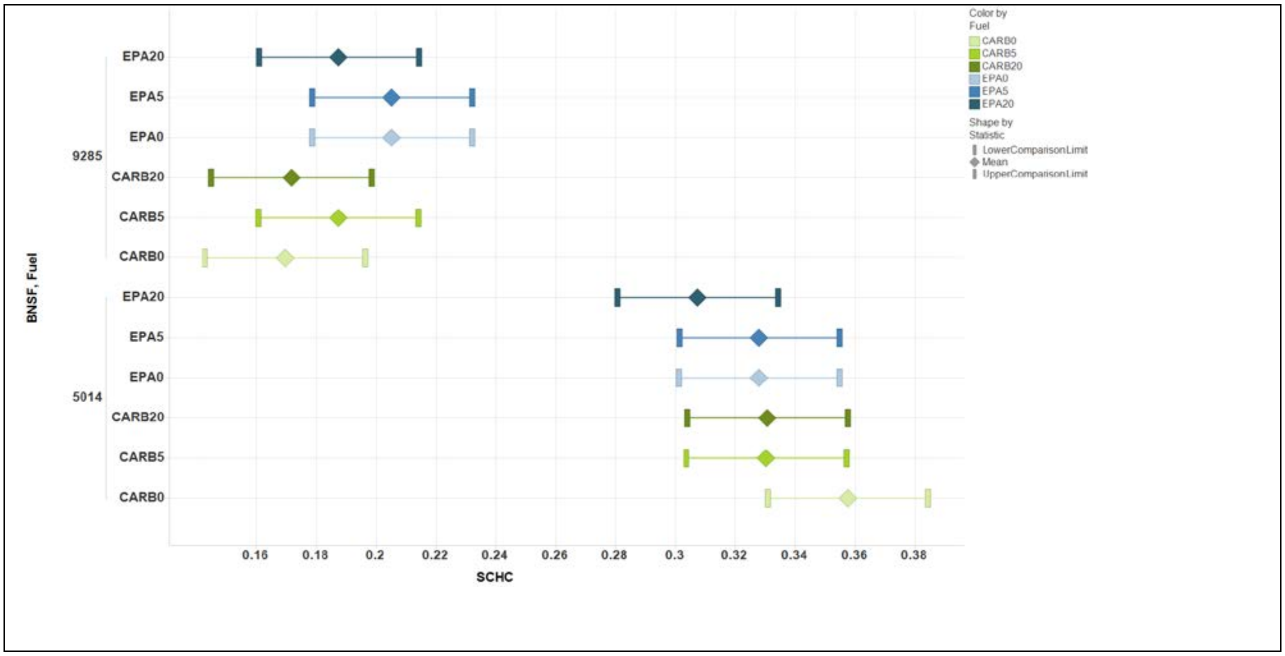


Figure 21. EPA Switch Cycle HC Emissions Summary

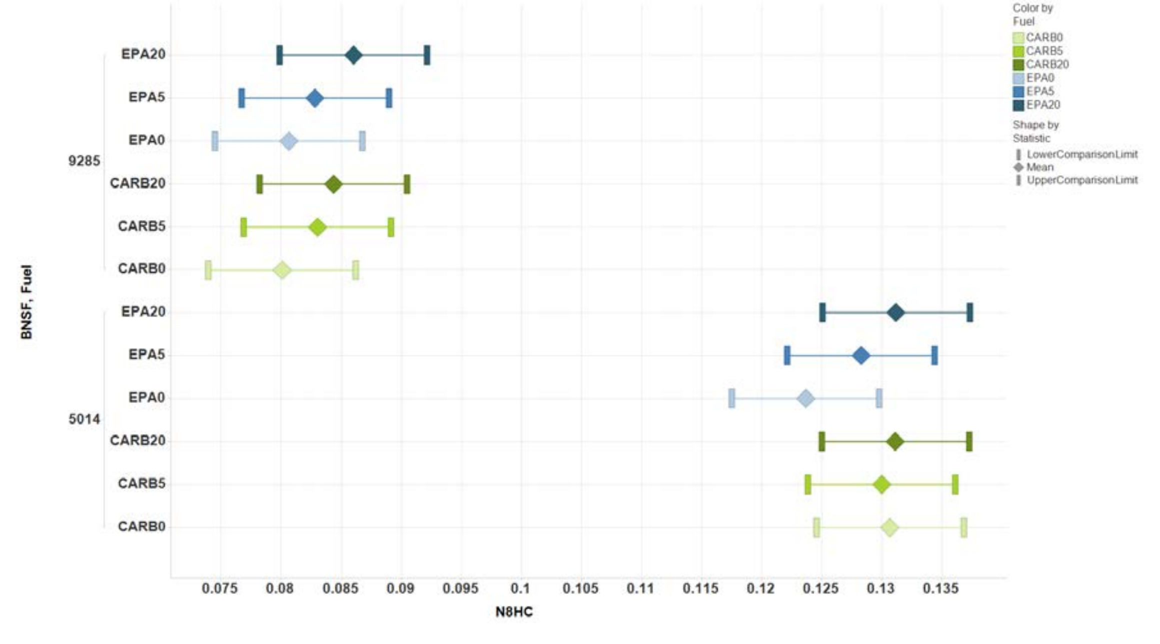


Figure 22. EPA Notch 8 HC Emissions Summary

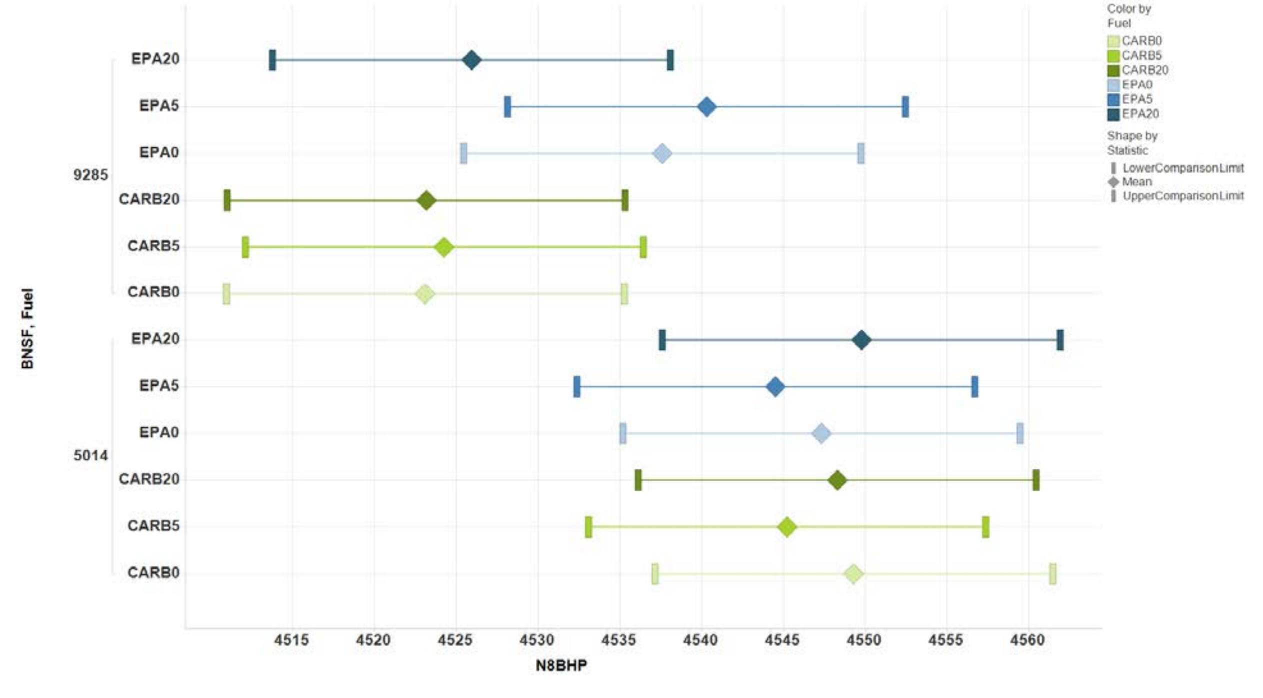


Figure 23. EPA Notch 8 BHP Summary

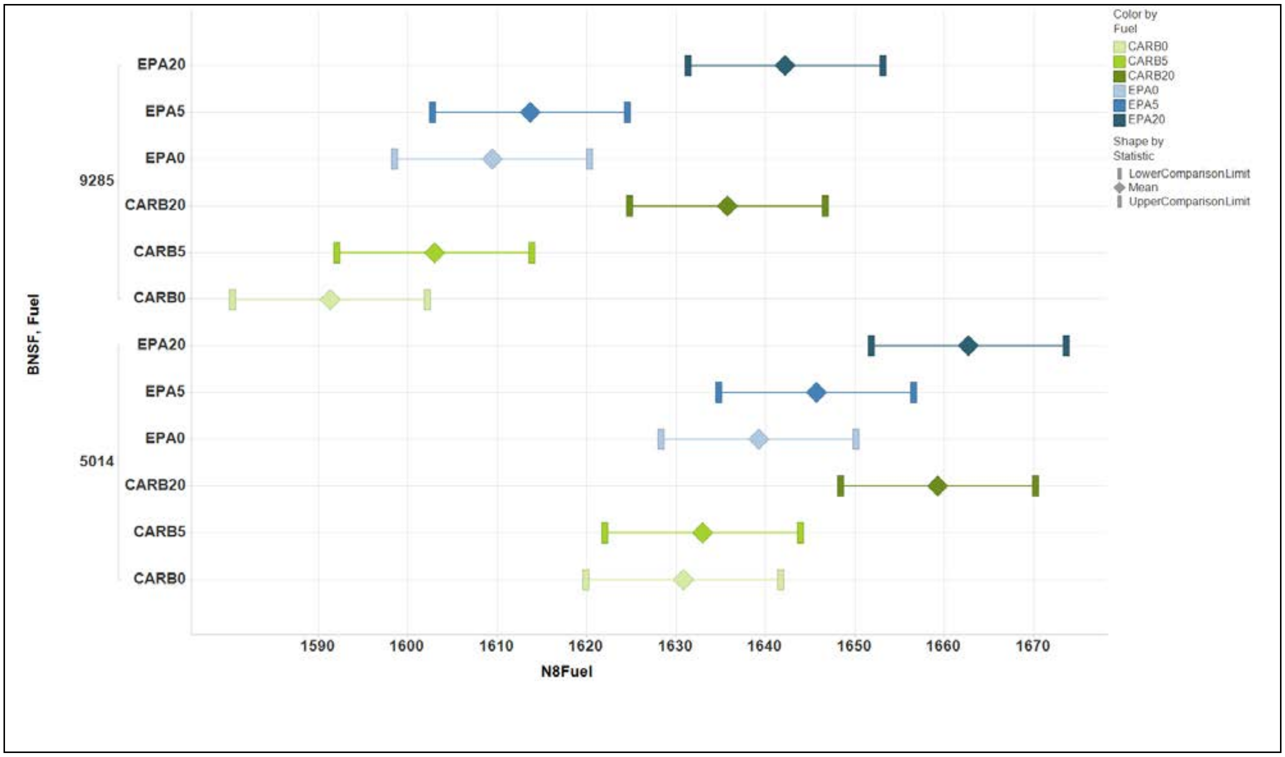


Figure 24. EPA Notch 8 Fuel Mass Flow Rate (lb/hr) Summary

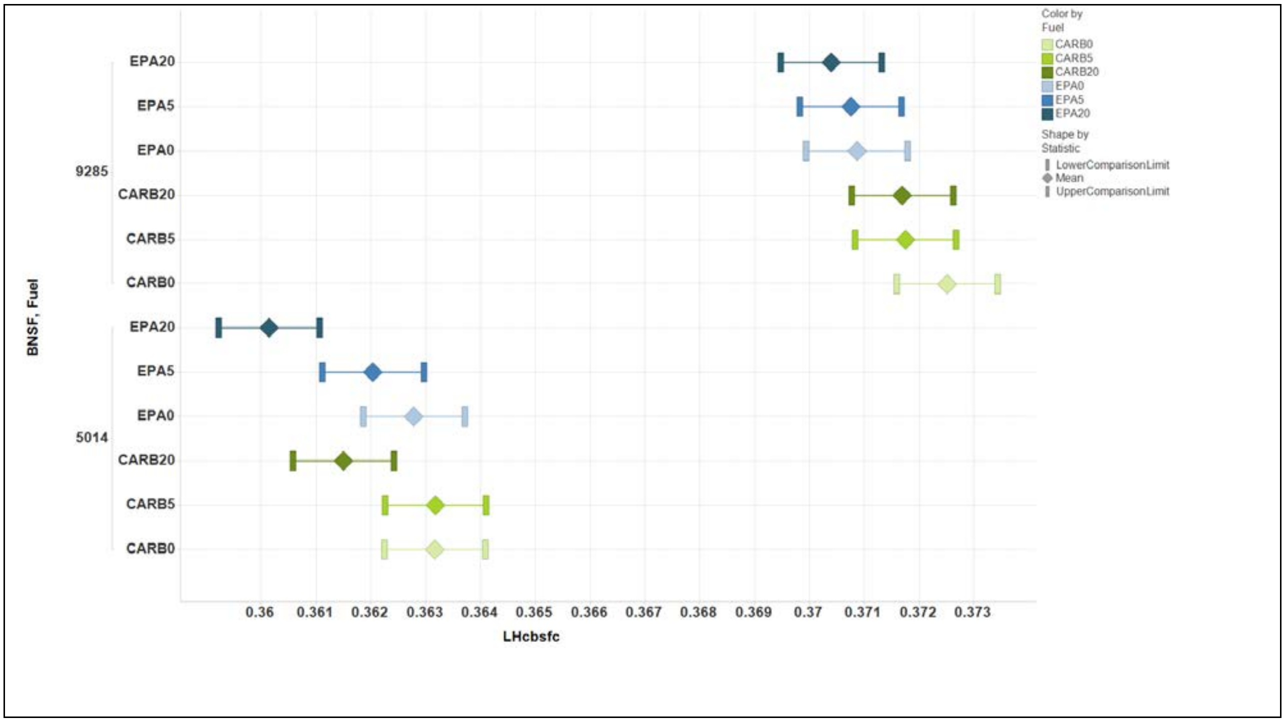


Figure 25. EPA Line-Haul Cycle Corrected BSFC (lb/hp-hr) Summary

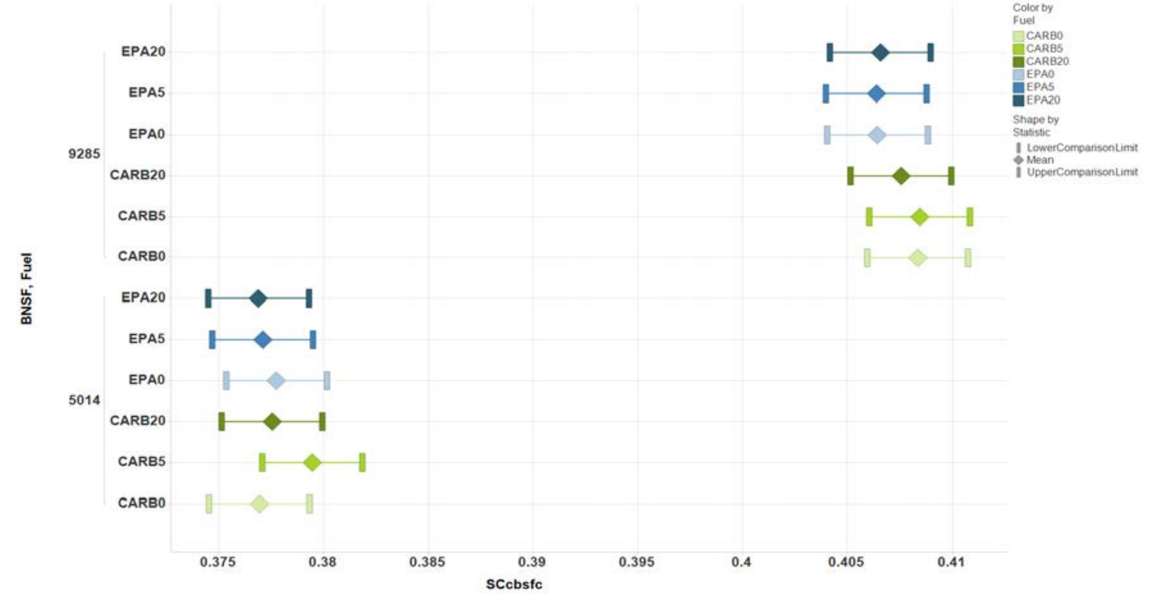


Figure 26. EPA Switch Cycle Corrected BSFC (lb/hp-hr) Summary

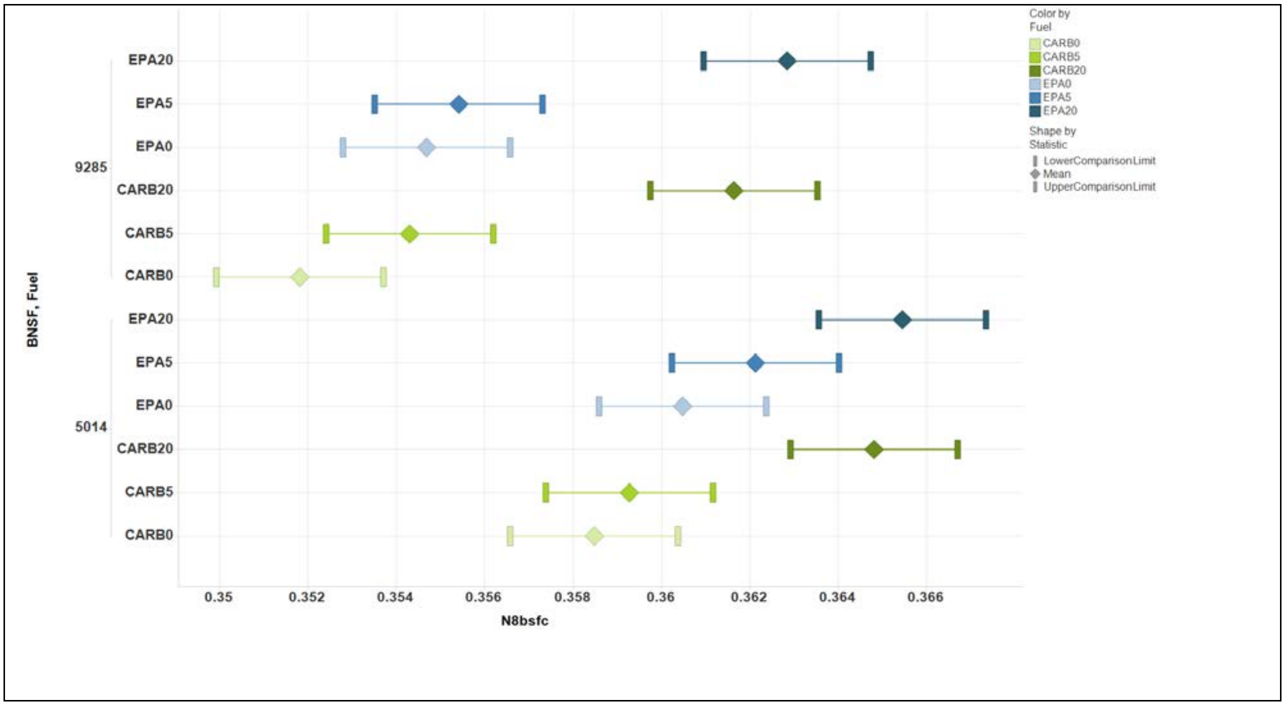


Figure 27. Notch 8 Corrected BSFC (lb/hp-hr) Summary

4. Conclusions

