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Federal Railroad Administration

LOCOMOTIVE BIOFUEL STUDY: PRELIMINARY STUDY ON THE USE AND THE EFFECTS OF BIODIESEL IN LOCOMOTIVES

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Melissa Shurland (FRA), Wade Smith (Amtrak), Steve G. Fritz (SwRI), H. Christopher Frey (NCSU)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Railroad Passenger Corporation 810 N. Alameda Los Angeles, CA 90012
Southwest Research Institute 6220 Culebra Road San Antonio, Texas 78238
North Carolina State University 2701 Sullivan Drive Raleigh, NC 27695

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13. ABSTRACT (Maximum 200 words)

Section 404 of the Passenger Rail Investment and Improvement Act (PRIIA), 2008, mandated that the Federal Railroad Administration (FRA) undertake a Locomotive Biofuel Study to investigate the feasibility of using biofuel blends as locomotive engine fuel. This report summarizes three research initiatives undertaken by FRA to assess the viability of biodiesel as an alternative fuel for locomotives. The first initiative consisted of using a 20 percent blend of biodiesel in a passenger locomotive in revenue service to study air emissions and engine wear. The second initiative measured the emissions of Tier 1+ and Tier 2 locomotives operating on 5 percent and 20 percent blends of biodiesel, respectively. Those emissions were compared with those generated by conventional diesel fuel. The third initiative investigated the availability of biodiesel, rail yard and revenue service engine performance and emissions on various blends of biodiesel, as well as the practicability of using an alternative method to measure those emissions. The results from these research initiatives show that while it may be feasible to use biodiesel in blends of up to 20 percent in locomotive engines and reveal some impact on emissions, additional research is needed to understand the long term effects of high blends of biodiesel on locomotive engine components.

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ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

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1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

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1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

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1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
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1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

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METRIC TO ENGLISH

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1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

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1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

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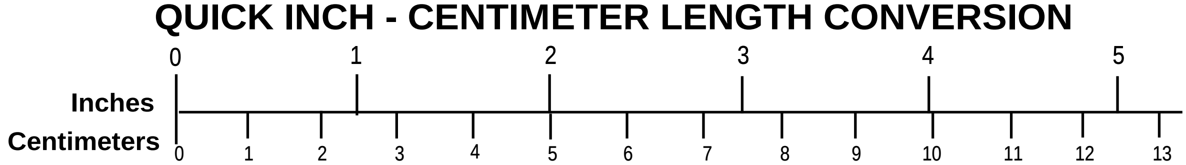
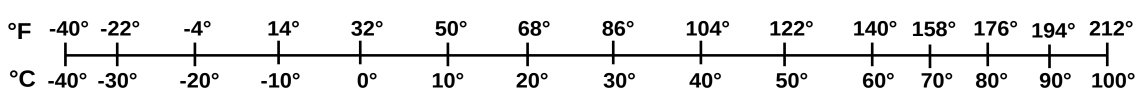


QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION



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

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- Steve G. Fritz of the Southwest Research Institute for conducting the *Locomotive Emissions of Various Blends of Biodiesel* study, as well as providing valuable insight into the effects of biodiesel on locomotive engines. Mr. Fritz also supports FRA and the railroad industry in collecting and analyzing defects of locomotive engine components from engines that used biodiesel. This effort supports increased understanding of engine durability issues.
- H. Christopher Frey of North Carolina State University for conducting *the Locomotive Biofuel Study* that investigated costs, availability of biodiesel, and alternative methods to measure emissions of the engine in dynamic operations.
- FRA would also like to thank Manuch Nickanjam for his leadership of the *SAE TC7 Biodiesel in Railroad Applications* industry forum. The support of the SAE TC7 and Manuch enabled FRA and the railroad industry to candidly discuss the effects of biodiesel in locomotive engines and to identify a path forward for a qualitative analysis of biodiesel on locomotive engine durability.

The support of these individuals and organizations allowed FRA to gain valuable knowledge about the viability of biodiesel as an alternative fuel.

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Executive Summary

The Federal Railroad Administration (FRA) funds research to investigate the feasibility of using biodiesel as a locomotive fuel. The FRA Rail Energy, Environment, and Engine Technologies Research Program (Rail E3) supports the development of advanced technologies to improve the fuel efficiency of rail equipment while reducing air emissions. The Alternative Fuel-Biodiesel Research project focuses on determining the extent to which U.S. railroads, both passenger and freight, can use biofuel blends to power locomotives that operate on diesel fuel.

Title IV, Section 404 of the Passenger Rail Investment and Improvement Act (PRIIA), 2008, (Division B of Public Law 110-432) authorized the FRA, in consultation with the Secretary of Energy and Administrator of the Environmental Protection Agency (EPA), to conduct a Locomotive Biofuel Study. FRA funded three research initiatives that addressed the requirements of PRIIA Section 404: (1) Biodiesel Intercity Passenger Rail Revenue Service Tests, (2) Locomotive Emissions Measurement of Various Blends of Biodiesel, and (3) Locomotive Biofuel Study. The Biodiesel Intercity Passenger Rail Revenue Service test investigated the feasibility of using B20 biodiesel fuel (20 percent biodiesel fuel blended with 80 percent diesel fuel) in a passenger locomotive in revenue service, emissions of the test locomotive after 12 months of B20 biodiesel fuel use, and the effects of biodiesel on engine components after the 12-month test program. The Locomotive Emissions Measurement of Various Blends of Biodiesel performed Federal certified emissions tests on two freight locomotives using 5 percent biodiesel blends and 20 percent biodiesel blends. The engines' emissions performances on biodiesel were compared with their performance on CARB diesel and EPA certification fuel. Finally, the Locomotive Biofuel Study, which is still in progress, will provide additional data on using biodiesel in passenger locomotives in blends higher than 20 percent biodiesel. This study will also provide information on the cost and availability of biodiesel as experienced by the North Carolina State Department of Transportation during this study.

These research studies found that while it is feasible to use biodiesel in locomotive engines, blends of 20 percent and higher resulted in increases in fuel consumption and gaseous emissions of the tested locomotive engines. Moreover, the long term effects of biodiesel on engine components are not fully understood and so additional research is needed. Locomotive manufacturers and the railroad industry recommend an extensive locomotive durability field test protocol to further analyze the long term effects of biodiesel. This field test would follow the procedures outlined in the Locomotive Maintenance Officers Association (LMOA) Oil Field Test Protocol. Of particular interest to the railroad industry is understanding the engine durability performance of locomotives through the multiple locomotive performance and endurance testing methodology of the Field Oil Test Protocol. This assessment would consist of testing Tier 1, 2, 3, (and possible 0 and 4) locomotives from both major locomotive manufacturers, General Electric (GE) Transportation and Electro-Motive Diesel (EMD). The multiple locomotive engine durability test program would require four test locomotives for each EPA certification level (Tiers 1–3) and two control units, requiring a total of 36 test locomotives. Locomotive owners are reluctant to engage in such a test program because it could adversely affect their business model and operating procedures and potentially result in fuel related engine problems that would void the locomotive manufacturer's warranty. Furthermore, FRA research into the viability of biodiesel as an alternative fuel is ongoing, as are discussions within the rail industry to identify opportunities for collaboration on the multiple locomotive engine performance durability test programs. Therefore, FRA cannot make a determination on a premium blend of biodiesel for rail applications.

1. INTRODUCTION

Biodiesel, an alternative to diesel fuel, is manufactured from plant oils (e.g., canola, soy, rapeseed, palm, etc.) or animal fats. Biodiesel is manufactured through a transesterification process in which the oils and fats are reacted with an alcohol such as methanol in the presence of a catalyst such as sodium into fatty acid methyl esters (FAME; also known as biodiesel) and glycerine.

The Federal Railroad Administration (FRA) funds research to investigate the feasibility of using biodiesel as a locomotive fuel. Title IV, Section 404 of the Passenger Rail Investment and Improvement Act (PRIIA), 2008 (Division B of Public Law 110-432) authorized "the Federal Railroad Administration, in consultation with the Secretary of Energy and Administrator of the Environmental Protection Agency, to conduct a Locomotive Biofuel Study. This study focused on determining the extent to which freight railroads, Amtrak, and other passenger rail operators could use biofuel blends to power locomotives and other vehicles that operate on diesel fuel, as appropriate."

Section 404 of PRIIA 2008 required FRA to conduct a study to investigate the following—and ultimately recommend a premium locomotive biofuel blend.

(1) the energy intensity of various biofuel blends compared with that of diesel fuel;
(2) environmental and energy effects of using various biofuel blends compared with the effects of using diesel fuel, including emission effects;
(3) the cost of purchasing biofuel blends;
(4) whether sufficient biofuel is readily available;
(5) any public benefits derived from the use of such fuels; and
(6) the effect of biofuel use on locomotive and other vehicle performance and warranty specifications.

FRA funded three biodiesel research initiatives that would address the requirements of PRIIA Section 404. These research studies found that biodiesel in blends of 20 percent and higher could increase fuel consumption and the nitrogen oxide emissions of the tested locomotive engines. Prompted by the finding that biodiesel can be used in locomotive engines without engine modification in blends of up to 20 percent biodiesel, the FRA research focused on the use of biodiesel, instead of other biofuels such as ethanol, in locomotive engines.

In October 2008, FRA launched a Steering Committee in cooperation with Amtrak to develop a test plan for a revenue service trial of B20 (20 percent biodiesel and 80 percent #2 diesel fuel blend). The Steering Committee identified various areas of research needed to truly assess the feasibility of using biodiesel as an alternative fuel. In addition to revenue service tests as laid out in the test plan developed by the Steering Committee, emissions testing and evaluation of the long term effects of the fuel on engine durability were recommended. With the support of the Steering Committee and funding from FRA, Amtrak launched the 12-month Biodiesel Intercity Passenger Rail Revenue Service Test.[1] At the end of the 12-month period of over-the-road testing, emissions testing and engine tear-down inspections were conducted on the Amtrak passenger locomotive engine. However, these tests and inspection did not provide sufficient information to allow FRA to reach any definitive conclusions about the effectiveness of biodiesel

[1] Smith, W., Shurland, M., Biodiesel in Passenger Rail Revenue Service Test, DOT/FRA/ORD-13/43.

as an alternative fuel for locomotive engines. FRA needed to engage in further research to understand (1) the effects of biodiesel on the emissions of other tiered locomotive engines, (2) the cost of biodiesel compared with the cost of diesel, (3) the effects of biodiesel on a locomotive engine and its components, and (4) the availability of biodiesel. Therefore, FRA subsequently issued two independent research grants to Southwest Research Institute (SWRI) and North Carolina State University (NCSU) to address the outstanding research questions. In order to understand the effects of alternative fuels such as biodiesel on the in-service performance of locomotive engines, emissions tests and long term engine durability tests must be conducted across a wide range of locomotive engine models.

1.1 Background

For each research initiative, FRA partnered with the railroad industry. For the Biodiesel Intercity Passenger Rail Revenue Service Test initiative, FRA teamed up with Amtrak and other industry stakeholders to plan and execute the research. A Steering Committee was established that consisted of representatives from General Electric (GE) Transportation, Electro-Motive Diesel, Oklahoma Department of Transportation, Texas Department of Transportation, Chevron Oronite, and biodiesel suppliers.

The second initiative consisted of a research grant issued to SWRI to determine the "Locomotive Emissions Measurement of Various Blends of Biodiesel[2]." This initiative was also undertaken with guidance from the railroad industry. In 2009, SAE International, formerly the Society of Automotive Engineers, established the TC7 Subcommittee, Biodiesel in Railroad Applications, at the request of the major Class I railroads. The subcommittee membership consisted of representatives from FRA, all major Class I U.S. railroads, the Association of American Railroads (AAR), major locomotive manufacturers, engine oil and lubricant suppliers, and the National Biodiesel Board. The charter of this subcommittee was to identify issues of concern to the railroads, engine and equipment manufacturers, and fuel suppliers upon introduction of biodiesel blends to the North American diesel pool, as well as to formulate and propose a practical path forward. With the support of this subcommittee, SWRI, on behalf of FRA, developed a randomized test matrix to perform triplicate emissions tests on a Tier 1+ and Tier 2 locomotive using six test diesel fuels (0 percent, 5 percent, and 20 percent blend of biodiesel with EPA and California Air Resources Board (CARB).

Finally, FRA entered into an agreement with NCSU to investigate additional aspects of the Locomotive Biofuel Study such as fuel characterization, in-use emissions, and cost and availability of various blends of biodiesel. The NCSU study is still in progress; the gathering of additional revenue service test data is currently under way. This report will provide the preliminary results from this ongoing study.

1.2 Objectives

The objective of the FRA Biodiesel Research program is to develop knowledge regarding the viability of biodiesel as an alternative fuel for locomotive engines. In order to understand the effects of alternative fuels such as biodiesel on locomotive engines, in-service performance,

[2] Hedrick, John C. and Fritz, Steven G., Locomotive Emissions of Various Blends of Biodiesel. DOT/FRA/ORD-14/XX

emissions, and long term engine durability must be assessed across a wide range of engine models. This research program supported projects that conducted investigations into the performance of passenger locomotives in revenue service on 20 percent blend of biodiesel. The projects also evaluated emissions testing of passenger and freight locomotives on 5 percent and 20 percent blend of biodiesel and reviewed the characteristics of various blends of biodiesel. The objective of this report is to provide a comprehensive overview of the FRA research program and the results gathered thus far.

1.3 Organization of the Report

This report is organized into three main sections that detail the three research initiatives undertaken. Each section will discuss the research methodology, results, and conclusions. At the end of this report, a summative conclusion will discuss the overall research findings and address the requirements of PRIIA Section 404 Locomotive Biofuel Study.

2. BIODIESEL INTERCITY PASSENGER RAIL REVENUE SERVICE TEST

This project was funded by FRA to assess the feasibility of using B20 biodiesel fuel in a passenger locomotive in revenue service. This revenue service trial was designed to demonstrate the use of B20 biodiesel. For this test, the biodiesel used was a blend of 20 percent pure biodiesel (B100) from beef tallow and 80 percent ultra-low sulfur diesel (ULSD). This section of the report outlines the 12-month revenue service trial of the Heartland Flyer train operating on B20 biodiesel, the associated engine emissions testing, and the tear down inspection of the locomotive engine power assemblies. The revenue service trial was meant as a demonstration of biodiesel in a passenger locomotive in revenue service and not as an evaluation of biodiesel as a locomotive fuel. The trial did, however, align with Amtrak's environmental sustainability program by promoting research of alternative options for rail transportation fuel.

2.1 Background

The biodiesel revenue service trial was initiated in a proposal made by Oklahoma Department of Transportation to Amtrak for the use of B20 biodiesel in the Heartland Flyer train. Amtrak and FRA saw merit in the idea and formed a Steering Committee consisting of representatives from Amtrak, FRA, Oklahoma Department of Transportation, GE Transportation Services (GE), Electro-Motive Diesel, and biodiesel fuel suppliers. The Steering Committee held a monthly teleconference to develop the biodiesel revenue service test implementation plan. The test implementation plan called for fuel and oil analyses, emissions testing, and engine inspection along with the revenue service test. For this demonstration, Amtrak selected Engine #500. Engine #500 is a 3200 hp General Electric P32-8 manufactured in 1991. During the trial, a P42 locomotive was placed into the consist for service protection or to provide head end power (HEP) if there were more than three coach cars in the train consist. The Heartland Flyer train consist is normally operated with one P-42 4250 HP GE locomotive, one non-power control unit, 2 bi-level coach cars, and one bi-level snack/coach car. Additional cars may be added to the train depending on ridership.

Amtrak operates the Heartland Flyer (Train numbers 821/822) under State-funded contracts with the Oklahoma and Texas Departments of Transportation to provide daily service (7 days/week), with regularly scheduled station stops in Oklahoma City, Norman, Purcell, Pauls Valley, and Ardmore, OK, and in Gainesville and Fort Worth, TX. The distance between Fort Worth, TX, and Oklahoma City, OK, is 206 miles, or 412 miles round trip. The Heartland Flyer made 443 round trips during the revenue service trial. Three hundred and thirty one (331) round trips totaling 136,372 route miles were made using B20 on Engine #500. Actual equipment mileage during this time period totaled 152,622 miles. Preventative maintenance, service and inspection, equipment modifications, or track outages took place on those days when Engine #500 was not in service on the Heartland Flyer route.

2.2 Research Methodology

Prior to starting the in-service test, two new power assemblies were installed on Engine #500 with the intent to inspect these power assemblies at the end of the trial. Being new, these two assemblies were the "baseline" against which to evaluate the engine wear after 12 months of biodiesel use. Biodiesel has solvent properties that may cause it to react adversely to a variety of materials found in locomotive engines. GE performed emissions testing of Engine #500 using B20 biodiesel. GE's participation in the revenue service trial and performance of the emissions tests does not constitute approval for use of biodiesel blends in GE locomotives. Failure to adhere to the approved fuels cited in the locomotive manufacturer's operations and maintenance instructions may result in the engine warranty being voided, if fuel-related failure occurs.

2.2.1 Revenue Service Test

Amtrak operated the Heartland Flyer in normal passenger service while using B20 biodiesel fuel and maintained normal operating and safety procedures and practices. The test locomotive was fueled in the "direct to train" method—the engine's fuel tank was filled by a fuel truck containing splash-blended biodiesel. Thus, no modifications needed to be made to the railroad facility infrastructure to accommodate use of the new fuel. Amtrak performed required maintenance and inspection on the locomotive during the test period in accordance with Amtrak's maintenance and inspection practices and the Code of Federal Regulations (CFR) Title 49 Parts 229.21 and 236.587. These service inspections required the unit to be taken out of service and moved to Amtrak's Chicago, IL, maintenance facilities where this work was completed. Discussions with Amtrak mechanical department representatives and review of the mechanical documentation revealed that no mechanical repairs or maintenance have been required as a result of the alternative use of B20 biodiesel fuel during the trial.

2.2.2 Fuel and Engine Oil Analyses

Prior to the commencement of the biodiesel revenue service trial, the fuels used were evaluated to ensure they met their respective specifications as determined by the American Standards for Testing and Materials (ASTM) before blending (i.e., the ULSD diesel fuel and the B100 biodiesel fuel) and after blending (i.e., the B20 biodiesel fuel). Throughout the revenue service trial, the blended fuel was subject to periodic testing to ensure that the blended product met the ASTM specification for B20. Any changes to the fuel supply required a new and complete evaluation of the new supply before use.

Anomalies in the test results of the B100 and B20 biodiesel fuel initial samples are discussed further in the Results subsection of this section. Prior to the commencement of the revenue service trial, a new batch of the B100 and B20 biodiesel fuels was sampled and retested and determined to be within tolerance of all applicable ASTM specifications.

During the field trial, Direct Fuels tested the B100 fuel supply weekly; certificates of analysis were made available to the fuel driver with every load delivered to Amtrak. The ULSD fuel was also tested. All ULSD samples were within relevant testing specifications with the exception of one sample collected near the end of the trial. The analytical testing of the B20 blend was conducted on a monthly basis, by ANA Laboratories per ASTM D7467, and the blend was determined to be within the limits of specification.

Similarly, engine lubrication oil was subjected to testing prior to commencement of the field trial and during the trial. ANA Laboratories tested the engine used oil for metals, fuel and water, oxidation, nitration, soot, and sulfate. In addition to the aforementioned tests, the used oil samples were tested by Chevron Oronite for base number (BN) per ASTM D4739, acid number (AN) (ASTM D664), pentane insolubles (ASTM D7317), viscosity increase (ASTM D445), oxidation, wear metals (ASTM D5185), fuel dilution (ASTM D3524), and biodiesel dilution by

Chevron Oronite's proprietary methods. The engine oil was changed every 92 days during scheduled PM servicing.

Each of the wear metals measured in the lubricating oil analysis indicates specific aspects of engine wear. For example, Aluminum (Al) is indicative of wear of pistons, bearings, housing metal, thrust washers, converter and pump bushings, and dirt entry. Chromium (Cr) is a wear indicator for chromed parts such as piston rings and bearings. Iron (Fe) indicates wear of gears, shafts, cylinders, liners, valve train components, other steel components, and rust. Molybdenum (Mo) indicates wear of piston rings. Many of the other metals analyzed, such as Sodium (Na), Potassium (K), Calcium (Ca), Barium (Ba), Magnesium (Mg), Phosphorus (P), and Zinc, are additives to the lubricating oil itself. Some of these additives are used as dispersants and detergents, while others are for anti-wear or anti-freeze. Some metals, such as Lead (Pb), Tin (Sn), and Nickel (Ni), are indicators of wear of bearings and bushings, many of which are not in the combustion flow path.

2.2.3 Locomotive Exhaust Emissions Testing

The locomotive exhaust emissions were analyzed following the commencement of the revenue service test. The exhaust emissions testing was done in accordance with the FTP as defined in 40 CFR Part 92, "Emission Standards for Locomotives and Locomotive Engines." The B20 revenue service test locomotive was taken to the GE Locomotive Emissions Testing Facility in Erie, PA, for the emissions testing. Once at GE, the locomotive was inspected and loaded to determine its powering cycle. Engine #500's fuel supply system was disconnected and a system capable of measuring the net rate at which fuel is supplied to the engine was connected. The engine was operated for a period of time in all its powering modes (low idle, idle, dynamic brake, and notch 1 to notch 8), simulating in-service load conditions. During the test, Engine #500's power output produced by the alternator/generator at each throttle setting was recorded as measurements of current flow through the electrical resistor grid of the locomotive.

Following the loading tests, the engine exhaust was sampled and tested for various gaseous and particulate emissions. The emissions were measured over two steady-state test cycles, simulating the line-haul and switch engine duty cycle of the locomotive. The duty cycle simulations for the emissions testing consisted of operating Engine #500 at different power levels, from low idle to notch 8. Switch engine operations were simulated by operating the engine in steady-state conditions (much of the time in low idle, idle, and the low power notches). The performance of line-haul operations was simulated by operating the engine much of the time in steady-state condition in the high power notches, particularly notch 8. Two sets of emissions tests were completed on the locomotive, one using the B20 fuel available in the onboard fuel tank and the other using EPA locomotive certification petroleum diesel fuel stored at the facility. Samples of B20 and the certification diesel fuels were collected for analysis at the GE testing facility. Gaseous emission and particulate matter (PM) sampling, smoke opacity, and fuel consumption tests were performed as part of the test protocol. Details of the emissions sampling and testing according to 40 CFR Part 92 are further discussed in Section 3.