This project blended conventional EPA Grade No. 2-D S15 ULSD certification diesel fuel and a commercially available Grade No. 2-D CARB ULSD diesel fuel with B-100 biodiesel to produce EPA5, EPA20, CARB5, and CARB20 biodiesel fuels. These six fuels were triplicate tested in a GE Tier 1 Plus locomotive and an EMD Tier 2 locomotive.

General emissions and fuel economy trends for biodiesel seen in other studies and in other applications were seen in this study. Higher blend levels of biodiesel were associated with lower CO and PM, higher levels of NOx, and fuel consumption. Diesel fuel with 20 percent biodiesel often resulted in statistically significant differences from the fuel with 0 percent or 5 percent biodiesel, while the difference between 0 percent and 5 percent biodiesel was generally not statistically significant. Different trends between the locomotives could be explained by differences in emissions certification levels and oil consumption.

Appendix A.
Request for Quote Letter to All BQ-9000 Companies

Request for Quote Letter to All BQ-9000 Companies

November 24, 2011

To: BQ-9000 Producers

Fr: National Biodiesel Board, Jefferson City, MO

Re: Request for Quote for B100 for use in Federal Railroad Administration Locomotive Test

To whom it may concern:

The National Biodiesel Board (NBB) in conjunction with the Federal Railroad Administration (FRA) and Southwest Research Institute (SwRI) in San Antonio, Texas, are in the process of soliciting quotes