Results of the emission testing using the B20 biodiesel fuel and EPA certification fuel were compared against the EPA emission limits for Tier 0 locomotive engines and against each other.

2.2.4 Engine Power Assembly Mechanical Tear Down and Inspection

Amtrak removed two power assemblies from Engine #500 and replaced them with two new units (baseline units). These two new power assemblies were the baseline units with which to assess the effects of biodiesel on the engine after 12 months of using B20 fuel. They were installed in position 2 of the engine on the right and left side, 2R and 2L. Following the revenue service trial and the engine exhaust emissions testing, the two baseline units were removed and inspected. The inspections were conducted to identify any adverse effects of the B20 fuel on engine components such as the connecting rods, bearing, pistons and piston rings, to name a few, that were expected to be directly or indirectly impacted by the use of B20 fuel. General engine condition was evaluated to include engine cleanliness (rocker box and crankcase), visual inspection of locomotive, and review of operational history. The power assemblies were photographed during the post-revenue service inspection. The removal of the baseline units was done by Amtrak maintenance facility personnel and inspected by Chevron Oronite, who also conducted analyses at their laboratory. Additionally, 5R and 5L power assemblies were removed. These power assemblies were not newly installed but were removed and inspected to better assess the wear of baseline power assemblies, 2R and 2L.

Figure 1. 2R Power assembly cylinder with piston removed

2.3 Results

The Amtrak Heartland Flyer passenger train was tested in revenue service using B20 blend of biodiesel fuel for a period of 12 months. During that period, fuel consumption data was recorded. Following the revenue service trial of B20 biodiesel, the engine underwent emissions testing, and four of its power assemblies were torn down and inspected.

2.3.1 Revenue Service Test Results

At the end of the revenue service trial, 178,946 gallons of B20 fuel had been delivered to locomotive Engine #500. The cost variance comparing the price of biodiesel with regular ULSD #2 during the trial period totaled $21,175. During the revenue service trial, the cost of B20 ranged from $0.00 to $0.31 per gallon more than ULSD. On average, this was a $0.13/gallon price difference for biodiesel versus ULSD diesel fuel. Documentation supporting fuel delivery dates, quantity of fuel delivered, cost of fuel used during the biodiesel revenue service trial can be found in Smith and Shurland's report on the trial [1].

Daily inspections of Engine #500 while in revenue service were documented[3]. Based on review of this documentation and interview with Amtrak Mechanical personnel, no adverse mechanical impacts attributable to alternative fuel use were identified during the test period.

Moreover, on-time performance (OTP) during the revenue service trial for fiscal year 2010 and fiscal year 2011 were 81.4 percent and 86.9 percent, respectively. OTP metrics for the Heartland Flyer for the fiscal year prior to the trial was 83.8 percent. Therefore, using biodiesel to power Engine #500 did not impact its service performance.

2.3.2 Fuel and Engine Oil Analyses Results

The fuels used to develop B20 biodiesel fuel were evaluated to ensure they met their required specification before blending (i.e., the diesel fuel and the biodiesel fuel). Once blended, the B20 fuel was subject to periodic testing to ensure that the blended product met the ASTM biodiesel specification. The ULSD diesel fuel used to blend the B20 biodiesel fuel was tested according to ASTM D975 fuel specifications (see Appendix A). The B100 fuel was tested according to D6751, and it was found that certain parameters of the B100 sampled fuel failed to meet those standards. A new batch of B100 was tested and found to be in accordance with all criteria of D6751, which allowed for the blending of the B20 biodiesel fuel. Once blended, the B20 fuel was tested according to ASTM D7467. As with the B100, certain parameters of the initial B20 sample did not meet the D7467 specifications. Appendix A contains all tables of ASTM Fuel Specifications and analysis results.

During the field trial, Direct Fuels tested the B100 fuel supply weekly, per ASTM D6751, and certificates of analysis were made available to Amtrak. Samples of the certificates provided by Direct Fuels and received by Amtrak are contained in Smith and Shurland's work [1]. Likewise, the ULSD fuel was also tested, per ASTM D975.

Initial samples of B100 and B20, collected and analyzed before the start of the revenue service trial, were found to be in non-conformance with their ASTM standards, D6751 and D7467, respectively. The initial baseline B100 samples contained unacceptable concentrations of free and total glycerin. The test results indicated that the samples had a 0.230 percent by volume of free glycerin and 0.250 percent by volume of total glycerin, which is above the allowed maximum of 0.020 percent by volume and 0.240 percent by volume for free and total glycerin, respectively, per ASTM D6584.

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[3]Smith, W., Shurland, M., Biodiesel in Passenger Rail Revenue Service Test, DOT/FRA/ORD-13/43.

Table 1. ANA LABORATORY TEST RESULTS FOR B100 BIODIESEL FUEL RETEST SAMPLE

Test	Description	ASTM	Spec.	Results	Units
1)	Flash Point	D-93	130 min	146	°C
2)	Water and Sediment	D-2709	0.0500 max	0.0100	vol %
3)	Kinematic Viscosity @40C	D-445	1.9-6.0	4.67	cSt
4)	Sulfated Ash	D-482	0.020 max	0.001	wt %
5)	Sulfur	D-5453	15 max	0.0007	ppm
6)	Copper Strip Corrosion	D-130	No. 3 max	1a	rating
7)	Cetane Index	D-976	47 min	59.1	
8)	Cloud Point	D-2500	Report	17	°C
9)	Carbon Residue	D-524	0.0050 max	0.049	wt %
11)	Acid Number	D-664	0.50 max	0.28	mg KOH/g
12)	Free Glycerin	D-6584	0.020 max	0.00	vol %
13)	Total Glycerin	D-6584	0.240 max	0.00	vol %
14)	Phosphorous	D-4951	0.0010 max	<0.0001	wt %
14)	Distillation Temperature 90%	D-86	360 max	331	°C
15)	Calcium and Magnesium	EN14538	5 max	<1	ppm
16)	Sodium and Potassium	EN14538	5 max	<1	ppm
17)	Oxidations and Stability	EN14112	3 min	>10	hours

New B100 samples were determined to be in line with all ASTM specifications prior to the commencement of the trial. See Table 1 above. The initial baseline B20 sample was found to be unacceptable for aromaticity. High levels of aromatics in the fuel can impact the emissions of the locomotive. Therefore, it was important that the B20 samples meet the ASTM standards during and after the revenue service trial. The aromatic content was measured at 46.6 percent by volume of the fuel, whereas the ASTM specification for B20 fuel required a maximum of 35 percent aromatic content by volume of the fuel. Testing of subsequent batches of B20 fuel showed conformance with the ASTM standards, as can be seen in Table 2 below. The testing was conducted by ANA Laboratories. All fuel samples' test results for the Biodiesel Intercity Passenger Rail Revenue Service Test can be found in Appendix A and in Smith and Shurland's "Biodiesel in Passenger Rail Revenue Service Test" report [1].

Table 2. ANA LABORATORY B20 BASELINE SAMPLE RETEST RESULTS

Test	Description	ASTM	Spec.	Results	Units
1)	Flash Point	D-93	52 min	74	°C
2)	Water and Sediment	D-2709	0.0500 max	<0.0010	vol %
3)	Kinematic Viscosity @40°C	D-445	1.9-4.1	3.14	cSt
4)	Ash Content	D-482	0.01 max	0.003	wt %
5)	Sulfur	D-5453	15 max	9	ppm
6)	Copper Strip Corrosion	D-130	No. 3 max	1a	rating
7)	Cetane Index	D-976	40 min	53.3	
8)	Cloud Point	D-2500	Report	-7	°C
9)	Carbon Residue 10%	D-524	0.3500 max	0.040	wt %
10)	Aromaticity	D-1319	35 max	31	vol %
11)	Acid Number	D-664	0.3 max	0.19	mg KOH/g
12)	Free Glycerin	D-6584	Report	0.0	vol %
13)	Total Glycerin	D-6584	Report	0.0	vol %
14)	Distillation Temperature 90%	D-86	343 max	331	°C
15)	Biodiesel Content	D-7371	6-20	20	vol %
16)	Oxidation Stability	EN14112	6 min	>10	hours
17)	Lubricity	D-6079	520 max	195	microns

Samples of used oil from the engine were collected and analyzed. ANA Laboratories tested the engine used oil for metals, fuel and water, oxidation, nitration, soot and sulfate. In addition to the tests performed by ANA Laboratories, Chevron Oronite tested the used oil samples for BN, AN, pentane insoluble, viscosity increase, oxidation, wear metals, fuel dilution, and biodiesel dilution with its proprietary methods. The oil used in Engine #500 was 20W-40 multi-grade generation 5 locomotive oil. Used oil samples were collected approximately every 15 days.

Tests for the acidic and basic content of the used oil can indicate whether the engine oil underwent degradation while in service. Oil degradation can occur when there is a blow by the piston and the engine oil is contaminated with fuel. According to Chevron Oronite, the BN retention was good, dropping to a low of 7.37 mmKOH/g[4]. AN rose slightly over this same time period to 4.18 mm KOH/g before dropping. Chevron Oronite determined that biodiesel can degrade the piston rings, causing fuel mixture to leak outside of the cylinder. The change in AN could be attributed to a change in the oil, though this could not be confirmed. The ASTM D7317 and D445 determined the pentane insolubles in the used oil and kinematic viscosity of the used oil, respectively. Analyses of the used oil showed that coagulated insolubles by the LMOA method remained low with a maximum of 2.6 percent by weight, whereas the analyses of the viscosity of the engine used oil showed no significant increase in its viscosity.

[4] Smith, W., Shurland, M., Biodiesel in Passenger Rail Revenue Service Test, DOT/FRA/ORD-13/43.

Oxidation of the engine oil was measured by infrared method. Oxidation was under control and remained low for the duration of the test. Wear metals (FE, copper (Cu), and Pb) were measured using the inductively coupled plasma method. For all three, the levels were very low and well within the condemning limits. Fuel dilution (total) and biodiesel dilution were also monitored. As an acidic material, biodiesel dilution in the oil may be problematic because of its corrosivity to metallic surfaces. For the duration of the test, both total fuel dilution and biodiesel dilution were very low and in many observations were below measurement limit[5]. Results from Chevron Oronite analyses are contained within Reference [1].

In summary, all samples of used oil that have been collected and analyzed during the trial were routinely within tolerance of ASTM specifications and industry recommended values. These results indicate that in this revenue service trial, the biodiesel did not adversely affect the operations of the engine.

2.3.3 Locomotive Exhaust Emissions Test Results

Engine Exhaust Emissions testing was performed for HC, CO, NOx, and PM under line haul and switch duty cycles, according to 40 CFR Part 92. The particulate and gaseous emissions were measured at low idle, idle, dynamic brake, and notches 1–8. Smoke Opacity measurements were also taken according to 40 CFR Part 92, using both the EPA certification fuel and the B20 biodiesel.

2.3.3.1 Gaseous and Particulate Emission Test Results

Duty cycle composite emission test results using both the EPA certification fuel and B20 were well below limits established by EPA for Tier 0 engine gaseous emissions of HC, CO, NOx, and PM. There was an approximately 5 percent increase in NOx emissions observed from the use of B20 compared with use of EPA diesel certification fuel. However, this increase in NOx was expected and was within the range identified by other emission testing results published about use of B20 fuel[6]. There were no significant differences identified in the emission results when comparing the certification fuel with B20 for PM, HC, and CO, except at low idle. Results for PM, HC, and CO at low idle showed an increase in emissions when using the B20 fuel. Fuel consumption values also showed an increase at low idle with the B20 but not the diesel fuel. However, this disparity in the results observed at low idle between the B20 and certification fuel for the gaseous and particulate emissions and fuel consumption values were not replicated at idle, dynamic brake, or notch 1 through notch 8. The reason for this anomaly was not clear. GE Transportation Services, who performed the emissions testing on Engine #500, suggested that engine operating issues were as likely a cause as the fuel difference for the disparity between the emissions results at low idle. No loss in horse power was observed at low idle, idle, dynamic brake, or notches 1 through 8. Emissions test results are included in Appendix B. A summary of the emissions results are presented below in Tables 3 and 4.

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[5] Smith, W., Shurland, M., Biodiesel in Passenger Rail Revenue Service Test, DOT/FRA/ORD-13/43.

[6] Fritz, S., "Evaluation of Biodiesel Fuel in an EMD GP38-2 Locomotive." National Renewable Energy Laboratory Report No. NREL/SR-510-33436. (May 2004)

Table 3. Biodiesel Intercity Passenger Rail Revenue Service Test – Modal Emissions Results

Line Haul Duty-Cycle Results				
	BSHC	BSCO	BSNOx	BSPM
	(gm/hp-hr)			
B20 Fuel	0.38	0.90	8.3	0.13
EPA Certification (Diesel) Fuel	0.39	0.80	7.9	0.14
Tier 0 Limit	1.00	5.00	9.5	0.60
Switch Duty-Cycle Results				
	BSHC	BSCO	BSNOx	BSPM
	(gm/hp-hr)			
B20 Fuel	0.68	1.2	10.7	0.26
EPA Certification (Diesel) Fuel	0.68	1.2	10.0	0.24
Tier 0 Limit	2.10	8.00	14.0	0.72

Table 4. Biodiesel Intercity Passenger Rail Revenue Test – Smoke Opacity Emissions Test Results

Smoke Opacity Test Results			
	Steady-State	**30 Second Peak**	**3 Second Peak**
	% Opacity		
B20 Fuel	12	16	35
Diesel Fuel	11	15	34
Tier 0 Limit	30	40	50

Also measured was the smoke opacity of the engine on B20 and certification fuel. As mentioned previously, high aromaticity in the B20 fuel can affect the emissions of the engine (e.g., increase the smoke opacity). Table 4 shows the smoke opacity results. The percent opacity was measured at various time intervals. For each notch position of the engine, the opacity of the emitted smoke was recorded at 3 seconds peak interval, 30 seconds peak interval, and steady state. Data was again collected for both the B20 biodiesel and the certification diesel fuel. The test results showed that the B20 fuel performed comparably with the diesel fuel, and below the EPA limit for tier 0 engines.

Notwithstanding the disparity in emissions and fuel consumption observed at low idle between the B20 and diesel fuel test results, when comparing the B20 fuel and diesel fuel test results against each other and the EPA tier 0 limits, Engine #500 performed well. The fuel consumption and engine performance results indicated that Engine #500 performed as well on the B20 biodiesel as it did on the diesel fuel. Engine #500 was as able to make full horsepower using B20 biodiesel as it was using diesel fuel.

2.3.4 Engine Power Assembly Mechanical Tear Down and Inspection Results

Following the emissions testing of Engine #500, Chevron Oronite performed a mechanical inspection to evaluate the engine for deposits and wear. According to Chevron Oronite, the results of the testing showed no abnormal conditions related to engine deposits or engine wear. The condition of the parts was deemed comparable to the normal condition of parts on passenger and freight locomotive operations. The engine parts inspected showed normal piston deposits. The liner wear was minimal. Piston rings also showed low wear and were in serviceable condition. The engine bearings showed normal wear and even loading with no evidence of corrosion. Even though the inspection of the 2R and 2L connecting rod bearings showed normal wear, there was some evidence of small pitting; the pitting was subsequently determined not to have been caused by corrosion and would be investigated further. The inspection of Engine #500 after 12 months of B20 biodiesel use concluded that the two new power assemblies showed moderate piston deposits and a very clean engine surface lacking any sludge or deposit depth. A close up of the interior of the power assembly cylinder can be seen in Figure 2 below. Concluding the inspection of the power assemblies and the fuel and oil analyses, Chevron Oronite determined that the locomotive used in the Biodiesel Intercity Passenger Rail Revenue Service Test showed minimal to normal wear of the power assemblies.

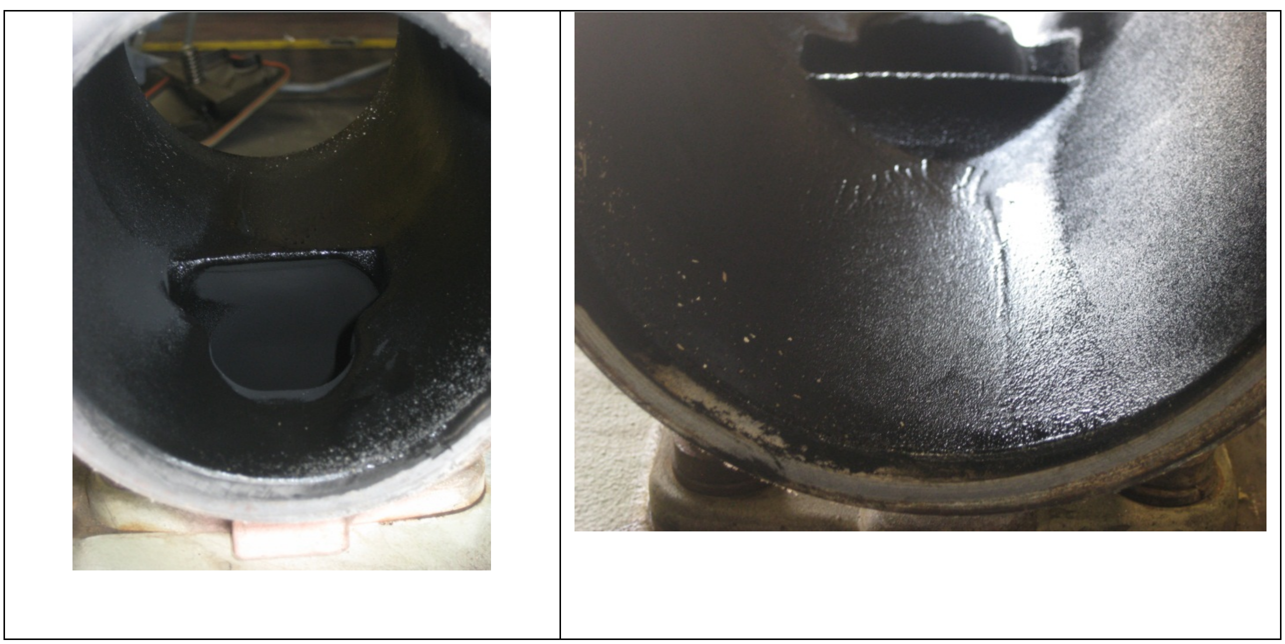


Figure 2. Interior views of power assembly cylinder showing buildup

2.4 Conclusions

Throughout the biodiesel revenue service trial, the test locomotive was provided with a total of 178,946 gallons of B20 biodiesel fuel that reliably met ASTM specifications.

Amtrak maintained its OTP for the Heartland Flyer train during the biodiesel revenue service trail, completing 331 roundtrips between Oklahoma City, OK, and Fort Worth, TX, totaling 136,372 route miles. A total of 152,622 equipment miles with B20 were logged during this period. No additional maintenance required on Engine #500 was attributed to the use of B20 fuel.

During the course of the trial, the cost of B20 biodiesel ranged from $2.16/gallon to $3.70/gallon compared with ULSD #2 which ranged from $2.14/gallon to $3.52/gallon. From day to day, the cost variance of B20 in comparison to ULSD ranged from $0.00 to $0.31/ gallon. This market fluctuation may have been partially attributable to changes in State law related to tax exemption for B20 which then resulted in changes to supply and demand.

Emissions tests were performed for HC, CO, NOx, and PM under line haul and switch duty cycles. The particulate and gaseous emissions were measured at low idle, idle, dynamic brake, and notch 1 through notch 8 and were found to be below the limits set by the EPA for Tier 0 class of locomotive engines. Similarly, smoke opacity measurements using both the EPA certification fuel and the B20 biodiesel fuel were below limits established by EPA for Tier 0 locomotive engines. An increase of approximately 5 percent in NOx was observed with use of B20 but not with diesel fuel. Moreover, test results indicated that it was possible to achieve full power using B20.

Inspection of the baseline power assembly units and engine oil analyses determined that 12 months of B20 biodiesel use by Engine #500 resulted in normal wear of the baseline units.

3. LOCOMOTIVE EMISSIONS MEASUREMENT FOR VARIOUS BLENDS OF BIODIESEL FUEL

FRA participated in the SAE International TC7 Biodiesel in Railroad Applications Subcommittee until the committee was disbanded in 2013. The subcommittee helped FRA identify an approach to meet the objectives specified in PRIIA Section 404. This interaction with the TC7 subcommittee allowed FRA to implement a multiphase, multiyear program to assess exhaust emissions, as well as evaluate how biodiesel will affect locomotive engine performance and durability over time. This research effort focused on investigating the emissions of two locomotive engines using a 5 percent and 20 percent blend, respectively, of biodiesel.

3.1 Background

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 FTP 40 CFR Part 92, as specified by the U.S. 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 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.

3.2 Research Methodology

3.2.1 Fuel Procurement and Analysis

3.2.1.1 B100 Biodiesel

A Request for Quote (RFQ) concerning the requirements for supplying biodiesel to this FRA project was developed by the National Biodiesel Board 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 did not qualify under the Renewable Fuel Standard-2 program. Between the final two companies, AGP was chosen as the vendor—they were the most cost-effective option (lowest cost per gallon delivered). All candidate B100 fuels for consideration were required to meet ASTM D6751 standards, and the blended biodiesel fuels (B5 and B20) met ASTM D975 and ASTM D7467 standards, respectively. In addition, all fuels procured were to be accompanied by a Certificate of Analysis (COA) to verify that quality specifications were met or exceeded at the time of receipt at the testing site in San Antonio, TX. The National Biodiesel Board provided the B100 test fuel at no cost to FRA and SWRI. Appendix C shows the COA that accompanied the biodiesel chosen for this project, and Table 5 shows the results of the B100 fuel analysis.

Table 5. 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

3.2.1.2 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 emission benefits comparable to that of a standard CARB diesel fuel.

For this project, a single batch of CARB diesel was procured by SWRI and stored in a clean storage tank at SWRI's test facility. A sample of the fuel was then taken and analyzed before blending. Results of the CARB diesel analysis indicated that the fuel parameters were within the certification limits for production, and so the fuel was determined to be a legal California diesel fuel. See analysis results in Table 6.

Table 6. CARB DIESEL FUEL 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

3.2.1.3 U.S. EPA S15 (ULSD)

The U.S. EPA ULSD fuel was purchased as a single batch, and the fuel met the properties listed in Title 40: Protection of Environment, Part 1065, Subpart H standards.

Table 7. U.S. 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

3.2.2 Fuel Blends

After analyses and approval for testing of the three different base fuels (CARB0, EPA0, and B100), the base fuels were blended in separate storage tanks (shown in Figure 3) to create CARB5, CARB20, EPA5, and EPA20 fuel blends. Appendix A shows the results of the fuel analysis for these fuel blends.