for providing biodiesel (B100) to be blended into B5 and B20 for emissions tests with two line-haul freight locomotives. The diesel portion of the blends will be EPA-certified ultra low sulfur diesel (ULSD) and California Air Resources Board (CARB)-certified ULSD. The tests are scheduled to be performed at SwRI this coming spring and early summer.

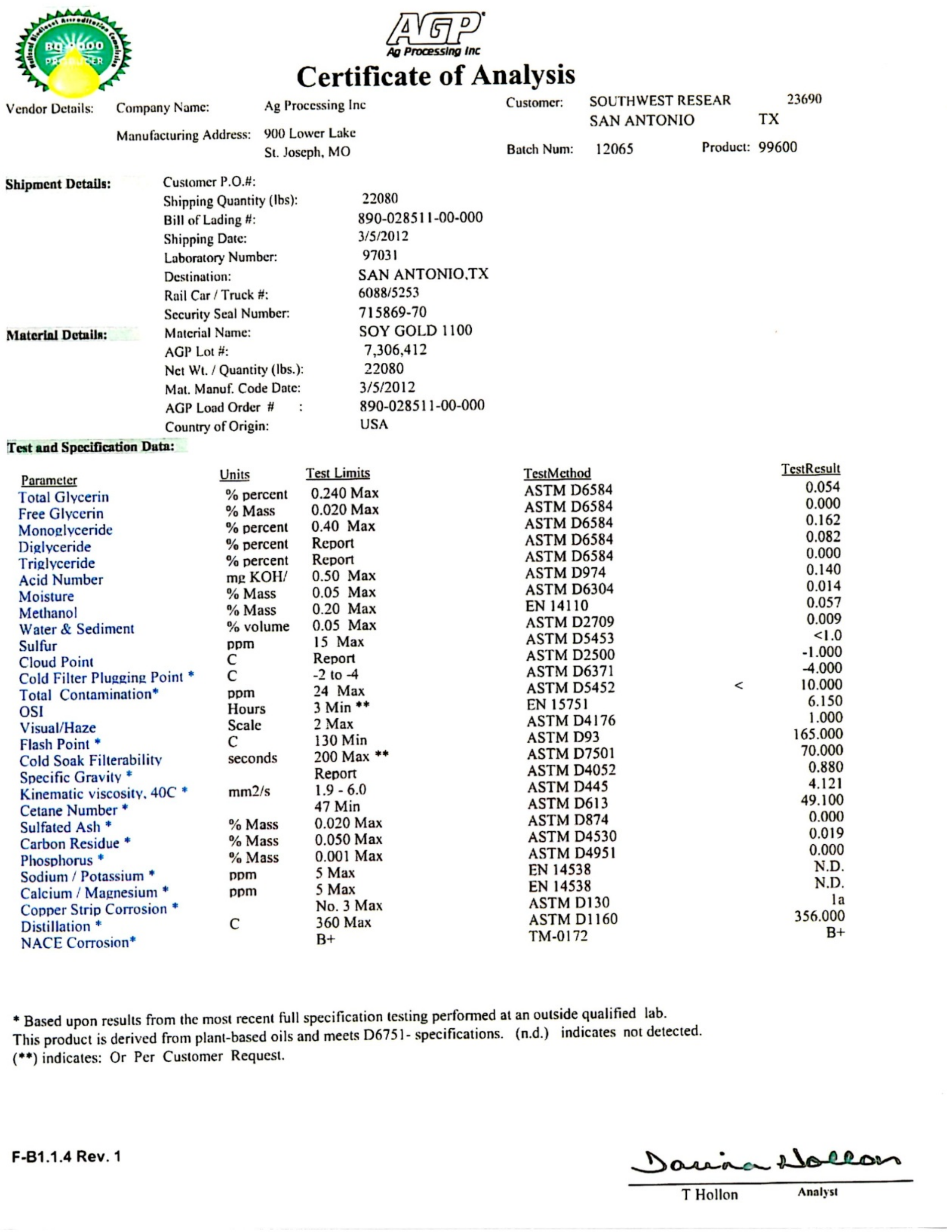
The purpose of this letter is to solicit a Request for Quote (RFQ) from current BQ-9000 companies to provide between 1,800 to 3,000 gallons of biodiesel (B100) to be blended into B5 and B20 for these tests. Only fuel from certified BQ-9000 facility will be considered and a letter of certification must be on file with the NBB.

The following are the specifics of the RFQ:

- ⇒ For NBB voting members, the value and cost of the fuel, with shipping, will be considered a project contribution to NBB and is therefore factored in when calculating weighted votes in NBB's annual Governing Board election.
- ⇒ A Certificate-of-Analysis (COA) shall be emailed to Richard Nelson (enersolresources@gmail.com) prior to the shipment of the fuel. Once reviewed by both parties, the fuel can then be shipped to SwRI.
- ⇒ The truck or transport vessel used for the shipping of the fuel shall be cleaned and inspected prior to loading and shipping.
- ⇒ The total cost of delivering between 1,800 to 3,000 gallons of a low cloud point B100 derived from an unsaturated feedstock to the SwRI Locomotive Technology Center, 203 Milam Street, San Antonio, TX 78202 between March 1 and March 15, 2012, must include fuel and all applicable taxes, delivery, and unloading into a separate storage tank.
- ⇒ Biodiesel (B100) must meet or exceed all specifications in the current ASTM D6751-11.
- ⇒ A COA must accompany the B100 biodiesel and be presented upon arrival. The fuel will be sampled and analyzed by SwRI at the time of arrival and the results of the sampling compared with those reported in the COA. If any discrepancy arises suggesting the delivered B100 does not meet D6751, a retain sample from the delivered B100 batch to SwRI will be sent to the B100 supplier to confirm the analysis. If it is then determined the B100 does not meet the current D6751 specification, the fuel batch will be deemed not suitable for the FRA project, and the B100 supplier will need to dispose of the batch at no cost to SwRI or the NBB.

A letter of interest and quote must be provided to Richard Nelson in Portable Document Format (PDF) no later than 5 p.m. December 16, 2011.

Appendix B.
Certificate of Analysis—AGP



AGP
Ag Processing Inc

Certificate of Analysis

Vendor Details: Company Name: Ag Processing Inc
Manufacturing Address: 900 Lower Lake
St. Joseph, MO

Customer: SOUTHWEST RESEAR 23690
SAN ANTONIO TX
Batch Num: 12065 Product: 99600

Shipment Details:

Customer P.O.#:
Shipping Quantity (lbs): 22080
Bill of Lading #: 890-028511-00-000
Shipping Date: 3/5/2012
Laboratory Number: 97031
Destination: SAN ANTONIO,TX
Rail Car / Truck #: 6088/5253
Security Seal Number: 715869-70

Material Details:

Material Name: SOY GOLD 1100
AGP Lot #: 7,306,412
Net Wt. / Quantity (lbs.): 22080
Mat. Manuf. Code Date: 3/5/2012
AGP Load Order # : 890-028511-00-000
Country of Origin: USA

Test and Specification Data:

Parameter	Units	Test Limits	TestMethod		TestResult
Total Glycerin	% percent	0.240 Max	ASTM D6584		0.054
Free Glycerin	% Mass	0.020 Max	ASTM D6584		0.000
Monoglyceride	% percent	0.40 Max	ASTM D6584		0.162
Diglyceride	% percent	Report	ASTM D6584		0.082
Triglyceride	% percent	Report	ASTM D6584		0.000
Acid Number	mg KOH/	0.50 Max	ASTM D974		0.140
Moisture	% Mass	0.05 Max	ASTM D6304		0.014
Methanol	% Mass	0.20 Max	EN 14110		0.057
Water & Sediment	% volume	0.05 Max	ASTM D2709		0.009
Sulfur	ppm	15 Max	ASTM D5453		<1.0
Cloud Point	C	Report	ASTM D2500		-1.000
Cold Filter Plugging Point *	C	-2 to -4	ASTM D6371		-4.000
Total Contamination*	ppm	24 Max	ASTM D5452	<	10.000
OSI	Hours	3 Min **	EN 15751		6.150
Visual/Haze	Scale	2 Max	ASTM D4176		1.000
Flash Point *	C	130 Min	ASTM D93		165.000
Cold Soak Filterability	seconds	200 Max **	ASTM D7501		70.000
Specific Gravity *		Report	ASTM D4052		0.880
Kinematic viscosity, 40C *	mm2/s	1.9 - 6.0	ASTM D445		4.121
Cetane Number *		47 Min	ASTM D613		49.100
Sulfated Ash *	% Mass	0.020 Max	ASTM D874		0.000
Carbon Residue *	% Mass	0.050 Max	ASTM D4530		0.019
Phosphorus *	% Mass	0.001 Max	ASTM D4951		0.000
Sodium / Potassium *	ppm	5 Max	EN 14538		N.D.
Calcium / Magnesium *	ppm	5 Max	EN 14538		N.D.
Copper Strip Corrosion *		No. 3 Max	ASTM D130		1a
Distillation *	C	360 Max	ASTM D1160		356.000
NACE Corrosion*		B+	TM-0172		B+

* Based upon results from the most recent full specification testing performed at an outside qualified lab.
This product is derived from plant-based oils and meets D6751- specifications. (n.d.) indicates not detected.
(**) indicates: Or Per Customer Request.