Figure 3. Interior views of power assembly cylinder showing buildup

3.3 Test Sequence

With 2 locomotives (1 GE and 1 EMD), 6 fuels, and triplicate tests (for each fuel on each locomotive), a total of 36 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 8. With replication and randomization in the design of this study, SWRI was able to statistically evaluate fuel effects within each locomotive and assess interactions between locomotives and the test fuels.

Table 8. 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

3.4 Test Fuel Delivery System and Procedures

Multiple steps were taken to verify that there was no cross-contamination of the fuels during testing. The steps focused on ensuring 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 tote label name and color code match 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 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 locomotive fuel pump (engine off) for a minimum of 6 minutes and purge all return fuel from locomotive.
7. Verify fuel tote label matches test to be run (final check).

8. Start and warm up engine.
9. Operate 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 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.

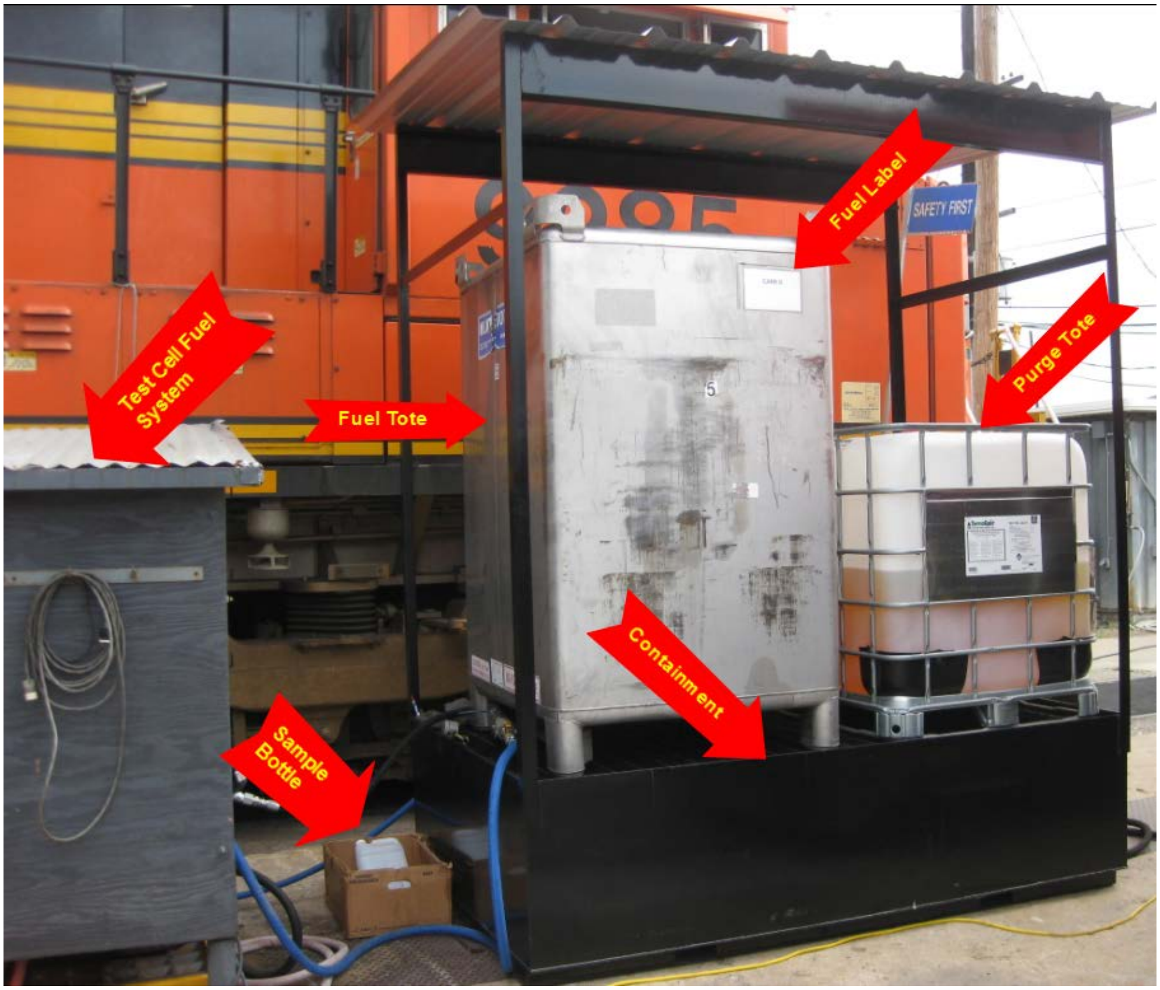


Figure 4. Test Fuel and Purge Totes

3.5 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. Both locomotives were donated temporarily by BNSF Railway (BNSF) for these tests.

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 9[7].

Figure 5. BNSF9285, a Tier 2 EMD SD70ACe

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

Figure 6. BNSF9285 Locomotive Emissions Sticker

Table 9. 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 standards. The locomotive emissions sticker is shown in Figure 8 and details of the GE 7FDL engine are shown in Table 10[8].

[8] http://www.getransportation.com/

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

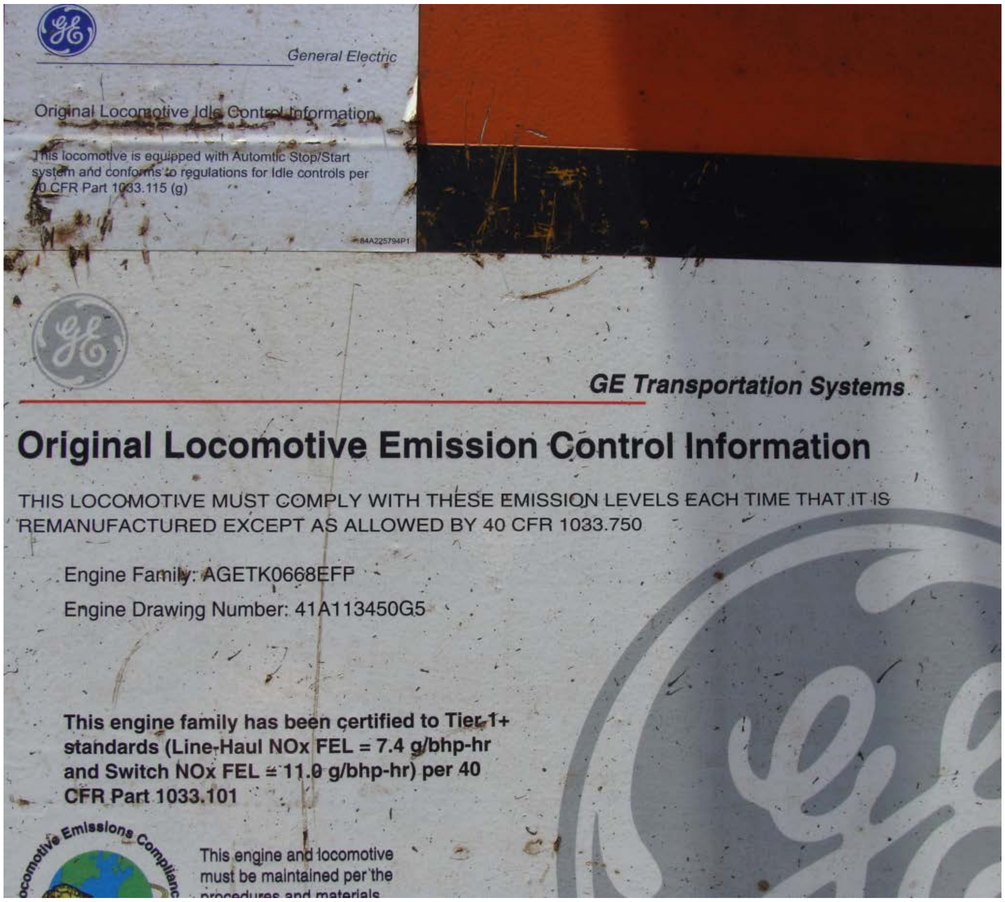


Figure 8. BNSF5014 Locomotive Emissions Sticker

Table 10. 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

3.6 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 ensure a consistent fuel supply temperature to the engine.

3.7 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 HC, CO_2, NO_X, O_2, and PM 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.

3.7.1 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 with propane. NOx concentrations were measured using a California Analytical Instruments Model 400 heated chemi-luminescent 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 non-dispersive infrared 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 calculated 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.

3.7.2 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 is "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.

3.7.3 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[9]. Table 11 shows the U.S. EPA test cycle and weighting factors applied to each notch.

Table 11. 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%

Table 12 shows the U.S. EPA locomotive exhaust emissions standards. BNSF5014 was designed to meet Tier 1 Plus standards, and BNSF9285 was designed to meet Tier 2 standards, as highlighted in Table 12 below.

[9] CFR Title 40: Protection of Environment, Control of Air Pollution from Locomotives and Locomotive Engines; PART 92, Section 92.132.

Table 12. 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

3.8 Test Results

With replication and randomization in the design of this study, SWRI was able to statistically evaluate fuel effects within each locomotive and assess interactions between the locomotives and the fuels. For many of the results and cycles, the interactions were significant. For the purposes of these analyses, SWRI used "significant" to indicate statistically significant with alpha equal to 0.05 (α=0.05). SWRI 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. Tables 13 and 14 show the results from the Tier 1 Plus and Tier 2 locomotive emissions tests.

Table 13. 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 14. 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		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	EPA 0	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		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	EPA 5	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		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	EPA 20	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		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	CARB 0	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		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	CARB 5	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		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	CARB 20	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%**

SWRI created comparison intervals around each of these 12 means. When the intervals do not overlap for a pair of fuels within a locomotive, it can be concluded that 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 9–25. The following discussion is based on comparisons using these figures.

General trends for biodiesel seen in other studies and in other applications were also observed 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.

<u>Carbon Monoxide (CO):</u>

Within each locomotive, the EPA and CARB base fuels did not have significantly different CO emissions. In locomotive BNSF9285, the only significant effect of biodiesel was that CARB0 had significantly higher emissions than CARB20 or EPA20. In locomotive BNSF5014, CARB20 and EPA20 both had significantly lower emissions than the other fuels, while the B5 fuels were not significantly different from their base fuels. The following charts show the emissions results for carbon monoxide for both locomotives.

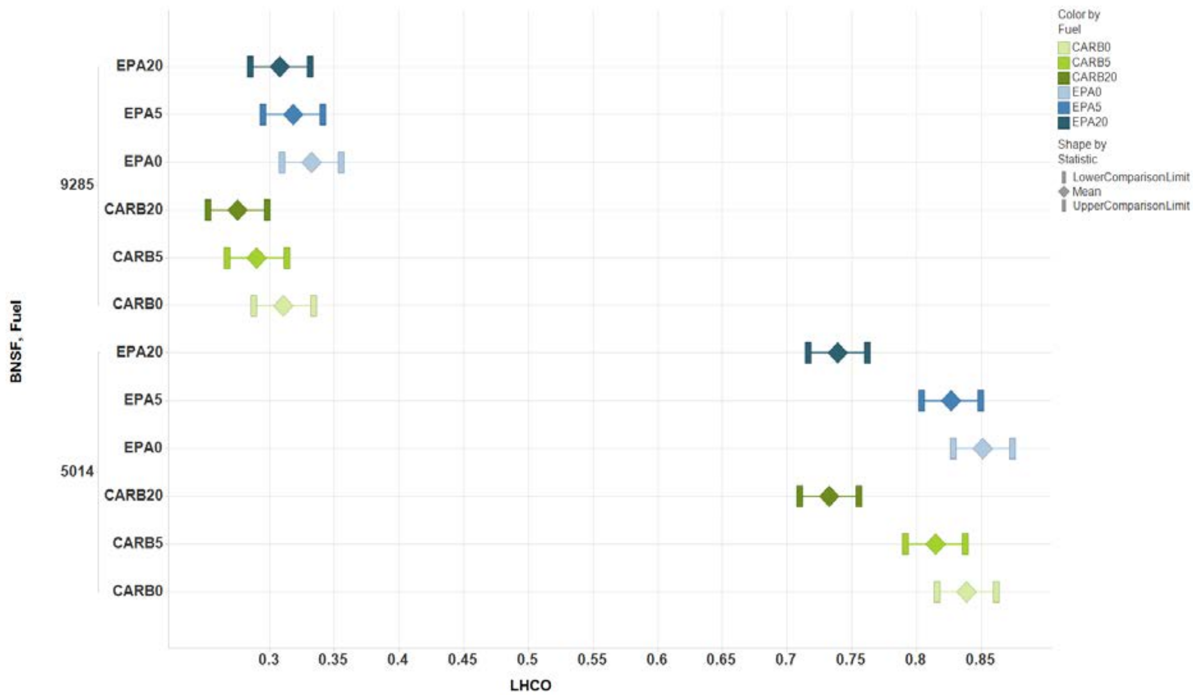


Figure 9. U.S. EPA Line-Haul Cycle CO Emissions Summary

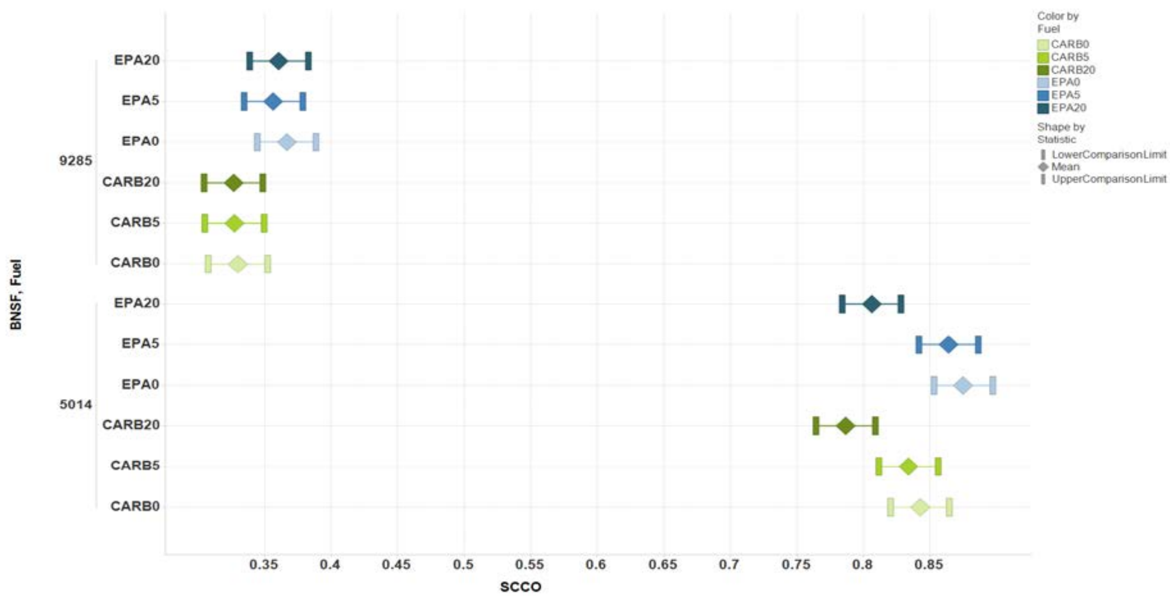


Figure 10. U.S. EPA Switch Cycle CO Emissions Summary

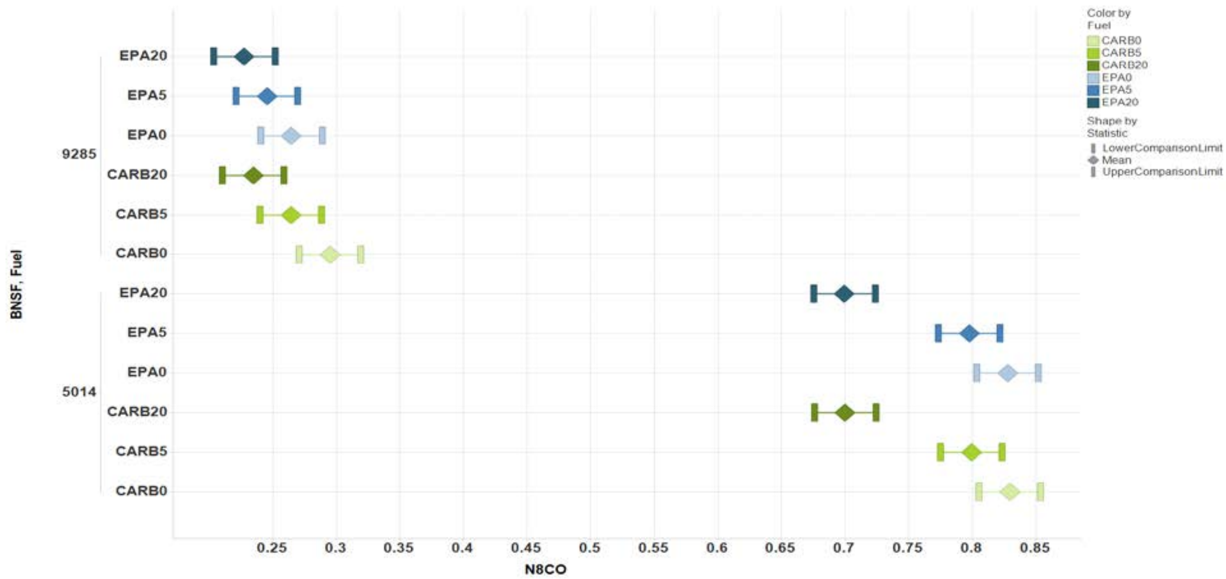


Figure 11. U.S. EPA Notch 8 CO Emissions Summary

<u>Oxides of Nitrogen (NOx):</u>

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 the 5 percent biodiesel. For none of the combinations was the 5 percent biodiesel significantly different from its base fuel. See Figures 12–14 below.

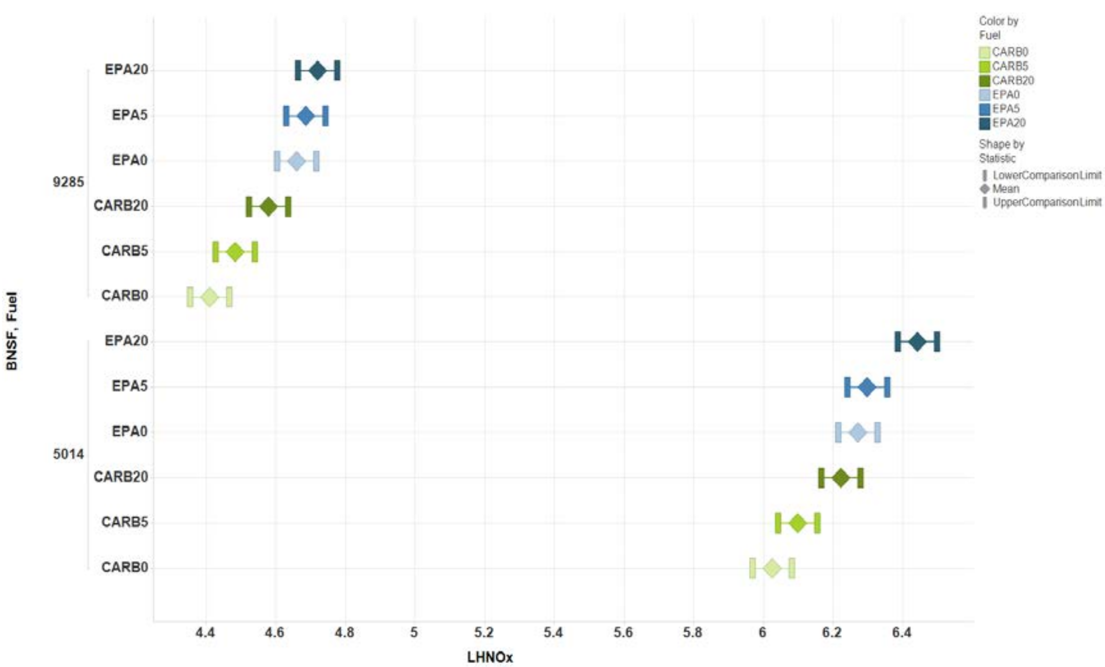


Figure 12. U.S. EPA Line-Haul Cycle NOX Emissions Summary

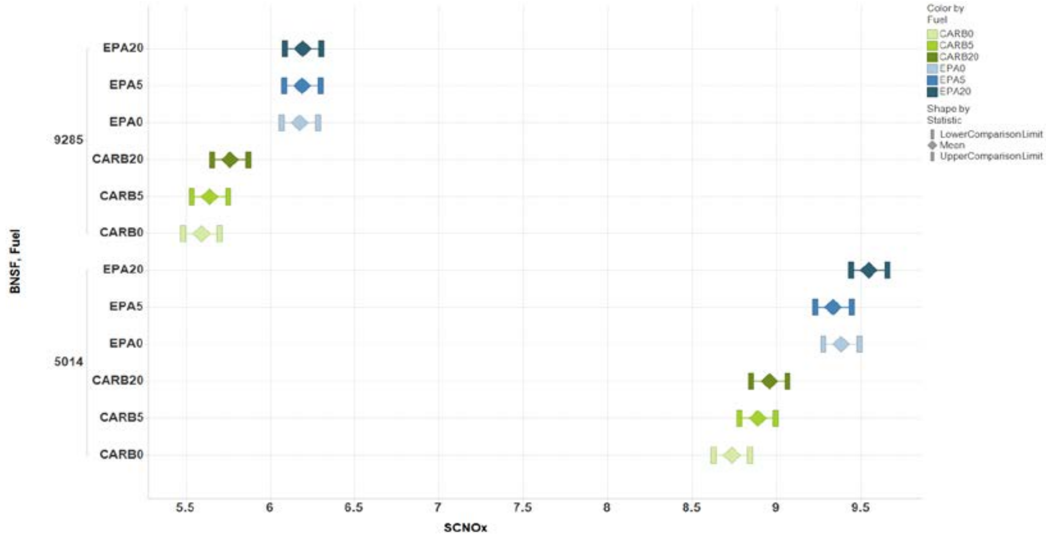


Figure 13. U.S. EPA Switch Cycle NOx Emissions Summary

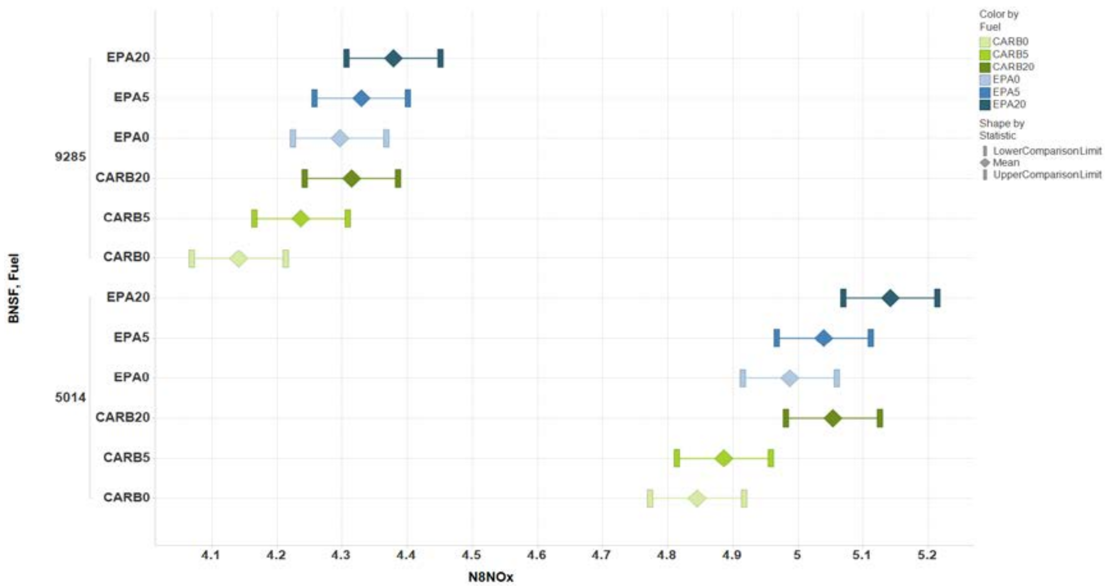


Figure 14. U.S. EPA Notch 8 NOx Emissions Summary

Particulate Matter (PM):

With locomotive BNSF5014 for line-haul, EPA0 had significantly higher PM emissions than CARB0. Also, with locomotive BNSF5014 for line-haul and notch 8, EPA20 had significantly lower PM than EPA5 or EPA0, and CARB20 had significantly lower PM emissions than CARB0.

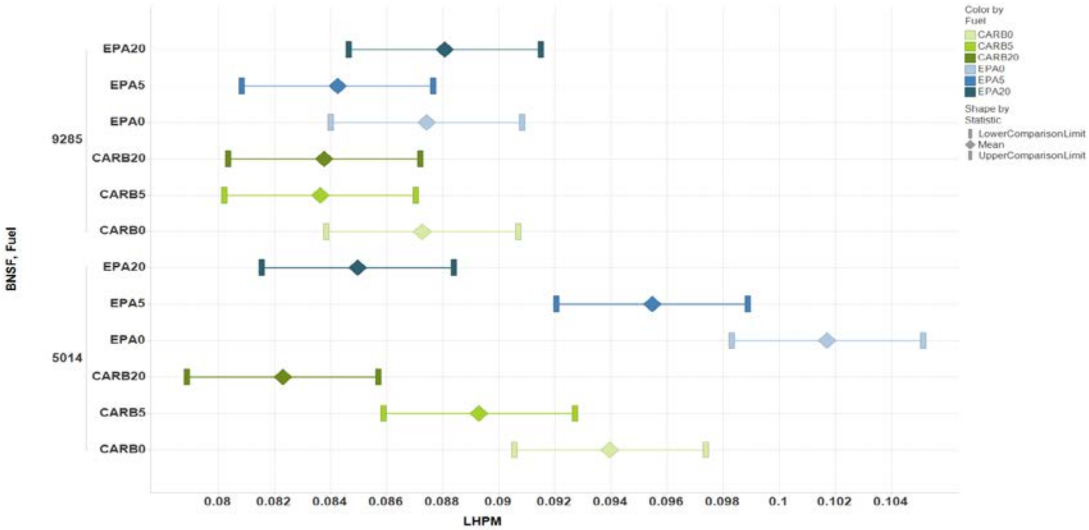


Figure 15. U.S. EPA Line-Haul Cycle PM Emissions Summary

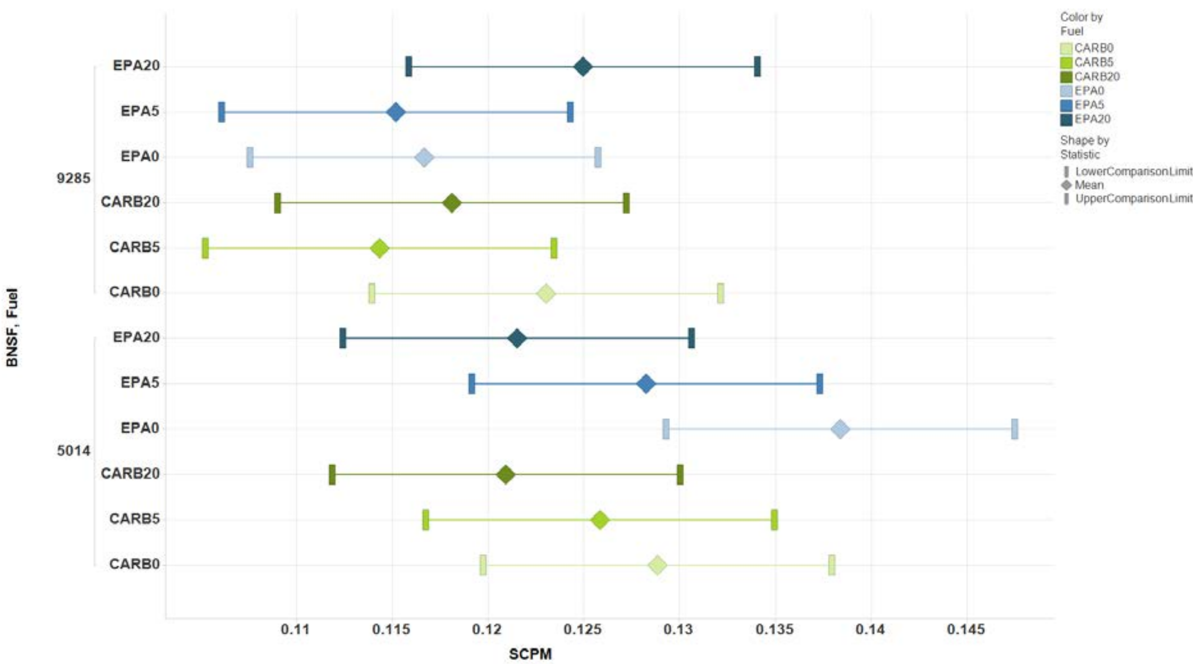


Figure 16. U.S. EPA Switch Cycle PM Emissions Summary

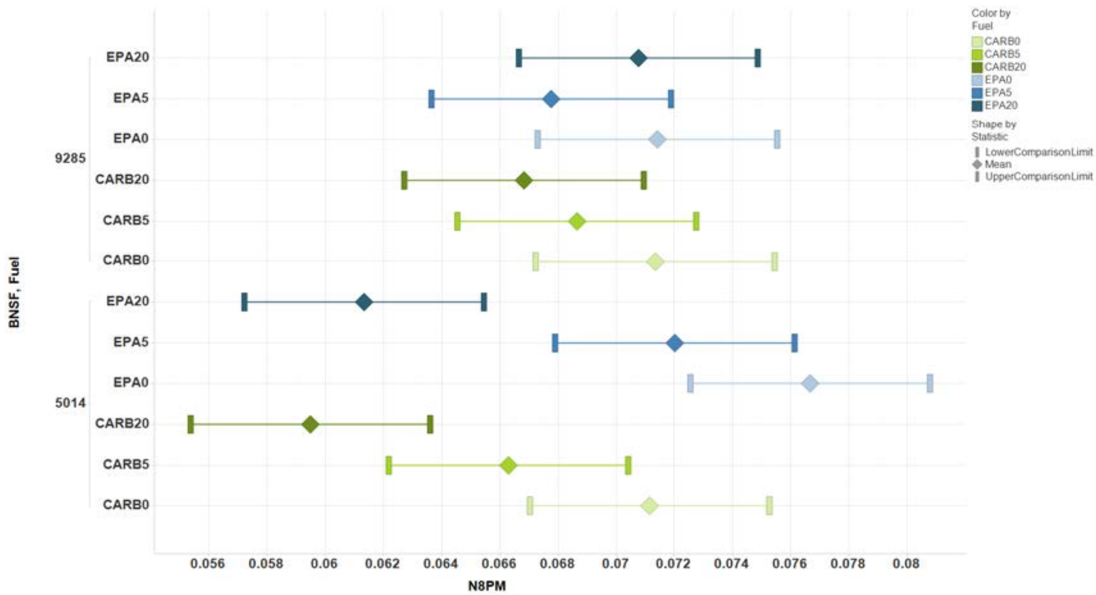


Figure 17. U.S. EPA Notch 8 PM Emissions Summary

<u>Hydrocarbons (HC):</u>

There were no significant differences among the six fuels' hydrocarbon emissions of the locomotives in this cycle.

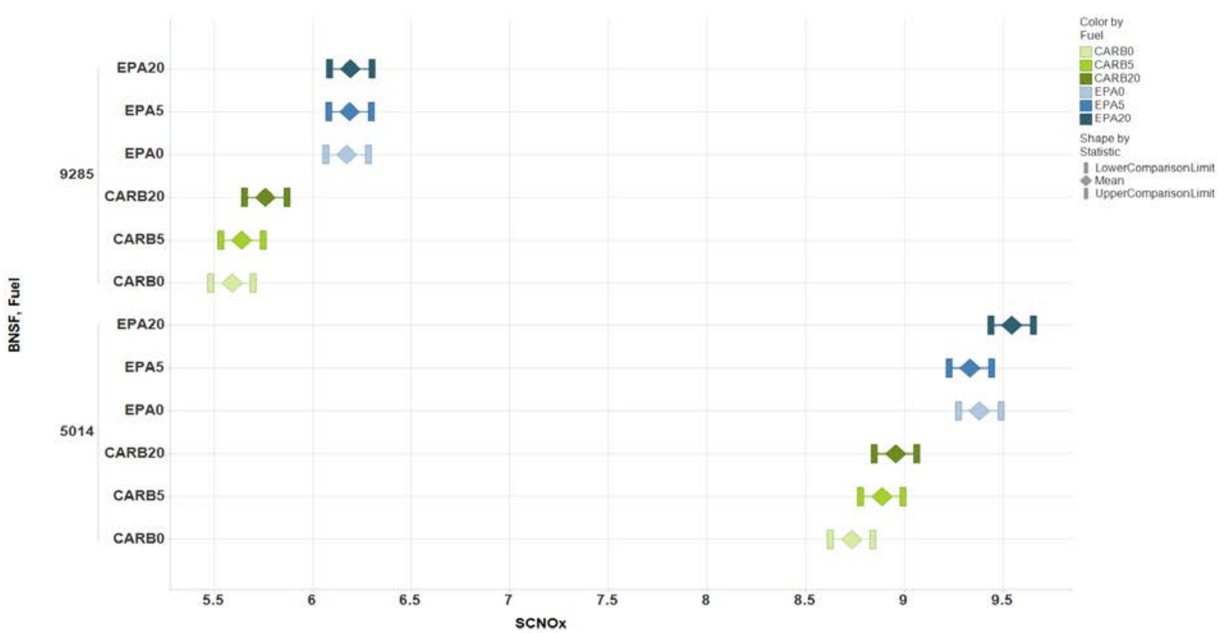


Figure 18. U.S. EPA Line-Haul Cycle HC Emissions Summary

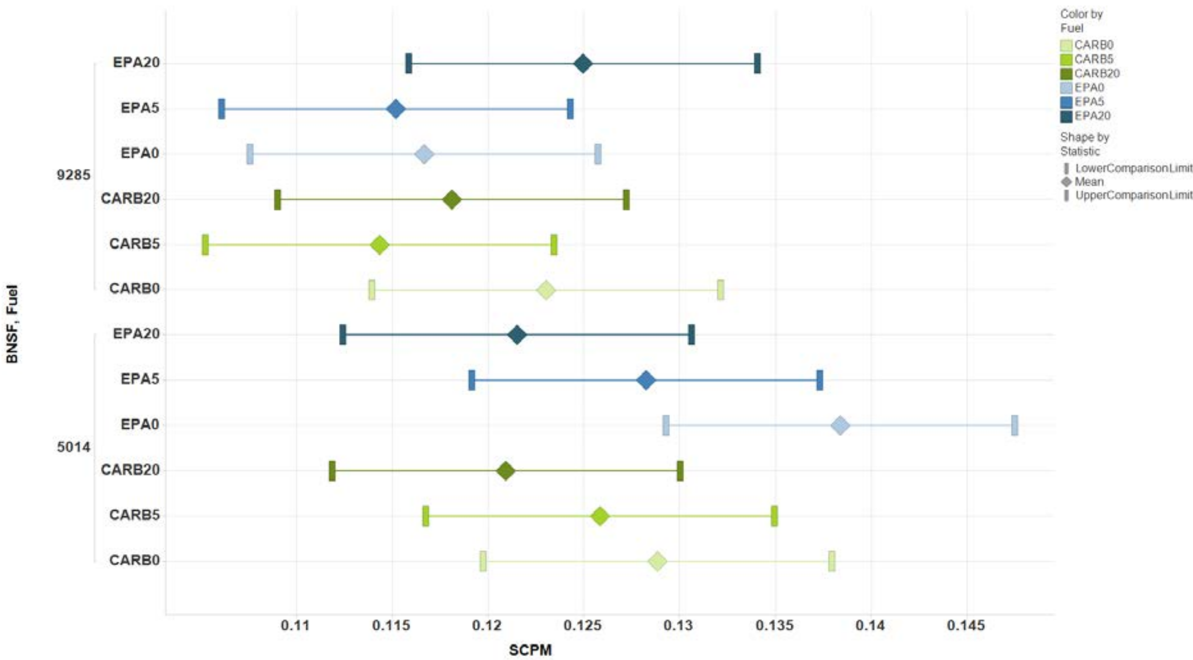


Figure 19. U.S. EPA Switch Cycle HC Emissions Summary

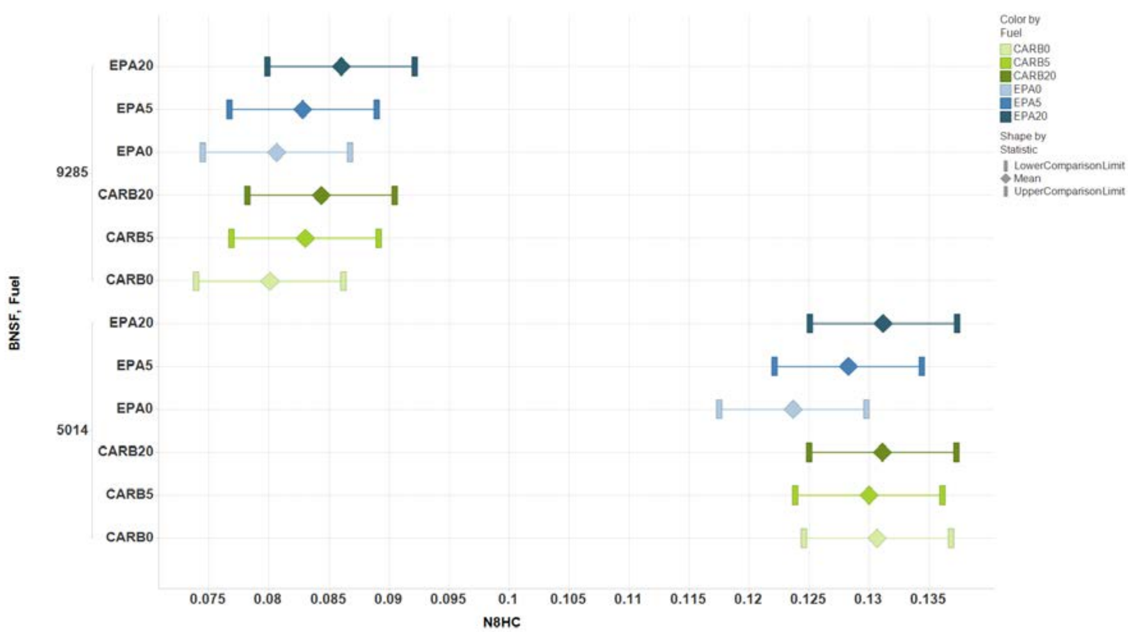


Figure 20. U.S. EPA Notch 8 HC Emissions Summary

<u>Notch 8 Brake Horse Power (BHP):</u>

There were no significant differences among the six fuels' BHP of the locomotives.

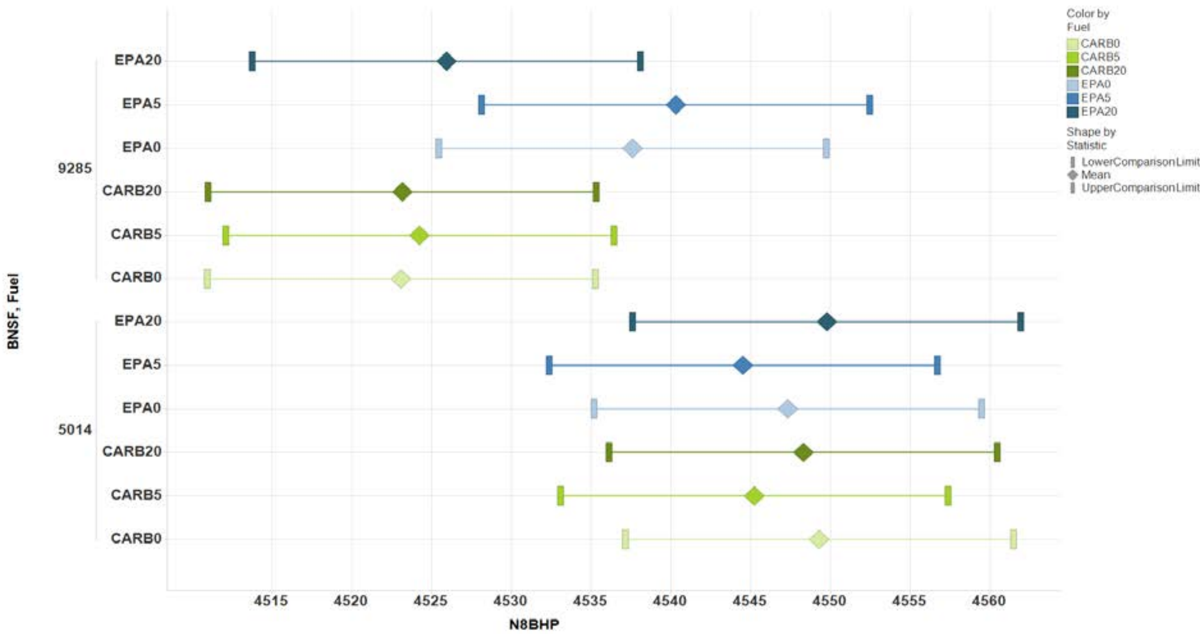


Figure 21. U.S. EPA Notch 8 BHP Summary

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 BNSF9285. EPA20 used significantly more fuel (mass flow rate) than EPA0 in locomotive BNSF5014.

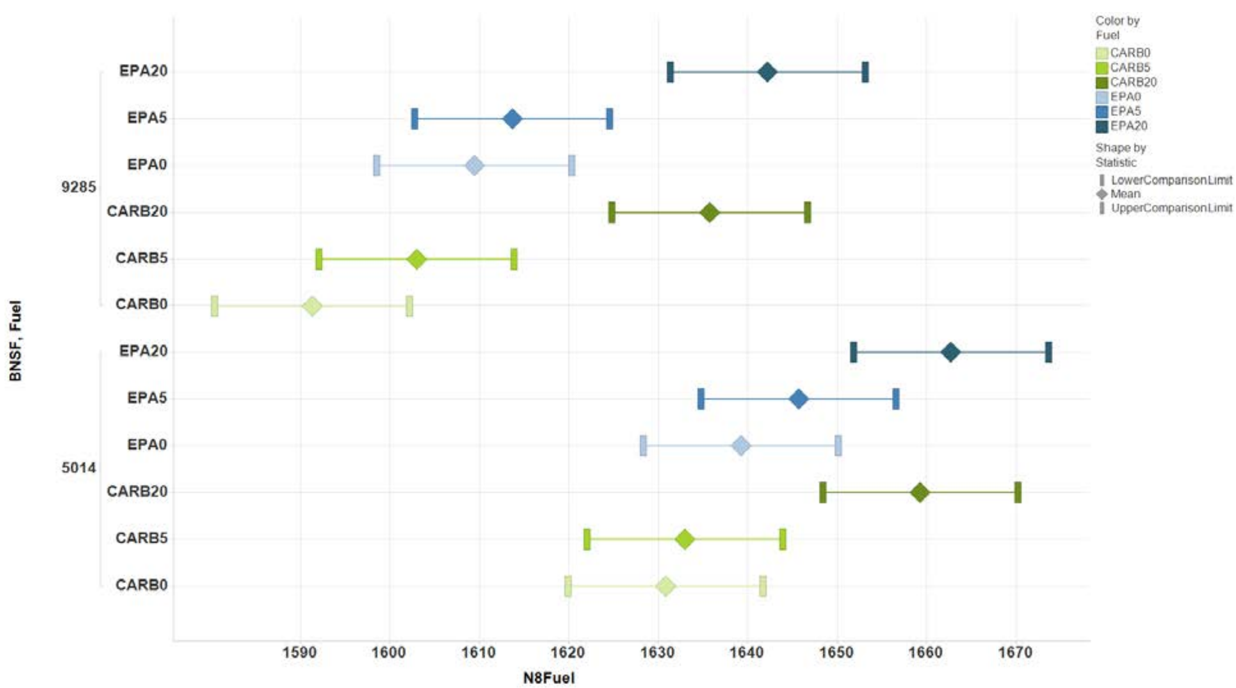


Figure 22. U.S. EPA Notch 8 Fuel Mass Flow Rate (lb/hr) Summary

Corrected Brake Specific Fuel Consumption (cBSFC):

For the line-haul cycle, the cBSFC was significantly higher for CARB0 than for EPA20 for locomotive BNSF9285. For locomotive BNSF5014 in 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.