F-B1.1.4 Rev. 1

T Hollon Analyst

Appendix C.
Results of Fuel Blends

		Fuel Code	EPA-5	EPA-20	CARB-5	CARB-20
		Project Number	03.17004.01.001	03.17004.01.001	03.17004.01.001	03.17004.01.001
		Received Date	7/18/2012	7/18/2012	7/18/2012	7/18/2012
		Laboratory	oddb-9866	oddb-9867	oddb-9868	oddb-9869
ASTM Method	**Test Property**	**Units**	**Results**	**Results**	**Results**	**Results**
D130	Copper Corrosion	*rating*	1A	1A	1A	1A
D2500	Cloud Point	°C	-11	-11	-12	-10
D2624	Electrical Conductivity	pS/M	131	128	95	126
	Temperature	°C	22.4	22.4	22.4	22.4
D2709	Water & Sediment	Vol%	<0.005	<0.005	<0.005	<0.005
D445	Viscosity at 40°C	cSt	3.003	3.102	3.364	3.399
D482	Ash Content	mass %	<0.001	<0.001	<0.001	<0.001
D5453	Sulfur Content	ppm	10.7	9.9	7.8	6.5
D6079	Lubricity by HFRR at 60°C					
	Major Axis	mm	0.255	0.240	0.396	0.221
	Minor Axis	mm	0.172	0.169	0.302	0.168
	Wear Scar Diameter	mm	0.214	0.205	0.349	0.195
	Description of the Scar	--	lightly abraded oval	lightly abraded oval	evenly abraded oval	lightly abraded oval
D613	Cetane Number	--	52.3	44.2	47.9	48.3
D976	Cetane Index	*calculated*	46.9	47.7	50.3	50.7
D93	Flash Point	deg. F	161	166	160	163
EN14112	Oxidation Stability by Rancimat	hours	9.6	10.4	16.6	7.5
D86	Distillation					
	IBP	degF	351	332	351	352
	10%	degF	411	407	442	452
	50%	degF	540	559	548	567
	90%	degF	634	638	629	634
	FBP	degF	673	670	660	659
	Recovered	mL	98.7	98.6	97.9	98.6
	Residue	mL	1.2	0.8	1.2	1
	Loss	mL	0.1	0.6	0.9	0.4

Appendix D.
Tier 1 GE Dash-9 44CW Emissions Results

BNSF5014 Tier 1 Plus GE Dash9-44CW Emissions Results

Table D-1 shows the U.S.-EPA line-haul and switch cycle emissions results from the Tier 1 Plus GE Dash9-44CW for the three tests on each of the six fuels. The individual cycle worksheets for this data set are provided in Appendix D. The data in Table D-1 includes the calculations for the average of the three tests.

TABLE D-1. TIER 1 PLUS GE DASH9-44CW EMISSIONS RESULTS

Test Code	Date	Fuel	Line-Haul Cycle					Switch Cycle					Smoke Opacity		
			corr. bsfc	HC	CO	NOx	PM	corr. bsfc	HC	CO	NOx	PM			
			lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	Max SS	30-Sec	3-Sec
FTP-6	9-Jul-12	**EPA 0**	0.363	0.20	0.83	6.3	0.10	0.379	0.33	0.87	9.4	0.15	11%	18%	30%
FTP-7 - C	9-Jul-12		0.363	0.20	0.88	6.3	0.10	0.379	0.33	0.87	9.4	0.13	15%	20%	33%
FTP-14	13-Jul-12		0.363	0.21	0.85	6.2	0.10	0.376	0.33	0.88	9.3	0.13	14%	19%	33%
		Average	**0.363**	**0.20**	**0.85**	**6.3**	**0.10**	**0.378**	**0.33**	**0.87**	**9.4**	**0.14**	**13%**	**19%**	**32%**
FTP-5	8-Jul-12	**EPA 5**	0.362	0.21	0.83	6.3	0.10	0.379	0.33	0.85	9.3	0.13	14%	19%	27%
FTP-8	9-Jul-12		0.363	0.20	0.84	6.3	0.10	0.377	0.33	0.87	9.3	0.13	17%	20%	33%
FTP-17	15-Jul-12		0.361	0.21	0.80	6.3	0.09	0.375	0.32	0.87	9.4	0.13	11%	19%	32%
		Average	**0.362**	**0.21**	**0.83**	**6.3**	**0.10**	**0.377**	**0.33**	**0.86**	**9.3**	**0.13**	**14%**	**19%**	**31%**
FTP-4	8-Jul-12	**EPA 20**	0.360	0.20	0.75	6.4	0.08	0.377	0.30	0.80	9.5	0.12	11%	17%	25%
FTP-9	10-Jul-12		0.360	0.20	0.72	6.5	0.09	0.377	0.31	0.80	9.6	0.12	12%	20%	31%
FTP-15	14-Jul-12		0.360	0.20	0.75	6.4	0.09	0.376	0.31	0.82	9.6	0.12	9%	16%	27%
		Average	**0.360**	**0.20**	**0.74**	**6.4**	**0.08**	**0.377**	**0.31**	**0.81**	**9.5**	**0.12**	**11%**	**18%**	**28%**
FTP-1	6-Jul-12	**CARB 0**	0.363	0.22	0.84	6.1	0.09	0.375	0.36	0.84	8.7	0.13	12%	19%	27%
FTP-12	12-Jul-12		0.363	0.21	0.84	6.0	0.09	0.377	0.34	0.84	8.7	0.13	13%	18%	26%
FTP-13	13-Jul-12		0.363	0.22	0.83	6.0	0.09	0.379	0.38	0.85	8.8	0.13	12%	20%	29%
		Average	**0.363**	**0.22**	**0.84**	**6.0**	**0.09**	**0.377**	**0.36**	**0.84**	**8.7**	**0.13**	**12%**	**19%**	**27%**
FTP-3	7-Jul-12	**CARB 5**	0.363	0.21	0.82	6.2	0.09	0.377	0.33	0.84	8.9	0.12	11%	19%	24%
FTP-10	10-Jul-12		0.362	0.20	0.81	6.1	0.09	0.376	0.32	0.82	8.8	0.12	14%	19%	29%
FTP-18	TBD		0.364	0.21	0.82	6.1	0.09	0.385	0.34	0.84	9.0	0.13	9%	17%	26%
		Average	**0.363**	**0.21**	**0.81**	**6.1**	**0.09**	**0.379**	**0.33**	**0.83**	**8.9**	**0.13**	**11%**	**18%**	**27%**
FTP-2	7-Jul-12	**CARB 20**	0.361	0.21	0.74	6.3	0.08	0.378	0.35	0.79	9.1	0.12	7%	14%	24%
FTP-11	12-Jul-12		0.361	0.21	0.71	6.1	0.08	0.377	0.33	0.75	8.8	0.12	7%	15%	26%
FTP-16	14-Jul-12		0.363	0.20	0.75	6.2	0.08	0.377	0.31	0.82	9.0	0.12	9%	16%	30%
		Average	**0.361**	**0.21**	**0.73**	**6.2**	**0.08**	**0.378**	**0.33**	**0.79**	**9.0**	**0.12**	**8%**	**15%**	**27%**