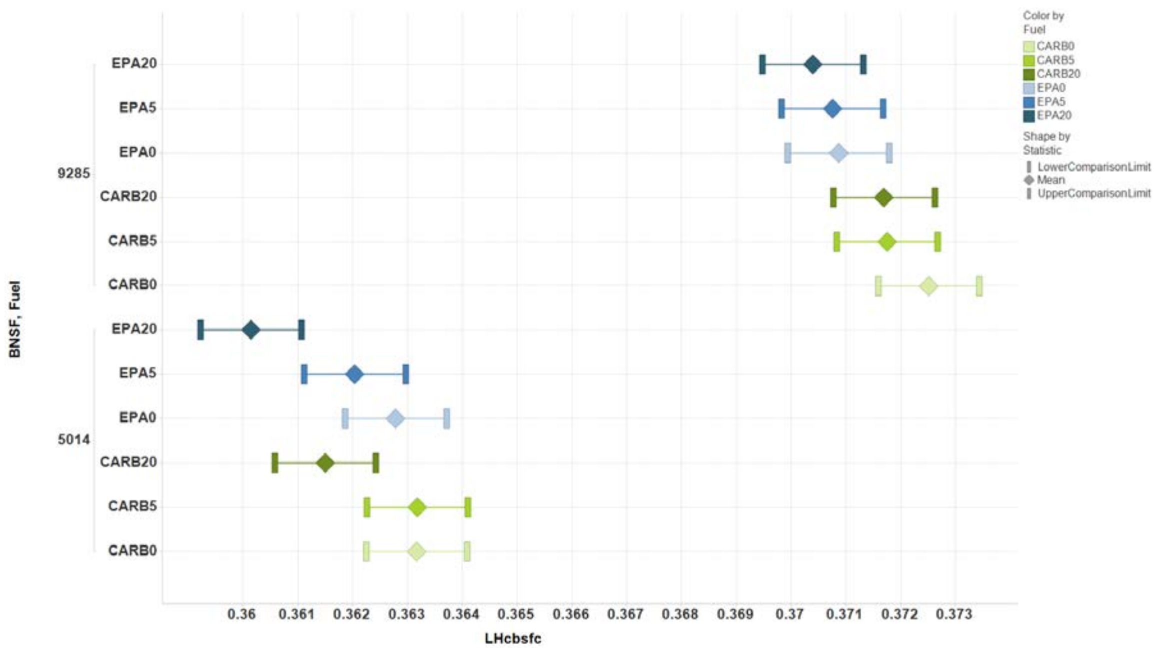


Figure 23. U.S. EPA Line-Haul Cycle Corrected BSFC (lb/hp-hr) Summary

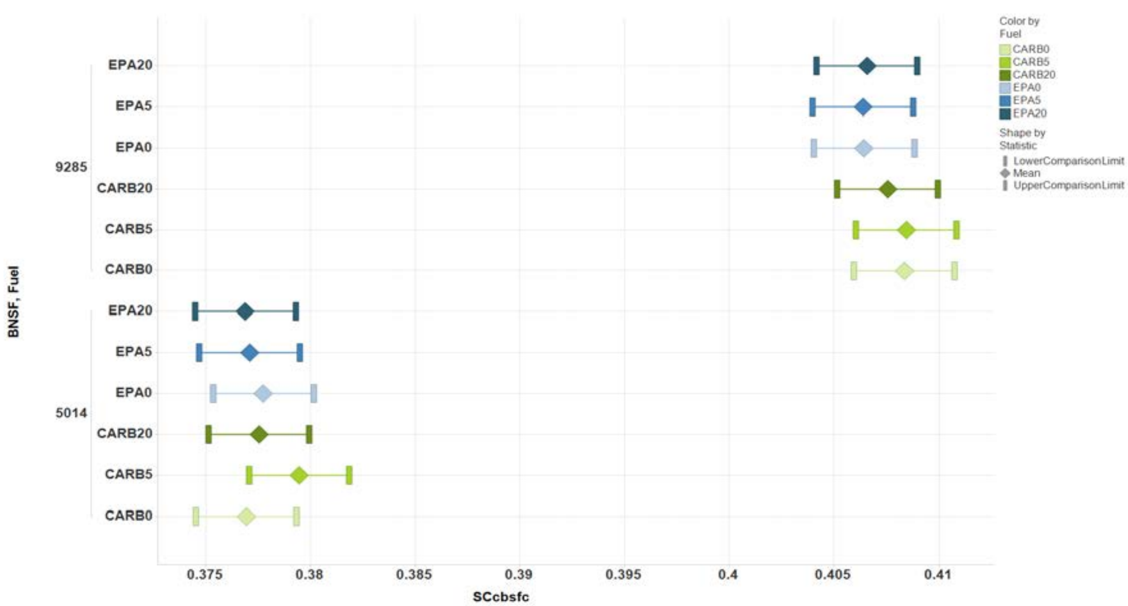


Figure 24. U.S. EPA Switch Cycle Corrected BSFC (lb/hp-hr) Summary

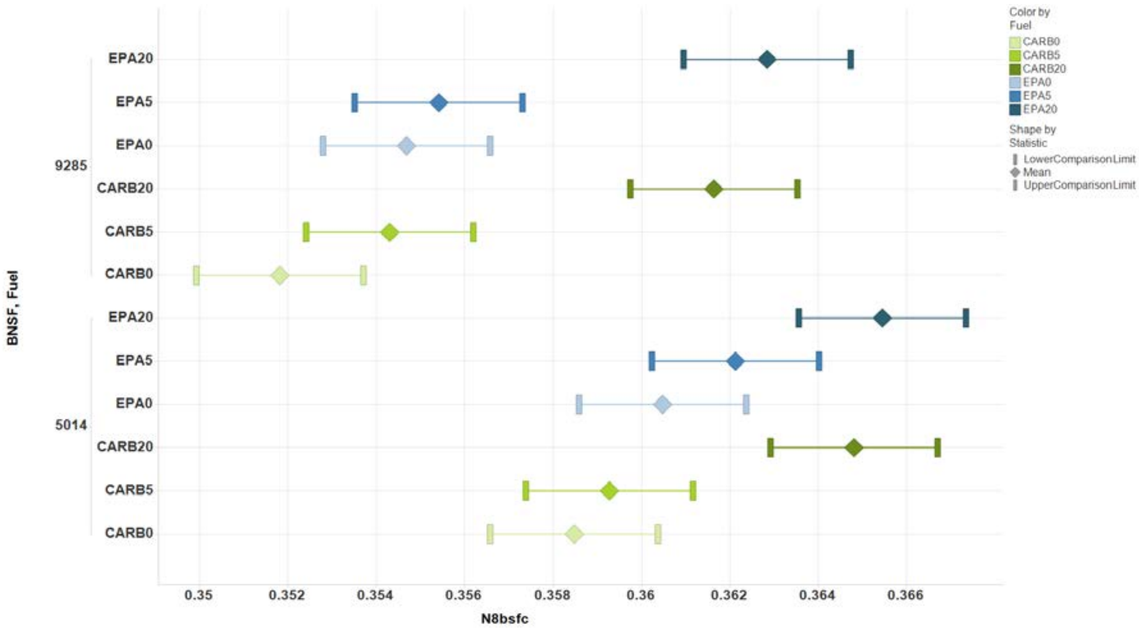


Figure 25. Notch 8 Corrected BSFC (lb/hp-hr) Summary

Table 15 shows the percent change between EPA0 and CARB0, CARB0 and CARB20, and EPA0 and EPA20 for the Tier 1 Plus engine, locomotive BNSF5014. 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 15 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. The switch cycle NOx and PM emissions trended the same as the line-haul emissions, but with smaller reductions.

Table 15. TIER 1 PLUS LOCOMOTIVE BNSF5014 RESPONSE TO CHANGE IN FUEL BLEND

Comparison of	Corr. BSFC (lb/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	NOx (g/hp-hr)	PM (g/hp-hr)
	Line-Haul Cycle				
CARB0 vs. EPA0	0.1%	6%	-1%	-4%	-8%
CARB0 vs. CARB20	-0.5%	-4%	-13%	3%	-12%
EPA0 vs. EPA20	-0.7%	-1%	-13%	3%	-16%
	Switch Cycle				
CARB0 vs. EPA0	-0.2%	9%	-4%	-7%	-7%
CARB0 vs. CARB20	0.2%	-8%	-7%	3%	-6%
EPA0 vs. EPA20	-0.2%	-7%	-8%	2%	-12%

Table 16 shows the percent change between the CARB0 and EPA0, EPA0 and EPA20, and CARB0 and CARB20 for the Tier 2 engine, BNSF9285. This table shows that the CARB0 fuel produced the expected level of emissions reduction when compared with EPA0, with the CARB0 base fuel providing 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 fuels 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 16. TIER 2 LOCOMOTIVE BNSF9285 EMISSIONS RESPONSE TO CHANGE IN FUEL BLEND

Comparison of	Corr. BSFC (lb/hp-hr)	HC (g/hp-hr)	CO (g/hp-hr)	NOx (g/hp-hr)	PM (g/hp-hr)
	Line-Haul Cycle				
CARB0 vs. EPA0	0.4%	-14%	-7%	-5%	0%
CARB0 vs. CARB20	-0.2%	2%	-11%	4%	-4%
EPA0 vs. EPA20	-0.1%	-3%	-7%	1%	1%
	Switch Cycle				
CARB0 vs. EPA0	0.5%	-17%	-10%	-9%	5%
CARB0 vs. CARB20	-0.2%	-1%	-1%	3%	-4%
EPA0 vs. EPA20	0%	-9%	-2%	0%	7%

3.9 Conclusion

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 also observed in this study. Higher blend levels of biodiesel were associated with lower CO and PM, as well as 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.

It is important to note that the emissions performance of these two test locomotive engines is not representative of all locomotive engines, and thus a conclusion cannot be drawn about how other models and tiered-level locomotives will perform on 5 percent biodiesel and 20 percent biodiesel in comparison with conventional diesel fuel.

4. NORTH CAROLINA STATE UNIVERSITY LOCOMOTIVE BIOFUEL STUDY

The research discussed in this section of the report continued FRA's investigation of the feasibility of using biodiesel blends as locomotive engine fuel. For this study, NCSU investigated various blends of biodiesel with considerations towards the following: (1) the energy intensity of the various blends compared to diesel fuel; (2) environmental and energy effects of using those blends blends compared to diesel fuel, including emission effects; (3) the cost of purchasing the biodiesel blends; (4) availability of biodiesel; (5) any public benefits derived from the use of such fuels; and (6) the effect of biofuel use on locomotive and other vehicle performance and warranty specifications. Locomotive engine performance and emissions were determined through locomotive testing, using various biodiesel blends.

4.1 Background

The NCSU Locomotive Biofuel Study was initiated to provide additional answers about the efficacy of using biodiesel as an alternative fuel for rail transportation and was funded under grant agreement number FR-RRD-0023-10. Working with North Carolina Department of Transportation (NCDOT), NCSU devised a test plan to evaluate rail yard and revenue service performance and conduct emissions testing on three NCDOT locomotives. The tests were performed using baseline No. 2 diesel fuel, 5 percent, 10 percent, 20 percent, and 40 percent biodiesel fuel. The tested locomotives were originally manufactured by EMD. Locomotives NC1810, NC1859, and NC1893 were the first to be tested. This section of the report focuses on the NC1810 and NC1893 locomotives tested and the preliminary results obtained.

4.2 Research Methodology

4.2.1 Fuels Characterization

NCSU sampled various blends of biodiesel to measure, compare, and assess the characteristics of the different blends of fuels used in three locomotives. The following tests were conducted on the fuel samples to provide an understanding of how the fuel characteristics changed as the percent of biodiesel was increased in the blended fuel.

- Elemental Composition of the Fuel
- Lubricity
- Acid Number (ASTM D664)
- Carbon Residue
- Cetane (ASTM D613)
- Cloud Point (ASTM D2500)
- Cold Soak Filtration (ASTM D7501-09)
- Copper Strip Corrosion (ASTM D130)
- Distillation, T90 (ASTM D1160)
- Flash Point (ASTM D93)
- Kinematic Viscosity, 40C
- Oxidation Stability (EN 14112)
- Phosphorus (ASTM D4951)

- Sodium and Potassium Combined, and Calcium and Magnesium Combined (EN 14538/ICP)
- Sulfated Ash (ASTM D874)
- Sulfur (D5453)
- Total and Free Glycerin (ASTM D6584)
- Visual Appearance (ASTM D4176)
- Water and Sediment (ASTM D2709)
- Percent Moisture (ASTM 4928 or 4377)
- Heating Value – British Thermal Units (BTU)
- Specific Gravity
- Total Particulate Contamination (ASTM 6217)

The fuel characteristics, as determined by the tests above, yield insight into the performance of biodiesel during engine combustion, energy output, emissions, storage, cold weather operations, etc.

NCDOT collected fuel samples which were then sent to SWRI for fuel characteristic testing according to the applicable ASTM standard protocols. The following fuel blends were sampled and tested: ULSD, 10 percent biodiesel blend, 40 percent biodiesel blend, and 60 percent biodiesel blend. For each of the fuels, literature-based estimates were used for data analysis. Fuel properties for ULSD and B100 were based on data obtained from "Biodiesel Handling and Use Guide, 4th Edition" [7]. Fuel properties for the other biodiesel blends were inferred based on the volume ratios of ULSD and B100. Literature research data and SWRI-measured fuel properties for ULSD, B10, B40, and B60 are summarized in Tables A9 to A12 of Appendix A.3, respectively.

4.2.2 Lubricating Oil Analyses

As a part of the 90-day inspection of each locomotive in the NCDOT fleet, oil samples were taken from the prime mover and HEP engines and sent to the Gregory Poole Fluid Analysis Laboratory. These fluid analyses characterize wear metals present in the oil (e.g., Cu, Fe, Cr, Al, Pb, Sn, Si, Na, K, Mo, Ni, Ca, Mg, Zn, P, and Ba), as well as oil condition (e.g., soot, oxidation, nitration, sulfation, water, antifreeze, fuel, and viscosity). Each of the wear metals measured in the lubricating oil analysis is indicative of specific aspects of engine wear. For example, Aluminum (Al) is indicative of wear of pistons, bearings, housing metal, thrust washers, converter and pump bushings, and dirt entry. Chromium (Cr) is a wear indicator for chromed parts such as piston rings and bearings. Presence of the metal iron indicates wear of gears, shafts, cylinders, liners, valve train components, other steel components, and rust. Molybdenum (Mo) indicates wear of piston rings. Many of the other metals analyzed, such as Sodium (Na), Potassium (K), Calcium (Ca), Barium (Ba), Magnesium (Mg), Phosphorus (P), and Zinc, are additives to the lubricating oil itself. Some of these additives are used as dispersants and detergents, while others are for anti-wear or anti-freeze. Some metals, such as Lead (Pb), Tin (Sn), and Nickel (Ni) are indicators of wear of bearings and bushings, many of which are not in the combustion flow path.

The particle count measurement helps assess whether there is excessive wear or dirt. The oxidation and nitration measurements assess how much the oil has absorbed oxygen and nitrogen, which is an indicator of wear of the oil itself. The sulfation measurement indicates how much sulfur has been taken up by the oil, which is an indicator of blow-by. (Blow-by is combustion gas that gets past the cylinder rings into the crankcase of the engine.) Thus, sulfur is an indicator of engine wear, especially for the piston rings.

The water, antifreeze, and diesel measurements indicate contamination of the oil by the coolant and fuel systems, which would indicate a significant fluid entry.

The viscosity measurement is an indicator of lube oil wear. High viscosity is associated with oxidation of the oil. Low viscosity is associated with fuel getting into the crankcase. Of the various assessments of wear metals by the lube oil analysis, the most relevant to the combustion gas flow path are those related to cylinder, piston, and piston ring wear: Al, Cr, Fe, and Mo. Signs of engine wear in the crankcase are elevated levels of Pb, Sn, and Ni. The Al and Cr wear metals were at 1 ppm or less for each of four engine oil samples over a period of 1 year. The Fe and Mo levels were at approximately 10 ppm or less. Pb and Sn were at 7 ppm or less, and Ni was not detected. These examples are indicative of desirable results. Each set of lubricating oil analyses is given one of three color-coded conclusions:

- Green: No Action Required
- Yellow: Monitor
- Red: Action Required

According to a member of the Gregory Fluid Analysis Laboratory, these color-coded conclusions are based on trends among wear metals over previous samples. There are not any specific criteria that determine the conclusions; the conclusions are instead based on the discretion of the laboratory analyst. In general, there are ranges in metal concentrations that the laboratory analyst looks for to determine whether engine wear may be present. However, these concentration ranges are proprietary and not available to the public.

For the prime mover engine, if a fluid analysis recommends action (coded red), a second sample of the engine oil is sent 90 days later for analysis to determine whether the engine oil needs to be replaced, or whether the first test result might have been a false-positive. If the retest is also coded red by the laboratory, then all of the lubricating oil in the prime mover engine is drained and replaced.

For the HEP engine, all lubricating oil is drained during the 180-day inspection of each locomotive, after an oil sample has been taken and sent for analysis.

4.2.3 Fuel Price Analysis

In order to determine the difference in fuel costs for operating the NCDOT fleet on various blends of biodiesel compared with ULSD, the fuel receipts for all ULSD and biodiesel deliveries were collected and analyzed.

Currently, three locomotives in the NCDOT fleet operate on biodiesel. From September 2012 to date, NC 1810 has been fueled with five biodiesel fuel blends: (1) 90 percent diesel and 10 percent soy-based biodiesel; (2) 80 percent diesel and 20 percent soy-based biodiesel; (3) 60 percent diesel and 40 percent soy-based biodiesel; (4) 40 percent diesel and 60 percent soy-based biodiesel; and (5) 20 percent diesel and 80 percent soy-based biodiesel. NC 1893 has been operating on a blend of 90 percent diesel and 10 percent soy-based biodiesel since July 2013. NC 1859 operated on a blend of 60 percent diesel and 40 percent soy-based biodiesel from September through early November 2013 and has been operating on a blend of 80 percent diesel and 20 percent soy-based biodiesel since. In the upcoming months, one additional locomotive in the NCDOT fleet will operate on biodiesel as part of this research project.

4.2.4 Rail Yard and Over-the-Road Measurement of Locomotive Fuel Use and Emission Rates

NCSU, working with NCODT, prepared the locomotive engines for field data collection. Rail yard measurements of the fuel use and emissions of the prime mover and HEP engines for each of the three locomotives for the selected fuels, including ULSD, were recorded using portable measurement systems. NCDOT developed a detailed schedule for conducting measurements of the three locomotives on ULSD, B10, and B20. As long as no problems were encountered with B20, the research plan allowed for additional tests using B40. NCDOT developed a staggered schedule in which the first locomotive was fueled with ULSD for a period for baseline rail yard and over-the-road measurements, with some allowance for the need to retest if the data collected were not consistent. Subsequently, the same locomotive was cycled through B10 and B20 approximately every 2 months, to be followed by a cycle on B40 if no problems were observed with B20. During each locomotive-fuel measurement cycle, NCSU conducted rail yard and over-the- road measurements of emissions, and NCDOT collected data on lubricating oil composition and engine cylinder wear. Thus, each locomotive was scheduled to undergo an 8-month test cycle. The emissions tests were conducted using a Portable Emissions Measurement System (PEMS).

The PEMS used in this project was the OEM-2100 Montana system manufactured by Clean Air Technologies International, Inc. The Montana system is comprised of two parallel five-gas analyzers, a particulate matter (PM) measurement system, an engine sensor array, a global position system (GPS), and an onboard computer. The two parallel gas analyzers simultaneously measure the volume percentage of CO, CO_2, HC, NO, and O_2 in the vehicle exhaust. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. A temporarily mounted sensor array is used to measure Manifold Absolute Pressure (MAP), intake air temperature (IAT), and engine RPM in order to estimate air and fuel use. The onboard computer synchronizes the incoming emissions, engine, and GPS data. A GPS system measures vehicle position. For measurements conducted at the NCDOT rail yard at Capital Blvd in Raleigh, NC, GPS position is not needed; thus, a GPS unit is not used in these tests, but is used for over-the-road tests.

The gases and pollutants measured include O_2, HC, CO, CO_2, NO, and PM using the following detection methods:

- HC, CO, and CO_2 using nondispersive infrared (NDIR). The accuracy for CO and CO_2 are excellent. The accuracy of the HC measurement depends on type of fuel used.
- NO measured using electrochemical cell. On most vehicles with Tier 2 or older engines, NO_x is comprised of approximately 95 volume percent NO.
- PM is measured using light scattering, with measurement ranging from ambient levels to low double digits opacity.

The performance of the Montana system has been independently verified in comparison with that of a laboratory grade chassis dynamometer measurement system by Battelle (2003) as part of the U.S. EPA Environmental Technology Verification (ETV) program.

The PEMS is calibrated in the laboratory using a cylinder gas and in the field periodically recalibrated to ambient air to prevent instrument drift. To address the bias in the HC emissions measurement, NCSU plans to do supplemental rail yard measurements with a Fisher Scientific TVA-1000B, which measures total hydrocarbons (THC) and employs a unique simultaneous flame ionization detection (FID) and photoionization detection (PID) system. FID is the most accurate way to determine total hydrocarbons because it involves combusting the exhaust sample with a non-carbon fuel (hydrogen) and measuring the resulting increase in ionized carbon in the exhaust. NCSU strategy is to use the supplemental FID for stationary use in a rail yard setting to assess engine specific "correction factors" for HC by comparing FID and PID with NDIR, PID, and FTIR results under various engine loads. This approach generated data for the ratio of measurable HCs to THCs using the aforementioned methods from FID to establish a bias correction for use of non-FID methods. FID is not proposed for use onboard the train because hydrogen is needed for the flame ionization detection, and that is a safety hazard.

NCSU has conducted numerous comparisons of the emission factors provided by the PEMS with other data for similar engines. In this work, NCSU's primary goal was to compare relative differences in emission rates for one fuel versus another for the same engine. NCSU obtained consistent results when comparing relative differences in emission rates for B20 versus petroleum diesel in many studies using on-road vehicles [11]. The relative differences in emission rates for HC, CO, PM, and NO obtained from PEMS data are quite reasonable when compared with independent studies done using engine dynamometer data.

The Montana System is designed to measure emissions during the actual use of the vehicle or equipment in its regular daily operation. The complete system comes in two weatherproof plastic cases, one of which contains the monitoring system itself, while the other holds sample inlet and exhaust lines, tie-down straps, AC adapter, power and data cables, various electronic engine sensor connectors, and other parts. The system typically runs off the 12V DC vehicle electrical system, using a cigarette lighter outlet or other power source. The power consumption is 5-8 Amps at 13.8 V DC. In rail yard tests, the Montana system is connected to a shore-based power supply using a power converter.

In order to measure MAP, a pressure sensor is installed on the engine. The sensor is attached to the engine via a port that allows the pressure of the air entering the engine to be measured. This port can be found on most heavy duty diesel engines after the turbocharger. However, the test locomotive engines do not have such a port that could be used to measure the MAP. Thus, in recent previous work, ports were created by a locomotive mechanic for each tested engine. An NCDOT mechanic drilled a hole and welded a fitting for the port in the intake air manifold for both the main engines. However, for the HEP engine, a new intake air pipe was fabricated with a port and replaced the existing pipe downstream of the turbocharger. As an example, Figure 26 depicts the location of a fabricated port on the intake air manifold of one of the test engines. A barb fitting is screwed into the port. Plastic tubing is used to connect the MAP sensor to the barb fitting. The MAP sensor is attached to a convenient location in the engine compartment, away from a hot surface of the engine. The MAP sensor provides manifold air pressure data for the computer of the main unit of the Montana system through a cable that connects the sensor to the back of the main unit.

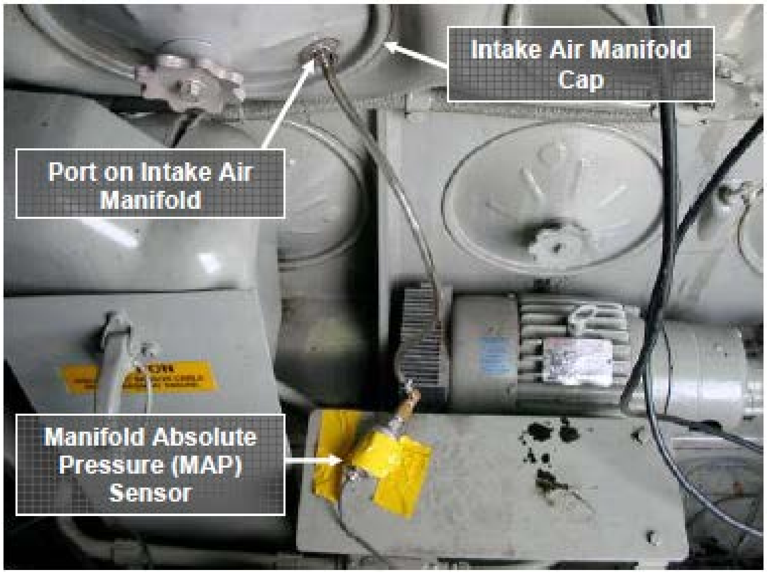


Figure 26. Example of Placement of the Manifold Absolute Pressure Sensor on the Test Engine

The engine speed sensor is an optical sensor used in combination with reflective tape to measure the time interval of revolutions of a pulley or wheel that rotates at the same speed as the engine crankshaft. The engine speed sensor has a strong magnet to attach easily to metal materials. The reflective tape must be installed on a surface that rotates at the same rate as the crankshaft. Figure 27 shows the placement of the reflective tape and the optical sensor for the test engine. Some of the key factors in placement of the sensor include: (1) avoid proximity to the engine cooling fan and other moving components; (2) place the sensor in a location where the magnet can securely affix the sensor to a surface; and (3) place the sensor so that its cable can reach the sensor array box, which is also located in the engine compartment. The signal from the RPM sensor is transmitted by cable to a sensor array box, which in turn transmits the signal by a second cable to the main unit of the Montana system.

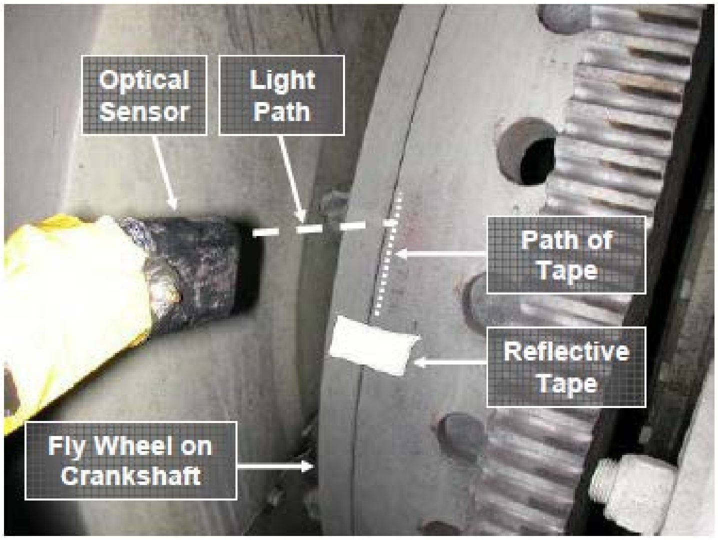


Figure 27. Example of Placement of Optical Engine RPM Sensor and Reflective Tape on the Test Engine

The engine intake air sensor was installed in the intake air flow path. The sensor has a metal part that can detect temperature. With duct tape or a plastic tie, the intake air temperature sensor was fixed near the intake air flow where the MAP port is located.

The PEMS used a two-point calibration system that includes "zero" calibration and "span" calibration. Zero calibration is performed using ambient air at frequent intervals (every 5-15 minutes at power up, every 30 minutes once fully warmed up). Although zero-air stored in bottles or generated using an external zero-air generator can be used, it is believed that the ambient air pollutant levels are negligible compared with those found in undiluted exhaust. Therefore, ambient air is viewed as sufficient for most conditions. For zero calibration purposes, it is assumed that ambient air contains 20.9 *vol*-% oxygen, and no NO, HC, or CO. CO_2 levels in ambient air are approximately 300–400 ppm, which are negligible compared with the typical levels of CO_2 in exhaust gases. Span calibration is performed using a BAR-90 low concentration calibration gas mixture, which has a known gas composition. The calibration gas includes a mixture of known concentrations of CO_2, CO, NO, and hydrocarbons, with the balance being N_2. Span gas calibration in analyzers is very stable and tends not to drift significantly from their span calibrations. Data from several laboratories using various vehicles and fuels suggests that when the Montana System is operated simultaneously with the laboratory system, the difference is typically less than 10 percent for aggregate mass NO_x and CO_2. The accuracy of HC and CO measurements depends on the fuel used and on the emission levels [12].

The tests of the prime mover engines follow a prescribed sequence and timing of throttle notch settings, including idle and notches one through eight, as shown in Table 17, with sufficient time to enable steady state operation of the engine while avoiding overheating, particularly at notch settings six through eight.

Table 17. Rail Yard Test Schedule for Prime Mover Enginer

Notch Position	Time (min)
Idle for Warm-Up	45
Notch 8	3
Idle for Cooling	5
Notch 7	3
Idle for Cooling	5
Notch 6	3
Idle for Cooling	5
Notch 5	3
Notch 4	3
Notch 3	3
Notch 2	3
Notch 1	3
Idle	3

For the HEP engines, the duty cycle will include varying the electrical load by running the tests at idle and with one to five passenger cars, as shown in Table 18, with the air conditioning unit operational. A qualified mechanic provided by NCDOT operated the engines and measured the electrical load during the tests.

Table 18. Rail Yard Test for Head End Power Engine

Electrical Loads	Time (min)
Idle for Warm-Up	45
No	3
Low	3
Medium	3
High	3

Fuel Use and Emissions

Fuel-based emission rates, in g/gal, are estimated based on exhaust gas and fuel compositions. Fuel-based emission rates are estimated independently of data for fuel flow and are subsequently multiplied by fuel flow rate per unit engine output, in gal/bhp-hr, to estimate mass per unit engine output emission rates, in g/bhp-hr. However, there is no feasible way to accurately measure fuel usage during rail yard and over-the-road measurements since fuel is taken from an onboard tank and locomotive engines continuously return unspent fuel to the tank. For ULSD, fuel flow rate is estimated based on the following factors: (a) engine RPM, displacement, compression ratio, and airbox pressure; (b volumetric efficiency; and (c) exhaust gas composition. The first two sets of factors are used to estimate the mass air flow (m_{air}) into the engine based on the ideal gas law, adjusted using volumetric efficiency to account for the difference in actual mass air flow observed during dynamometer measurements of the same model of engine compared with the estimate from the ideal gas law. The exhaust gas composition is used to infer the air-to-fuel ratio (AFR). With estimates of both m_{air} and AFR, the fuel flow and exhaust flow rates can be estimated. The gram per gallon emission rates inferred for each pollutant are multiplied by the fuel flow rate to obtain mass per time emission rates. The mass per time emission rate is divided by the engine horsepower output to obtain mass per bhp-hr emission rates. These estimates are made separately for each throttle notch position.

For the biofuels, fuel mass flow rate is estimated based on: (a) the mass flow of fuel for ULSD; (b) the heating value of ULSD; and (c) the heating value of the biofuel. The biofuels typically have slightly less energy density than ULSD. Therefore, it takes slightly more volume or mass of fuel to provide the same energy input to the engine than it would with ULSD. These estimates are made for each notch position.

For PM, the PEMS reports a mg/m^3 concentration on a dry basis. The dry exhaust flow per gallon of fuel consumed is estimated by inferring the AFR from the exhaust composition based on the volume percent of carbon in the exhaust. The volume of exhaust produced per gallon of fuel is multiplied by the mass per volume concentration of PM to estimate the g/gal PM emission rate. The latter is multiplied by fuel flow per unit engine output to estimate the engine output-based PM emission rate, in g/bhp-hr.

Because biofuels can be subject to ‘clouding’ problems during cold weather, NCDOT halted the use of biodiesel during the winter months of December through February. Therefore, there was a hiatus in data collection during those months, and evaluation of data already collected for engine wear and emissions was conducted.

The NCSU study is ongoing because of delays encountered during the test program. The PEMS had to be repaired because of repeated exposure to the high particle loading from the locomotive engines. Track work on the test route caused delays in collection of data during the over-the-road segment of the test program. Additionally, there were failures of the locomotive’s mechanical or electrical components and damage to the test locomotive from accidents. The fuel tank of NC 1810 was punctured as a result of debris on the track—NC 1810 is out of service until the tank can be repaired. Therefore, this report will provide partial results from the test engines, engine NC1810 and NC1893.

4.3 Research Results

4.3.1 Fuel Characterization

Fuel properties of the ULSD and biodiesel were measured by SwRI according to ASTM standard protocols. To date, six fuel samples were measured: ULSD obtained on July 6, September 3, and October 22, 2013; B10 biodiesel obtained on September 10, 2013; B40 biodiesel obtained on

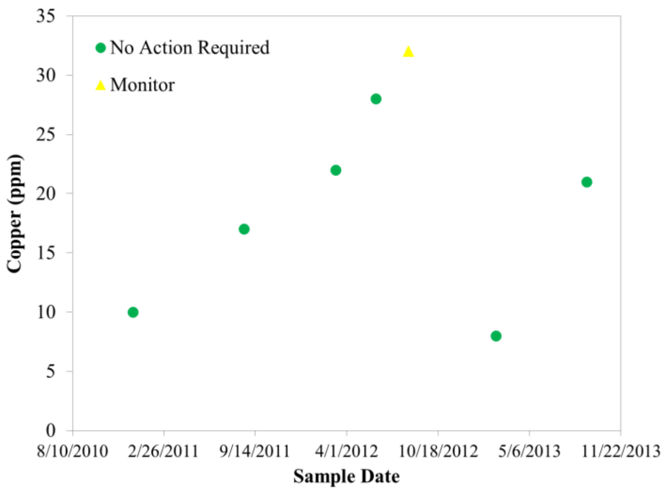
October 21, 2013; and B60 biodiesel obtained on August 12, 2013. For ULSD, the measured gross heating value and net heating value are within 1.6 percent of the literature values. The wt-% C is within 0.3 percent (relative basis), wt-% H is within 0.2 percent, and specific gravity is within 1.0 percent for measured average versus literature values. For B10 biodiesel, the gross heating value and net heating value are within 1.7 percent for measured versus literature values. The wt-% C is within 0.3 percent (relative basis), wt-% H is within 3.0 percent, and specific gravity is within 1.3 percent for measured versus literature values. For B40 biodiesel, the gross heating value and net heating value are within 0.6 percent for measured versus literature values. The wt-% C is within 0.3 percent (relative basis), wt-% H is within 0.5 percent, and specific gravity is within 0.2 percent for measured versus literature values. For B60 biodiesel, the gross heating value and net heating value are within 0.6 percent for measured versus literature values. The wt-% C is within 0.4 percent (relative basis), wt-% H is within 0.5 percent, and specific gravity is within 0.1 percent for measured versus literature values. Appendix A contains the results for the fuel analyses.

Table 19. Literature Fuel Properties for Ultra Low Sulfur Diesel, B10, B20, B40, B60, B80, and B100 Biodiesel Fuels

Properties	Unit	ULSD	B10	B20	B40	B60	B80	B100
Gross Heat	BTU/lb	19386	19188	18989	18593	18196	17800	17403
Gross Heat	MJ/Kg	45.092	44.630	44.169	43.247	42.324	41.402	40.479
Gross Heat	Cal/g	10777	10667	10557	10336	10116	9895	9675
Net Heat	BTU/lb	18176	17977	17778	17381	16983	16585	16188
Net Heat	Mj/Kg	42.278	41.815	41.353	40.428	39.503	38.578	37.653
Net Heat	Cal/g	10105	9994	9883	9662	9441	9220	8999
Cloud Point	°C	-35 to 5	-31.8 to 6	-28.6 to 7	-22.2 to 9	-15.8 to 11	-9.4 to 13	-3 to 15
Sulfur	ppm	≤ 15	≤ 15.9	≤ 16.8	≤ 18.6	≤ 20.4	≤ 22.2	≤ 24
Specific Gravity		0.850	0.853	0.856	0.862	0.868	0.874	0.880
Density @15°C	g/ml	0.8501	0.8525	0.8549	0.8596	0.8644	0.8692	0.8740
Carbon	wt%	87.00	86.00	85.00	83.00	81.00	79.00	77.00
Hydrogen	wt%	13.00	12.90	12.80	12.60	12.40	12.20	12.00
Oxygen	wt%	0.0	1.10	2.20	4.40	6.60	8.80	11.00
Cetane	No.	40 to 55	40.8 to 56	41.6 to 57	43.2 to 59	44.8 to 61	46.4 to 63	48 to 65
Flash Point	°C	60 to 80	64 to 89	68 to 98	76 to 116	84 to 134	92 to 152	100 to 170
Biodiesel	vol%	0.0	10.0	20.0	40.0	60.0	80.0	100.0
Viscosity	cSt	1.30 to	1.57 to	1.84 to	2.38 to	2.92 to 5.24	3.46 to 5.62	4.00 to 6.00
Initial Boiling Point	°F	180 to 340	194 to 341	207 to 342	234 to 344	261 to 346	288 to 348	315 to 350

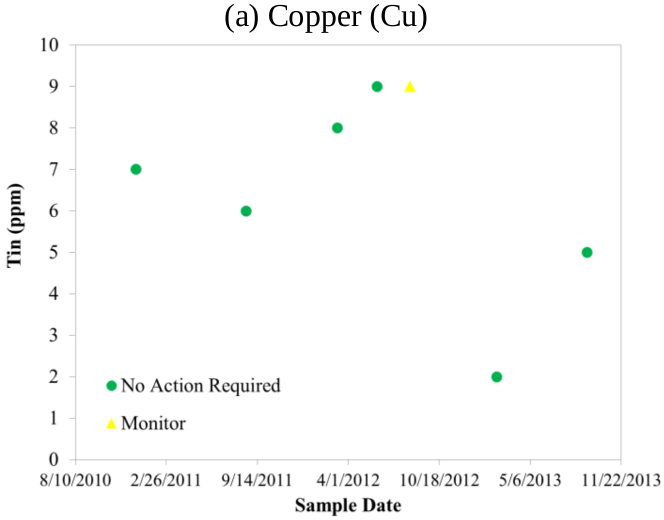
4.3.2 Fuel and Lubricating Oil Analyses

Lubricating oil analyses conducted by the Gregory Poole Fluid Analysis Laboratory were obtained from Herzog for all six locomotives in the NCDOT fleet from as far back as July 2010 to the most recent of November 2013. In total, 51 fluid analyses test results were gathered from the prime mover engines in the locomotive fleet, and 51 fluid analyses test results were gathered from the HEP engines in the locomotive fleet. It is apparent that, over time, most of the locomotives in the NCDOT fleet have had oil analyses come back with recommendations from the laboratory to monitor (yellow) or take action on (red) the lubricating oil. Based on the comments given on the oil analysis reports, the four wear metals that lead to results being coded yellow or red are Cu, Fe, Sn, and Pb. In order to assess the trends of these four wear metals over time for each engine, reported concentrations were graphed. See Figures 28 and 29 for analysis results of NC1810. Figure 28 shows the wear metal concentration for the prime mover engine, and Figure 29 shows the wear metal concentration for the HEP engine.

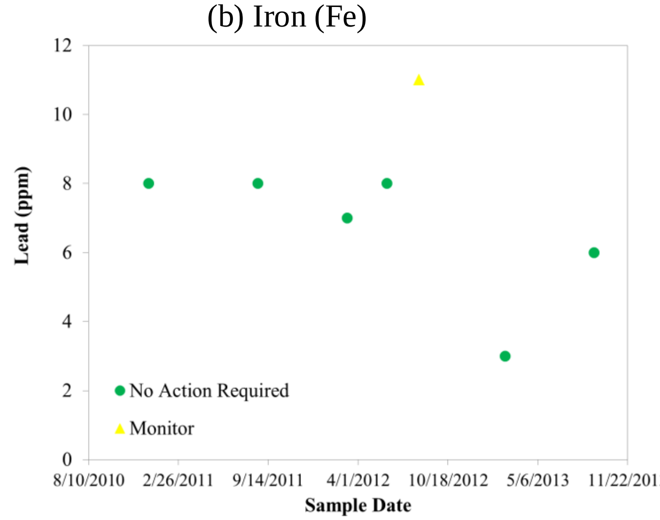


(a) Copper (Cu)

(b) Iron (Fe)

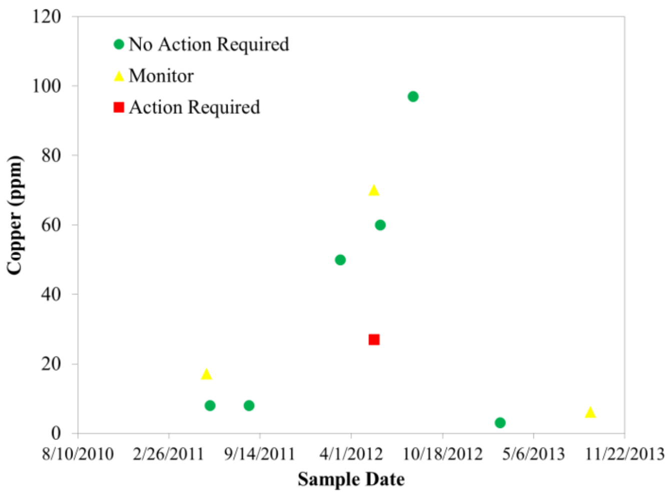


(c) Tin (Sn)

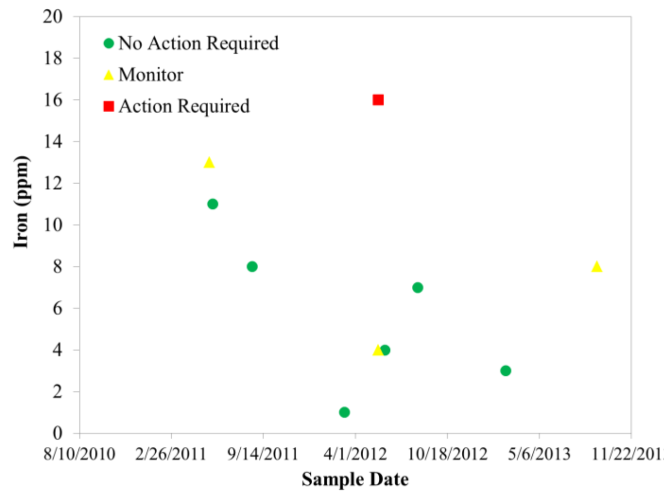


(d) Lead (Pb)

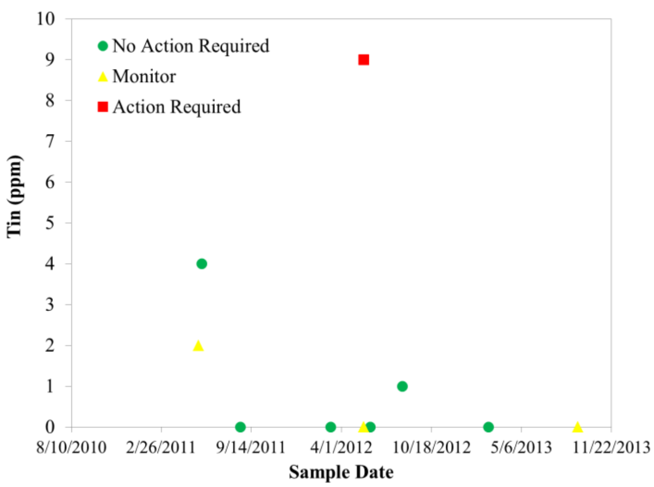
Figure 28. Wear Metal Concentrations in Oil Samples from NC 1810 Prime Mover Engine



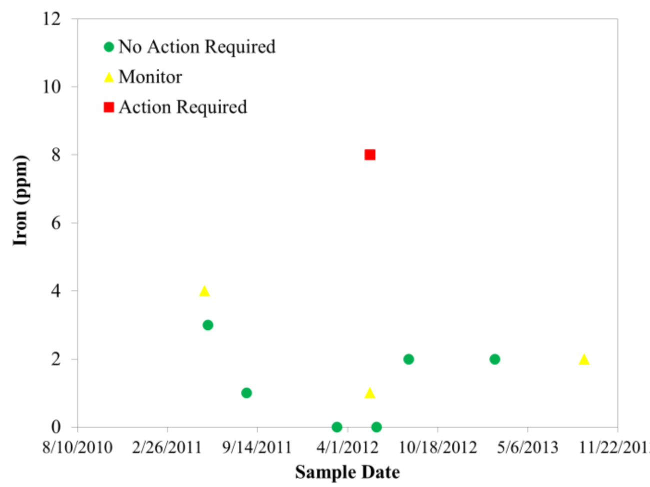
(a) Copper (Cu)



(b) Iron (Fe)



(c) Tin (Sn)



(d) Lead (Pb)

Figure 29. Wear Metal Concentrations in Oil Samples from NC 1810 Head End Power Engine

For the NC 1810 prime mover engine, the wear metal concentrations of Cu, Fe, Sn, and Pb were all increasing prior to the introduction of B10 biodiesel in September 2012, as shown in Figure 28. The most recent lube oil analyses for the NC 1810 prime mover, in February and September 2013 while the locomotive was operating on B20 and B60 biodiesel, respectively, indicated that no action was required. Tables 20 and 21 contain the results of the prime mover and HEP engine tests. The lubricating oil analyses give no indication that biodiesel use has affected the wearing and operation of the NC 1810 prime mover engine.