Table D-2 shows the percent change between EPA0 and CARB0, CARB0 and CARB20, and EPA0 and EPA20. The base fuels (CARB0 and EPA0) showed the expected emissions trends, with the CARB0 fuel generating 4 percent lower line-haul cycle NOx emissions and 8 percent lower PM emissions compared with the average EPA0 fuel. The CARB0 fuel produced a 7 percent NOx and PM emissions reduction over the switch cycle compared with the EPA0 test fuel. The HC emissions increased over both cycles with the CARB0 fuel, but the CO emissions were reduced with the CARB0 fuel over both test cycles.

The data in Table D-2 also shows that the CARB20 and EPA20 fuels caused a 3 percent increase in NOx emissions over the line-haul cycle, compared with the respective base fuels. The CARB20 reduced the line-haul PM emissions by 12 percent and the EPA20 reduced the PM emissions by 16 percent over the line-haul cycle; both of these trends are similar to previous biodiesel tests on a four-cycle medium speed diesel engine[7]. The switch cycle NOx and PM emissions trended the same as the line-haul emissions, but with smaller reductions.

TABLE D-2. BNSF5014 RESPONSE TO CHANGE IN FUEL BLEND

Comparison of	Line-Haul Cycle					Switch Cycle					Smoke Opacity		
	corr. bsfc	HC	CO	NOx	PM	corr. bsfc	HC	CO	NOx	PM			
	lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	Max SS	30-Sec	3-Sec
CARB 0 vs EPA 0	0.1%	6%	-1%	-4%	-8%	-0.2%	9%	-4%	-7%	-7%	-8%	0%	-14%
CARB 20 vs CARB 0	-0.5%	-4%	-13%	3%	-12%	0.2%	-8%	-7%	3%	-6%	-35%	-21%	-3%
EPA 20 vs EPA 0	-0.7%	-1%	-13%	3%	-16%	-0.2%	-7%	-8%	2%	-12%	-20%	-9%	-13%

---

[7] ICEF2010-35024, Proceedings of the ASME Internal Combustion Engine Division 2010 Fall Technical Conference, “The Effects of Biodiesel Fuel Blends on Exhaust Emissions from a General Electric Tier 2 Line-Haul Locomotive”; D. Osborne, S Fritz, D Glenn

Appendix E.
Tier 2 EMD SD70ACe Emissions Results

BNSF9285 Tier 2 EMD SD70ACe Results

Table E-1 shows the U.S.-EPA line-haul and switch cycle emissions results from the testing on the Tier 2 EMD SD70ACe locomotive for the three tests on each of the six fuels. The individual cycle worksheets for this data set are provided in Appendix E. The data in Table E-1 includes the calculations of the average of the three tests.