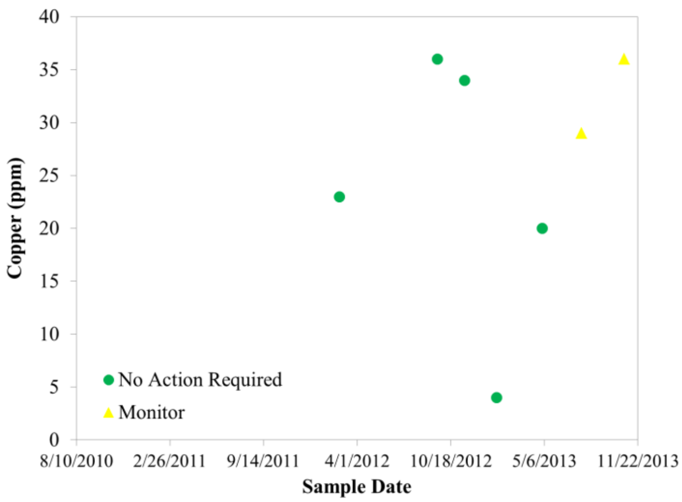
Table 20. Summary of Lubricating Oil and Engine Wear Analysis Summary for NC1810 Prime Mover Engine

Date	Summary	Fuel
12/21/201	No Action Required	ULSD
8/21/2011	No Action Required	ULSD
3/8/2012	No Action Required	ULSD
6/4/2012	No Action Required	ULSD
8/15/2012	Monitor: Iron and lead continue to increase and may indicate some crank and bearing wear.	B10
2/22/2013	No Action Required	B20
9/8/2013	No Action Required	B60

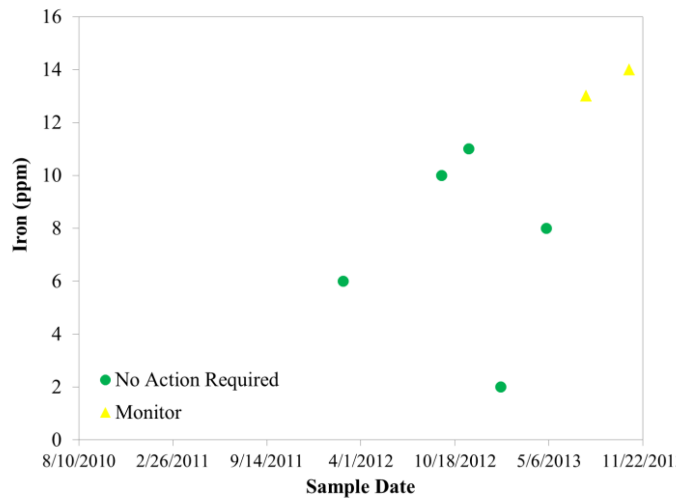
Table 21. Summary of Lubricating Oil and Engine Wear Analysis Summary for NC1810 HEP Engine

Date	Summary	Fuel
5/20/2011	Monitor: Silicon is higher than normal and may indicate some dirt entry; copper is high, and lead is elevated.	ULSD
5/27/2011	No Action Required	ULSD
8/21/2011	No Action Required	ULSD
3/8/2012	No Action Required	ULSD
5/21/2012	Monitor: Copper has increased and may indicate some bearing wear.	ULSD
5/21/2012	Action Required: Iron, tin, and lead have increased and may indicate some crank and bearing wear.	ULSD
6/4/2012	No Action Required	ULSD
8/15/2012	No Action Required	B10
2/22/2013	No Action Required	B20
9/8/2013	Monitor: Lead is elevated and may indicate possible bearing wear.	B60

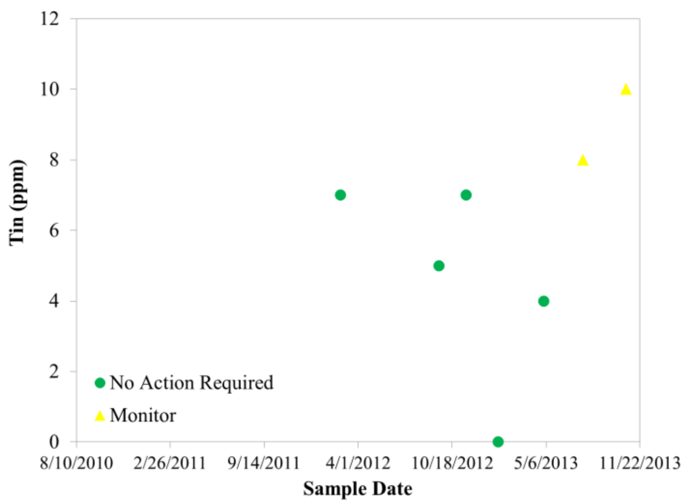
Figure 30 depicts the wear metal concentration in the oil sample drawn for the engine lubricating oil analysis of engine NC1893 prime mover engine, while Figure 31 depicts the wear metal concentration of the oil drawn from the HEP engine.



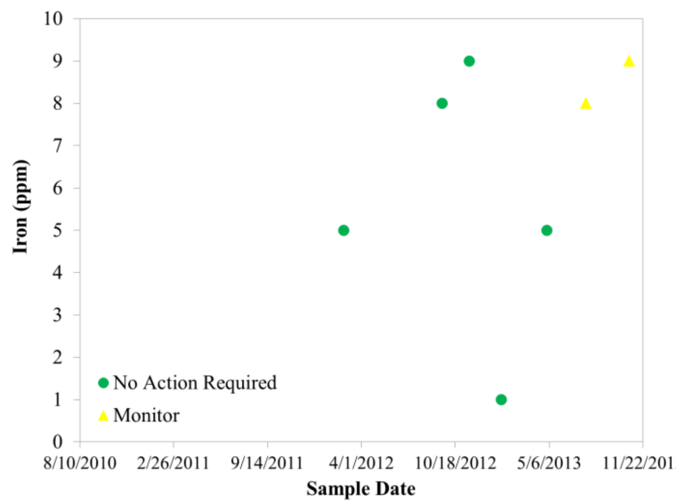
(a) Copper (Cu)



(b) Iron (Fe)

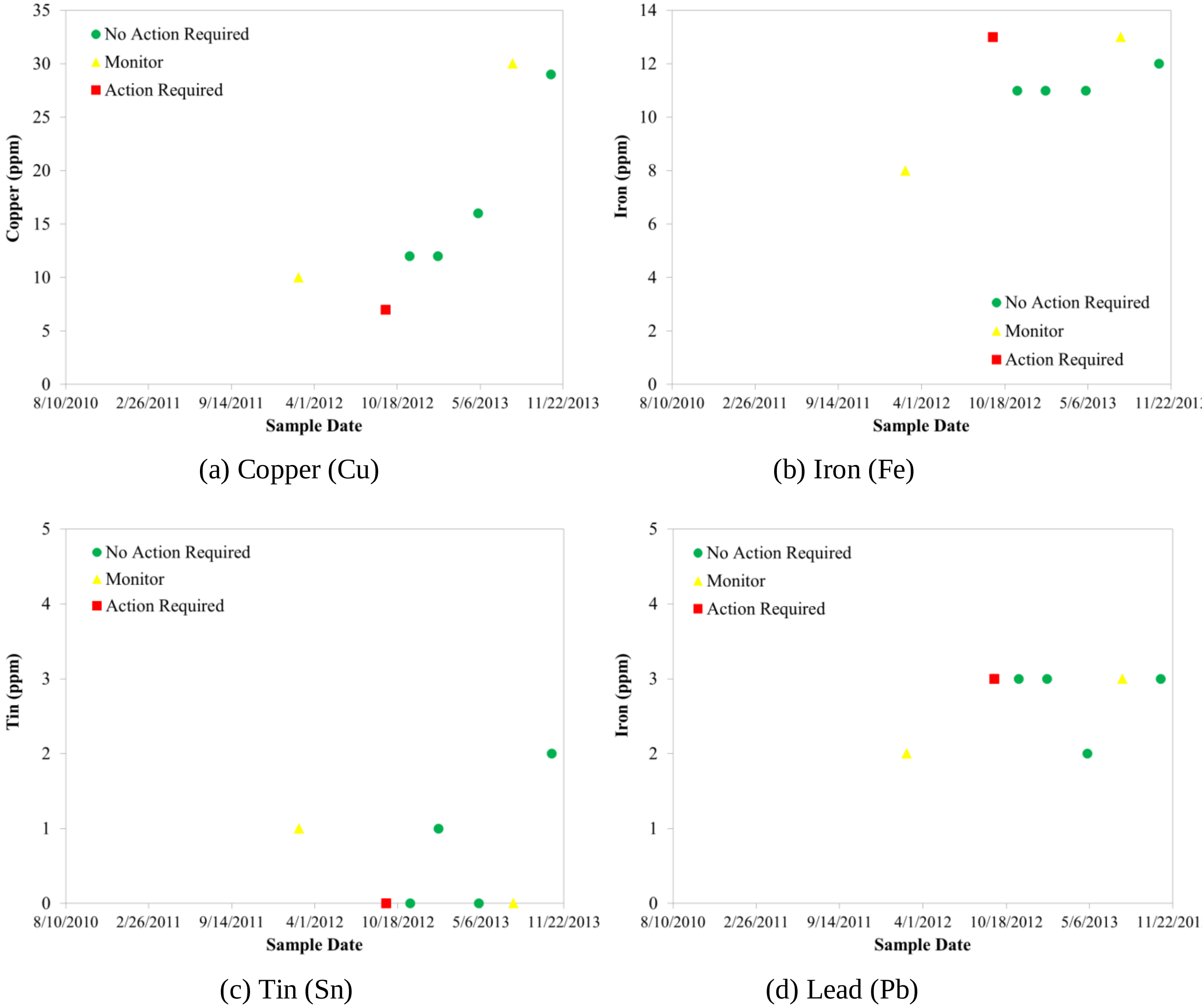


(c) Tin (Sn)



(d) Lead (Pb)

Figure 30. Wear Metal Concentrations in Oil Samples from NC 1893 Prime Mover Engine



(a) Copper (Cu)

(b) Iron (Fe)

(c) Tin (Sn)

(d) Lead (Pb)

Figure 31. Wear Metal Concentrations in Oil Samples from NC 1893 Head End Power Engine

Although Cu, Pb, and Sn concentrations increased in earlier lube oil analyses of the NC 1893 prime mover engine, the researchers do not believe that the use of B10 biodiesel caused the increased wear metal concentrations. The most recent lube oil analyses for the prime mover and HEP engines for NC 1893 came back as “No Action Required.” Tables 22 and 23 show the analysis results for the prime mover and HEP engines for NC1893.

Table 22. Lubrication Oil and Engine Wear Analyses Summary for NC1893 Prime Mover Engine

Date	Summary	Fuel
2/23/2012	No Action Required	ULSD
9/20/2012	No Action Required	ULSD
11/17/201	No Action Required	ULSD
1/24/2013	No Action Required	ULSD
5/1/2013	No Action Required	ULSD
7/24/2013	Monitor: Copper, lead, and tin are elevated. Possible bearing wear.	B10
10/24/201	Monitor: Copper, lead, and tin are elevated. Possible bearing wear.	B10

Table 23. Lubrication Oil and Engine Wear Analyses Summary for NC1893 HEP Engine

Date	Summary	Fuel
2/23/2012	Monitor: Copper and silicon are higher than normal; viscosity is a 30 weight; silicon may be residue from a recent repair, or could indicate some dirt entry.	ULSD
9/20/2012	Action Required: viscosity is a 20 weight.	ULSD
11/17/201	No Action Required	ULSD
1/24/2013	No Action Required	ULSD
5/1/2013	No Action Required	ULSD
7/24/2013	Monitor: Fuel dilution is high. Copper has increased. Possible bearing wear.	B10
10/24/201	No Action Required	B10

The oil analyses that return coded yellow or red indicate an increasing trend in the concentration of one or more of the wear metals.

Engine lubricating oil analyses conducted by the Gregory Poole Fluid Analysis Laboratory for locomotives in the NCDOT fleet were collected from Herzog Transit Services NC. Based on the current lube oil analyses, the use of biodiesel by the prime mover and HEP engines does not appear to have an adverse effect on engine wear for NC 1810 and NC 1893. Engine lubricating oil analyses will continue to be collected and evaluated for all locomotives in the NCDOT fleet. Special attention will be paid to the four locomotives that will operate on various biodiesel blends during the coming months.

4.3.3 Fuel Price Analysis Results

The fuel cost data to date were obtained from RailPlan International. It is important to note that B20 biodiesel is obtained through a North Carolina state procurement contract, while the other biodiesel blends are purchased without any discount.

Fuel prices for ULSD and each biodiesel blend used were obtained from RailPlan for the three locomotives in the NCDOT fleet fueled on biofuels from the beginning of the research project. Figure 1 depicts the price of ULSD per gallon from the start of the research project to now. Figure 2 depicts the difference in price between five different biodiesel blends (B10, B20, B40, B60, and B80) and ULSD. In some instances, the cost of B10, B20, B60, and B80 biodiesel is less per gallon than the cost of ULSD. On average, the cost of a gallon of ULSD in 2012 and 2013 was $3.13. The average cost of B20 biodiesel was 10 cents more per gallon than the average cost for ULSD. The average cost of B80 biodiesel was 6 cents less per gallon than the average cost for ULSD. Assuming that a locomotive consumes 200 gallons of fuel during a one-way trip between Raleigh and Charlotte, the use of B20 biodiesel would cost an additional $20.00 one-way, while the use of B80 biodiesel could save $12.00 one-way.

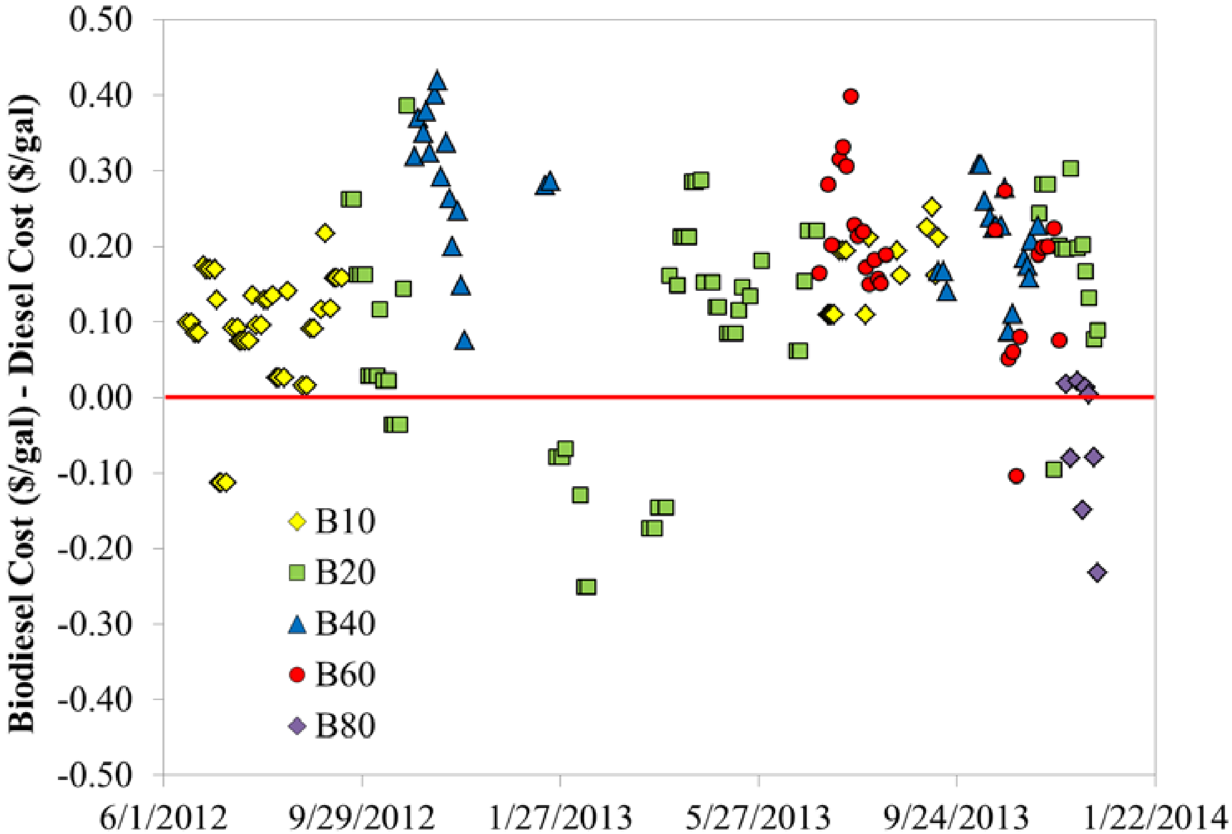


Figure 32. Difference in Ultra Low Sulfur Diesel and Biodiesel Prices for June 2012 through December 2013

4.3.4 Rail Yard and Over-the-Road Testing

4.3.4.1 Locomotive NC1810

Preliminary rail yard and over-the-road measurements were conducted on the prime mover engine of locomotive NC 1810 (City of Greensboro) with different fuel blends using a PEMS. The prime mover engine is an EMD 12-710G3B. The engine was originally manufactured in 1988 and was rebuilt by American Motive Power, Inc. (AMP) in 2010. The 140-Liter engine has a peak engine output of 3000 horsepower at an engine speed of 900 RPMs. The prime mover engine operated on four different fuel blends of petroleum diesel and soy-based biodiesel, as shown in Table 24.

Table 24. Fuel Characteristics and Dates Measured on NC 1810 Prime Mover Engine

Fuel Name	Percent Diesel	Percent Biodiesel	Fuel Supplier	Dates of Measurements	
				Rail Yard	Over-the-Road
ULSD	100	0	Petroleum Traders Corp.	June 7, 2012	June 6–8, 2012
B10	90	10	Monson Oil Co.	Sept. 14, 2012	Aug. 29–31, 2012
B20	80	20	Monson Oil Co.	Oct. 24, 2012	Oct. 18–20, 2012
B40	60	40	Red Star Oil Co.	Nov. 19, 2012	Nov. 16, 19, 21, 2012

The cycle average emission rates for the rail yard and over-the-road measurements of the NC 1810 prime mover engine are shown in Tables 25 to 27 and 28 to 30, respectively. The cycle average emission rates are based on the line-haul duty cycle used by the U.S. EPA for regulatory purposes. During rail yard measurements, dynamic braking is not observed; thus, the time apportioned for dynamic braking in the line-haul duty cycle (12.5 percent) is combined with the time apportioned for idling in the line-haul duty cycle (38.0 percent). Therefore, idling accounts for 50.5 percent of the duty cycle used to calculate rail yard cycle average emission rates.

Table 25. Preliminary Fuel-Based Cycle Average Emission Rates for the NC 1810 Prime Mover Engine with Four Fuel Blends Measured in the Rail Yard

Fuel	NO_x (g/gal)	HC (g/gal)	CO (g/gal)	Opacity-Based PM (g/gal)
ULSD	237	*n/a*[d]	17	8.1
B10	192	31	15	10.2
B20[c]	*187*	*11*	*13*	*14.3*
B40	256	14	8	11.7

Table 26. Preliminary Time-Based Cycle Average Emission Rates for the NC 1810 Prime Mover Engine with Four Fuel Blends Measured in the Rail Yard

Fuel	NO_x (g/s)	HC (g/s)	CO (g/s)	Opacity-Based PM (g/s)
ULSD	1.7	*n/a*[d]	0.2	0.05
B10	1.4	0.03	0.3	0.07
B20[c]	*1.6*	*0.07*	*0.2*	*0.06*
B40	1.7	0.03	0.1	0.06

Table 27. Preliminary Engine Output-Based Cycle Average Emission Rates for the NC 1810 Prime Mover Engine with Four Fuel Blends Measured in the Rail Yard

Fuel	NO_x (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity-Based PM (g/bhp-hr)
ULSD	8.1	*n/a*[d]	1.1	0.26
B10	7.0	0.17	1.3	0.33
B20[c]	*7.7*	*0.34*	*0.7*	*0.28*
B40	8.5	0.15	0.6	0.30

The cycle average emission rates are based on the U.S. EPA line-haul duty cycle used for regulatory purposes. NO_x, HC, and opacity-based PM emission rates are adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction. However, the CO_2 concentrations in the exhaust during the B20 rail yard measurement appeared to be unusually low, and thus, this test was repeated. Similarly, the HC concentrations measured during the ULSD rail yard test were erratic, unusually high, and differed substantially between the two gas analyzers. Therefore, the result was not valid and the test is scheduled to be repeated.

Table 28. Preliminary Fuel-Based Cycle Average Emission Rates for the NC 1810 Prime Mover Engine with Four Fuel Blends Measured Over-the-Road

Fuel	NO_x (g/gal)	HC (g/gal)	CO (g/gal)	Opacity-Based PM (g/gal)
ULSD	233	*n/a*	17	6.9
B10	188	68	16	12.4
B20	190	52	16	10.1
B40	227	20	22	10.0

Table 29. Preliminary Time-Based Cycle Average Emission Rates for the NC 1810 Prime Mover Engine with Four Fuel Blends Measured Over-the-Road

Fuel	NO_x (g/s)	HC (g/s)	CO (g/s)	Opacity-Based PM (g/s)
ULSD	1.7	*n/a*[d]	0.2	0.06
B10	1.4	0.19	0.3	0.12
B20	1.6	0.14	0.3	0.07
B40	1.8	0.04	0.3	0.08

Table 30. Preliminary Engine Output-Based Cycle Average Emission Rates for the NC 1810 Prime Mover Engine with Four Fuel Blends Measured Over-the-Road a,b

Fuel	NO_x (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity-Based PM (g/bhp-hr)
ULSD	7.8	*n/a*[d]	0.8	0.28
B10	6.4	0.85	1.5	0.53
B20	7.2	0.64	1.3	0.33
B40	8.0	0.20	1.2	0.37

As with the rail yard testing, the over-the-road testing cycle average emission rates are based on the U.S. EPA line-haul duty cycle used for regulatory purposes. NO_x, HC, and opacity-based PM emission rates were adjusted with multipliers of 1.053, 2.5, and 5, respectively, as bias correction. Dynamic braking was not observed during ULSD over-the-road measurements. Therefore, the researchers determined that idling accounts for 50.5 percent of the duty cycle used to calculate rail yard cycle average emission rates. HC concentration measured during the ULSD over-the-road measurement is based on the average HC concentration for two gas analyzers. The difference in concentrations reported by the two analyzers at a given notch was higher than expected. Therefore, these results may not be reliable; thus, the test is scheduled to be repeated.