TABLE E-1. TIER 2 EMD SD70ACE EMISSIONS RESULTS

Test Code	Comparison of		Line-Haul Cycle					Switch Cycle					Smoke Opacity		
			corr. bsfc	HC	CO	NOx	PM	corr. bsfc	HC	CO	NOx	PM			
			lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	Max SS	30-Sec	3-Sec
FTP-3	5-Jun-12	**EPA 0**	0.371	0.14	0.32	4.7	0.08	0.406	0.25	0.36	6.1	0.11	5%	9%	19%
FTP-10	10-Jun-12		0.371	0.12	0.35	4.6	0.09	0.406	0.19	0.38	6.1	0.12	5%	7%	13%
FTP-17	14-Jun-12		0.370	0.11	0.32	4.7	0.09	0.407	0.18	0.36	6.3	0.11	3%	5%	10%
		Average	**0.371**	**0.12**	**0.33**	**4.7**	**0.09**	**0.406**	**0.21**	**0.37**	**6.2**	**0.12**	**4%**	**7%**	**14%**
FTP-5	7-Jun-12	**EPA 5**	0.371	0.14	0.32	4.7	0.08	0.406	0.25	0.36	6.1	0.11	2%	5%	10%
FTP-8	9-Jun-12		0.370	0.12	0.30	4.7	0.08	0.405	0.18	0.34	6.2	0.11	4%	6%	10%
FTP-15	13-Jun-12		0.371	0.12	0.33	4.7	0.09	0.408	0.18	0.37	6.3	0.12	3%	4%	12%
		Average	**0.371**	**0.13**	**0.32**	**4.7**	**0.08**	**0.406**	**0.21**	**0.36**	**6.2**	**0.12**	**3%**	**5%**	**11%**
FTP-1	4-Jun-12	**EPA 20**	0.371	0.12	0.28	4.7	0.09	0.408	0.19	0.34	6.1	0.14	VOID		
FTP-12	11-Jun-12		0.371	0.12	0.31	4.7	0.09	0.406	0.19	0.37	6.1	0.13	4%	7%	14%
FTP-13	12-Jun-12		0.370	0.12	0.33	4.7	0.08	0.406	0.18	0.37	6.3	0.11	3%	6%	11%
		Average	**0.370**	**0.12**	**0.31**	**4.7**	**0.09**	**0.407**	**0.19**	**0.36**	**6.2**	**0.12**	**4%**	**6%**	**13%**
FTP-2	5-Jun-12	**CARB 0**	0.373	0.11	0.31	4.4	0.09	0.410	0.17	0.33	5.6	0.13	10%	12%	15%
FTP-11	11-Jun-12		0.373	0.10	0.32	4.4	0.09	0.408	0.17	0.34	5.6	0.13	4%	6%	10%
FTP-18	14-Jun-12		0.372	0.11	0.30	4.4	0.09	0.407	0.17	0.33	5.6	0.11	5%	6%	12%
		Average	**0.373**	**0.11**	**0.31**	**4.4**	**0.09**	**0.408**	**0.17**	**0.33**	**5.6**	**0.12**	**6%**	**8%**	**12%**
FTP-6 - C	8-Jun-12	**CARB 5**	0.371	0.12	0.27	4.5	0.08	0.407	0.20	0.31	5.6	0.12	4%	5%	8%
FTP-7	8-Jun-12		0.372	0.11	0.28	4.5	0.08	0.408	0.19	0.33	5.6	0.11	3%	5%	11%
FTP-14	12-Jun-12		0.372	0.11	0.31	4.5	0.08	0.410	0.17	0.35	5.6	0.11	5%	8%	16%
		Average	**0.372**	**0.11**	**0.29**	**4.5**	**0.08**	**0.408**	**0.19**	**0.33**	**5.6**	**0.11**	**4%**	**6%**	**12%**
FTP-4	6-Jun-12	**CARB 20**	0.372	0.11	0.28	4.6	0.08	0.409	0.17	0.34	5.8	0.11	4%	6%	12%
FTP-9	9-Jun-12		0.371	0.12	0.27	4.6	0.09	0.407	0.19	0.33	5.8	0.13	4%	4%	10%
FTP-16	13-Jun-12		0.372	0.10	0.27	4.5	0.08	0.407	0.16	0.32	5.7	0.11	5%	8%	15%
		Average	**0.372**	**0.11**	**0.28**	**4.6**	**0.08**	**0.408**	**0.17**	**0.33**	**5.8**	**0.12**	**4%**	**6%**	**12%**

Table E-2 shows the percent change between the CARB0 and EPA0, EPA0 and EPA20, and CARB0 and CARB20. This table shows that the CARB0 fuel produced the expected level of emissions reduction when compared with EPA0, with the CARB0 base fuel providing a 5 percent lower NOx emissions over the line-haul cycle and no change to the line-haul PM emissions. The CARB0 fuel also offered a 14 percent reduction in HC emissions and a 7 percent CO emissions reduction over the line-haul cycle.

Over the switch cycle, the CARB0 fuel produced a 9 percent NOx reduction with a 5 percent PM increase compared with the EPA0 fuel. Additionally, the HC emissions were reduced by 17 percent and the CO emissions were reduced by 10 percent with the CARB0 fuel.

A comparison of the EPA0 and the CARB0 fuel with the CARB20 and EPA20 fuels shows that the addition of the biodiesel caused a 4 percent increase in NOx emissions over the line-haul cycle for the CARB fuel and a 1 percent increase for the EPA fuel. Additionally, the CARB20 reduced the line-haul PM emissions by 4 percent and the EPA20 increased the PM emissions 1 percent over the line-haul cycle.

TABLE E-2. BNSF9285 EMISSIONS RESPONSE TO CHANGE IN FUEL BLEND

Comparison of	Line-Haul Cycle					Switch Cycle				
	corr. bsfc	HC	CO	NOx	PM	corr. bsfc	HC	CO	NOx	PM
	lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	lb/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr	g/hp-hr
CARB 0 vs EPA 0	0.4%	-14%	-7%	-5%	0%	0.5%	-17%	-10%	-9%	5%
CARB 0 vs CARB20	-0.2%	2%	-11%	4%	-4%	-0.2%	1%	-1%	3%	-4%
EPA0 vs EPA20	-0.1%	-3%	-7%	1%	1%	0.0%	-9%	-2%	0%	7%

Abbreviations and Acronyms

ASTM	ASTM International (formerly the American Society for Testing and Materials)
BSFC	Brake Specific Fuel Consumption
CARB	California Air Resource Board
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COA	Certificate of Analysis
COV	Coefficient of Variation
EPA	Environmental Protection Agency
EISA	Energy Independence and Security Act
FRA	Federal Railroad Administration
FTP	Federal Test Procedure
GHG	Greenhouse Gas
HC	Hydrocarbons
HCLD	Heated Chemiluminescent Detector
HFID	Heated Flame Ionization Detector
HHV	Higher Heating Value
HP	Horsepower
LHV	Lower Heating Value
LTC	Locomotive Technology Center
NDIR	Nondispersive Infrared
NOx	Oxides of Nitrogen
O_2	Oxygen
PHS	Public Health Service
PM	Particulate Matter
PPM	Parts per Million
RFQ	Request for Quote
RFS2	Renewable Fuel Standard 2
RVO	Renewable Volume Obligation
SAE	SAE International (Formerly Society of Automotive Engineers)
SwRI®	Southwest Research Institute®
TC7	Technical Committee 7
ULSD	Ultra Low Sulfur Diesel