For the rail yard tests, the lowest fuel-based NO_x emission rates were observed for B10 and B20, as were the lowest g/bhp-hr cycle average emission rates. The HC emission rates were generally low among all biofuel tests, with many of the notch average exhaust concentrations below the detection limit of the gas analyzer. Thus, the apparent differences in HC emission rates among the cycle average results are not likely to be significant. Likewise, the CO emission rates were also generally low among the four fuels and appeared to decrease with increasing biodiesel blend. The PM emission rates were approximately similar among the four fuels on a mass per engine energy output basis.

There is not a clear trend regarding which fuel leads to the lowest emission rate. The lowest cycle average emission rate for NO_x is associated with B10, whereas the lowest rates for HC, CO, and PM are associated with B40, B40, and ULSD, respectively. As noted from the review of existing literature, there appears to be less consistency in the trend of emission rates versus fuel blend for large two-stroke diesel engines than for the smaller four stroke engines for highway vehicles that have been the subject of more research and data collection.

There were some challenges during data collection that somewhat confound these results and the comparisons among them; therefore, these data are considered to be preliminary and should not be used to draw conclusions regarding the efficacy of biodiesel in changing engine emission rates. For example, there was inconsistency in the volume percent CO_2 measurements between the two parallel gas analyzers in the PEMS for the ULSD case. Although the volume percent of CO_2 reported by each analyzer was reasonable, the difference between them was unexpected, which undermines the reliability of the ULSD results. Therefore, this test should be repeated. For the B20 measurements in the rail yard, the volume percent of CO_2 observed was unusually low for some notch positions. The cumulative effect of measuring high dust engine exhaust appears to have led to the failure of one of the two gas analyzers in the PEMS, particularly with respect to measurement of HC, CO, and CO_2 at the time of the B20 and B40 measurements. Furthermore, the difference in HC concentrations for the ULSD measurement, and the erratic variation of concentrations for each analyzer, led to suspicion that the ULSD HC measurements results were not valid. This discovery resulted in the need to ship the gas analyzers to the original manufacturer in Europe to have them serviced. The PM measurements are reasonable in magnitude, but we also intend to have the PM sensor serviced. NCSU recommends that a complete set of tests be conducted again on NC1810 locomotive after the gas analyzers and PM detector have been serviced, to either confirm these results or to replace them with more valid results.

Based on the over-the-road results, the lowest cycle average NO_x emission rate is observed for B10. The lowest cycle average rates for HC, CO, and PM are associated with B40, ULSD, and ULSD, respectively, based on these preliminary results.

Given the preliminary nature of these results, it is premature to reach specific conclusions regarding the effect of each fuel on the cycle average emission rates, as measured with the PEMS. It appears that the cycle average NO_x emission rates may be approximately 15 percent lower for B10, 6 percent lower for B20, and approximately 4 percent higher for B40, than the emission rates for ULSD, based on averages of the rail yard and over-the-road results. However, these findings should be replicated with another round of tests in light of the various data quality problems with the PEMS gas analyzers that will be corrected with maintenance and repair. The HC emissions rates appear to be lower for B40 than for B10 or B20 and appear to decrease monotonically as the biofuel blend increases. The latter trend is reasonable given that increasing biofuel blend simultaneously increases the oxygen content of the fuel, which should help promote more oxidation of the fuel. The time-based CO emission rates, 0.1 to 0.3 g/s, are approximately similar among the fuels and for the rail yard and over-the-road measurements. On a g/bhp-hr basis, the lowest CO emission rates were observed for ULSD and B40. The CO emission rates decreased monotonically with increasing biofuel blend from B10 to B40 for both rail yard and OTR measurements, which is expected given the increasing oxygen content of the higher blends. For the rail yard measurements, the PM emission rates were approximately similar for all four fuels; for the OTR measurements, the PM emission rates were approximately similar for ULSD and B20. Overall, there is some indication that the use of an appropriately selected biofuel blend has the potential to reduce cycle average emission rates particularly for NO_x, HC, and CO. However, to increase confidence in the results, these measurements on NC 1810 were repeated according to a similar set of measurements made on two additional locomotives in the spring and summer of 2013. As previously mentioned, this research is ongoing. A comprehensive report will be published at the end of the research project and will examine the performance of the three engines on various blends of biodiesel.

4.3.4.2 Locomotive NC1893

Following the inconsistencies in the data collected from the first round of testing of locomotive NC1810, NCSU implemented a test plan that gathered triplicate data using two different PEMSs. This report discusses the findings from the testing of locomotive NC1893 on ULSD using the new test method. Locomotive NC1893 prime mover engine is an EMD 12-710G3B. The engine was originally manufactured in 1988 and was rebuilt by AMTRAK in 2012. The 140-Liter engine has a peak engine output of 3000 horsepower at an engine speed of 900 RPMs. The prime mover engine was operated on ULSD.

The PEMS utilized for measurements were the Montana system manufactured by Clean Air Technologies International, Inc. (CATI) and the SEMTECH-DS system manufactured by Sensors, Inc. The new PEMS is comprised of a heated flame ionization detector (FID) for total hydrocarbon measurement, a non-dispersive ultraviolet (NDUV) analyzer for nitric oxide and nitrogen dioxide measurement, a non-dispersive infrared (NDIR) analyzer for carbon monoxide and carbon dioxide measurement, and an electrochemical sensor for oxygen measurement. Emission concentrations are measured on a second-by-second basis.

Prior to each set of measurements, each PEMS was calibrated with a California Bureau of Automotive Repair (BAR) certified calibration gas (BAR-97 Low). Tables 26 and 27 show the cycle average emission rates for the rail yard measurements of the NC 1893 prime mover engine with the Montana and SEMTECH PEMS. The cycle average emission rates are based on the line-haul duty cycle used by the U.S. EPA for regulatory purposes. Three replicates of each rail yard measurement were conducted. During rail yard measurements, dynamic braking is not observed; thus, the time apportioned for dynamic braking in the line-haul duty cycle (12.5 percent) is combined with the time apportioned for idling in the line-haul duty cycle (38.0 percent). Therefore, idling accounts for 50.5 percent of the duty cycle used to calculate rail yard cycle average emission rates.

On average, the NO and HC cycle average emission rates calculated with the Montana PEMS were 11 percent higher than the cycle average emission rates calculated with the SEMTECH PEMS. The difference between Montana-measured and SEMTECH-measured CO cycle average emission rates was 0.2 g/bhp-hr.

Table 31. Preliminary Cycle Average Emission Rates for the NC 1893 Prime Mover Engine in the Rail Yard Using Montana PEMS Systems

	NOx (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity-Based PM (g/bhp-hr)
Replicate 1	**9.5**	**1.5**	**0.3**	**0.28**
Replicate 2	**10.1**	**1.86**	**0.4**	**0.27**
Replicate 3	**9.8**	**1.86**	**0.4**	**0.29**
Average	**9.8**	**1.74**	**0.4**	**0.28**

Table 32. Preliminary Cycle Average Emission Rates for the NC 1893 Prime Mover Engine in the Rail Yard Using the SEMTECH PEMS System

Fuel	NOx (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity-Based PM (g/bhp-hr)
Replicate 1	**8.6**	**1.13**	**0.6**	**n/a**
Replicate 2	**9.0**	**0.63**	**0.5**	**n/a**
Replicate 3	**8.9**	**0.60**	**0.5**	**n/a**
Average	**8.8**	**0.79**	**0.5**	**n/a**

The prime mover engine of NC 1893 was measured previously in the rail yard in December 2011, June 2012, and April 2013 after engine rebuild. Table 33 provides a comparison of the estimated cycle average emission rates. The June 2013 cycle average NOx, CO, and PM emission rates are of the same magnitude as the previous rail yard measurements. The June 2013 cycle average HC emission rates were up to 2.5 times higher than the April 2013 measurements, depending on the PEMS used for measurements.

Table 33. Cycle Average Emission Rates for Rail Yard Measurement of NC 1893 Prime Mover Engine

	NOx (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity-Based PM (g/bhp-hr)
December 16, 2011	**8.6**	**0.48**	**0.6**	**0.31**
June 25, 2012	**6.7**	**0.09**	**0.8**	**0.15**
April 30, 2013	**7.8**	**0.72**	**0.3**	**0.23**
June 21, 2013 – Montana	**9.8**	**1.74**	**0.4**	**0.28**
June 21, 2013 – SEMTECH	**8.8**	**0.79**	**0.5**	**n/a**
EPA Tier 0+	**8.0**	**1.00**	**5.0**	**0.22**
EPA Tier 1+	**7.4**	**0.55**	**2.2**	**0.22**

Table 33 shows the cycle average emission rates for the over-the-road measurements of the NC 1893 prime mover engine. These cycle average emission rates are based on the measured engine activity data (RPM, MAP, and IAT) and measured exhaust concentrations. There was little variability between measured engine activity data during all 3 days of measurements, which indicates that the prime mover engine was operating consistently during over-the-road measurements. Measured engine activity data during over-the-road measurements were similar to the measured engine activity data during rail yard measurements.

The cycle average over-the-road emission rates are quantitatively similar to the cycle average rail yard emission rates measured in June 2013. The cycle average over-the-road NOx emission rate was 22 to 31 percent lower than the cycle average rail yard NOx emission rates, depending on the PEMS. The cycle average over-the-road PM emission rate was 43 percent lower than the cycle average PM emission rate estimated from rail yard measurements. The cycle average over-the-road HC emission rate was 51 percent lower than the cycle average rail yard HC emission rate estimated with the Montana, but 9 percent higher than the cycle average rail yard HC emission rate estimated with the SEMTECH. The cycle average over-the-road CO emission rate was 50 to 60 percent higher than the cycle average CO emission rates estimated from rail yard measurements.

Table 34. Cycle Average Emission Rates for Over-the-Road Measurement of NC 1893 Prime Mover Engine

	NOx (g/bhp-hr)	HC (g/bhp-hr)	CO (g/bhp-hr)	Opacity-Based PM (g/bhp-hr)
June 2012	**8.9**	**2.32**	**0.5**	**0.15**
July 1, 3, 4, 2013	**6.8**	**0.86**	**0.8**	**0.16**
EPA Tier 0+	**8.0**	**1.00**	**5.0**	**0.22**
EPA Tier 1+	**7.4**	**0.55**	**2.2**	**0.22**

Researchers conducted 3 days of over-the-road emissions measurements on the prime mover engine of NC 1893. The cycle average over-the-road emission rates are quantitatively similar to the cycle average rail yard emission rates measured in June 2013. It has been observed during previous measurements of prime mover engines that cycle average over-the-road NOx emission rates are lower than rail yard measurements, and cycle average over-the-road PM emission rates are higher than rail yard measurements. Researchers observed this difference during the June 2013 rail yard and over-the-road measurements of NC 1893 in July 2013. Research is ongoing on engine NC 1893 to collect data on the engine performance on B10, B20 and B40 biodiesel fuel.

5. DISCUSSION

The FRA Alternative Fuel-Biodiesel Research project focuses on determining the extent to which U.S. railroads, both passenger and freight, can use biodiesel blends to power locomotives that operate on diesel fuel. Under this research project, three biodiesel research initiatives were funded: (1) Biodiesel Intercity Passenger Rail Revenue Service Tests, utilizing 20 percent biodiesel, (2) Locomotive Emissions Measurement of Various Blends of Biodiesel (B5 and B20), and (3) Locomotive Biofuel Study, utilizing B5-B40, to address research requirements established by congressional mandate of PRIIA Section 404. Section 404 of PRIIA requires FRA to conduct a Locomotive Biofuel Study to investigate: (1) the energy intensity of various biofuel blends compared with diesel fuel; (2) environmental, energy, and emission effects of using various biofuel blends compared with diesel fuel; (3) the cost of purchasing biofuel blends; (4) whether sufficient biofuel is readily available; (5) any public benefits derived from the use of such fuels; and (6) the effect of biofuel use on locomotive and other vehicle performance and warranty specifications.

FRA is unable to make a final recommendation on a premium blend of biofuels because of the lack of qualitative data on the long term effects (especially higher blends) of biodiesel on locomotive engine components and performance. According to a U.S. Department of Energy (DOE) study, locomotive engine manufacturers and fuel components suppliers have both acknowledged that low blends of biodiesel (in concentrations of up to 5 percent) that meet the ASTM D6751 fuel specifications will have minimal to no effect on the engine and components [7]. Currently, conventional diesel fuel for rail applications can contain up to 5 percent biodiesel fuel. Even though a 5 percent blend of biodiesel may have little effect on locomotive engine components, its effects on reducing emissions of locomotive engines, in comparison with the effect of diesel engines, are also minimal, which essentially reduces the overall benefits of the 5 percent biodiesel blended fuels. Higher blends of biodiesel, such as 20 percent biodiesel, which can reduce greenhouse gas emissions, could potentially harm locomotive engines in the long term. Further research is needed to assess the engine durability issues associated with using higher blends of biodiesel.

The results from the three FRA biodiesel research initiatives show that for the equipment tested, biodiesel in low blends (20 percent and lower) may be a viable alternative fuel for locomotives, when considering the engine performance and emissions of the locomotive engine. However, as stated, additional research is needed to understand the long terms effects of biodiesel usage and the performance of different models of locomotive engine on various blends of biodiesel in varying climates within the United States. As stated in the previous sections, a GE Tier 0, GE Tier 1 Plus, and an EMD Tier 2 locomotive were tested separately in these three research initiatives. In order to truly assess the performance of locomotives on biodiesel blended fuel, tests following the LMOA Oil Field Test Protocol are needed for both GE and EMD engines that are certified to Tier 0, 1, 2, 3 and possibly 4. Laboratory tests of the engine components are also needed. The LMOA Oil Field multiple locomotive engine durability test program would require two control units running on diesel fuel, in addition to the aforementioned units; the entire operation would require approximately 36 test locomotives. For this test, the locomotives would be operated in revenue service and the performance of the engine, engine oil analysis, and power assembly would be monitored and recorded. Components from locomotive engine fueling and combustion systems would undergo accelerated durability tests by being soaked in various blends of biodiesel for specific periods of time. The locomotive manufacturers have indicated that any consideration for relief from warranty for equipment defects related to fuel use will require an extensive test program similar to the LMOA Oil Field Test. In order to perform such tests, FRA will need to enter into agreement with locomotive owners because FRA does not own locomotives that can undergo the LMOA Oil Field test protocol. Locomotive owners are reluctant to engage in such test programs because it could adversely affect their business operations and operating procedures, as well as the AAR Locomotive Interchange Rules, and potentially result in fuel related engine problems that can void the equipment manufacturer's warranty. Therefore, FRA research into the viability of biodiesel as an alternative fuel is ongoing and discussions with the rail industry continue to identify opportunities for collaboration on existing locomotive engine performance durability test programs.

However, FRA successfully investigated the energy content of 5 percent and 20 percent biodiesel, in comparison with diesel fuel, as well as the fuel availability, costs, and public benefit. B100 biodiesel produces 8 percent less energy per gallon of fuel burned than diesel fuel[10], which results in an approximately 1 percent reduction in fuel economy when 20 percent biodiesel is burned in diesel engines. Table 17[11] below shows the low heating value of diesel fuel in comparison with various blends of biodiesel fuel. The net energy content of biodiesel fuel, also referred to as the low heating value of the fuel, is its heat of combustion (i.e., the heat released when a known quantity of the fuel is burned under specific conditions).

Table 35. Low Heating Value of Various Blends of Biodiesel and Diesel Fuels

Fuel	Low Heating Value (Btu/gal)
B100 Biodiesel Fuel	119,550
B20 Biodiesel Blend	126,227
B5 Biodiesel Blend	128,227
No. 2 Diesel Fuel	128,450

As can be observed in Table 35, the net energy content of biodiesel blends in concentrations higher than 20 percent result in a significant reduction in the fuel economy of locomotive engines.

Research into the availability of biodiesel in the United States showed an increase in the production of biodiesel in 2013 compared with production in 2011 and 2012. Figure 32 below shows biodiesel production in million gallons in the United States for the 3-year period between 2011 and 2013[12]. According to the U.S. Energy Information Administration (EIA), the total production of biodiesel from January to November was 1,204 million gallons. Sales of 100 percent biodiesel during that same period were in the range of 86 million gallons, and 33 million

[10]"Biodiesel Handling and Use Guidelines," U.S. Department of Energy, U.S. Department of Energy, DOE/GO-102004-1999 Revised 2004.

[11] http://cta.ornl.gov/bedb/appendix_a/Lower_and_Higher_Heating_Values_of_Gas_Liquid_and_Solid_Fuels.pdf

[12] http://www.eia.gov/biofuels/biodiesel/production/

gallons as blended biodiesel. Also, between January and November 2013 biodiesel production plants in the United States had the capability to produce, on average, 2,150 million gallons of biodiesel annually[13]. Therefore, consumption of biodiesel was just over 50 percent of the annual production capacity.

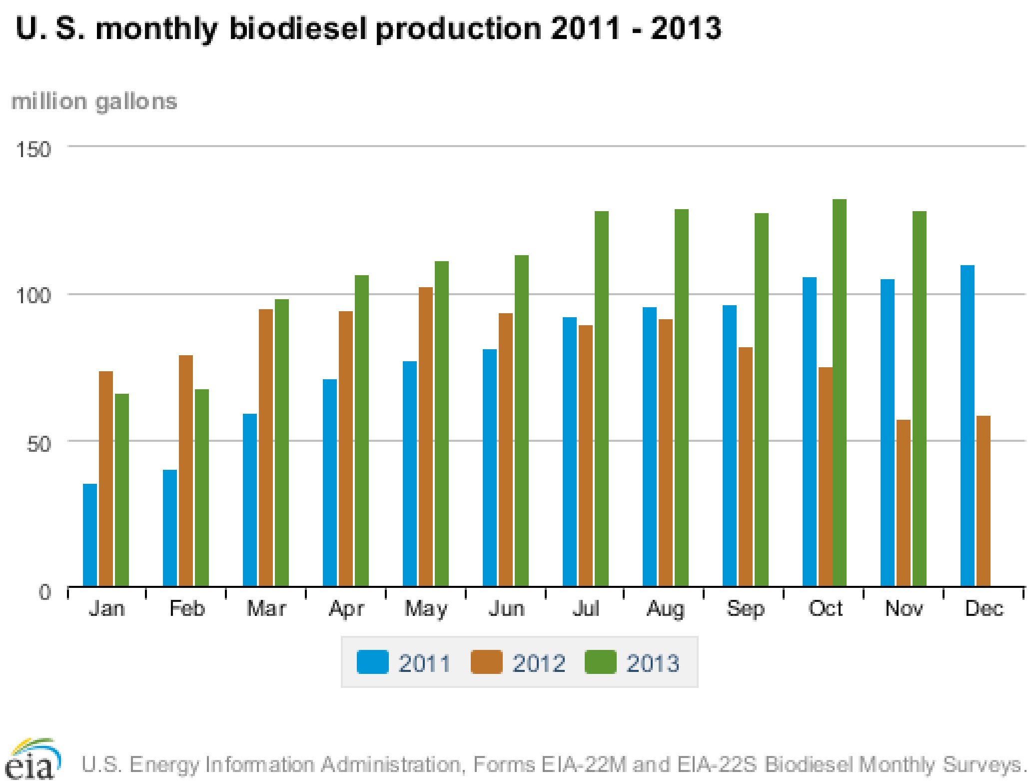


Figure 33. Biodiesel Fuel Production in the United States for 3-Year Period (2011–2013)

According to the EIA, U.S. Class I railroads consumed 0.50 quadrillion BTUs of energy (3.89 billion gallons of diesel fuel) in line-haul operations. If B20 biodiesel were to replace 100 percent of the diesel fuel consumed in rail transportation, it would require 791,981,316 gallons of biodiesel, displacing 724,639,938 gallons of diesel fuel. See below:

> 3,892,565,200 gallon of diesel was consumed in 2010 for the movement of goods and people by rail. B20 biodiesel fuel consists of 20 percent pure biodiesel and 80 percent diesel fuel. Therefore, substituting 100 percent of line-haul rail operations with B20 would require
>
> 3,892,565,200 x 0.20 = 778,513,040 gallons of pure biodiesel
> 3,892,565,200 x 0.80 = 3,114,052,160 gallons of No. 2 diesel.

However, the energy content of B20 per gallon is 126,277 Btu, which is a 0.983 reduction in comparison with diesel fuel (128,450 Btu/gal)). This means that 1.73 percent more by volume of B20 biodiesel would be required to maintain the current energy efficiency. Therefore, the actual

[13] http://www.eia.gov/biofuels/biodiesel/production/

amount of biodiesel required for such a scenario is 3,892565,200 x 1.0173 = 3,959,906,578 gallons B20, which would require the following amounts of fuel to be blended,

3,959,906,578 x 0.20 = 791,981,316 gallons of pure biodiesel
3,959,906,578 x 0.80 = 3,167,925,262 gallons of No. 2 diesel.

This substitution would result in the displacement of 724,639,938 gallons of diesel fuel (3,892,565,200 gallons of fuel consumed in 2010; 3,167,925,262 gallons of diesel fuel needed to produce B20). The production of biodiesel in the United States from January to November 2013 was 1,204 million gallons of biodiesel. The amount needed for 100 percent usage in the rail transportation sector is more than half of the amount available. If biodiesel for rail transportation applications were the only sector to be supplied, then the current production of biodiesel would be sufficient. However, the total amount of biodiesel produced is supplied to the entire transportation industry, including residential and commercial sectors.

"Biofuels Issues and Trends," published in October 2012 [10] by the EIA, discussed the price trend of biodiesel between 2009 and 2012. Figure 33 below displays this information. Biodiesel produced and sold by Iowan sources (brown trend line) are used since that State is a major producer of biodiesel, and cost data was readily available.[14] During this 4-year time period, biodiesel cost fluctuated between $3.00/gal and ~$5.80/gal.

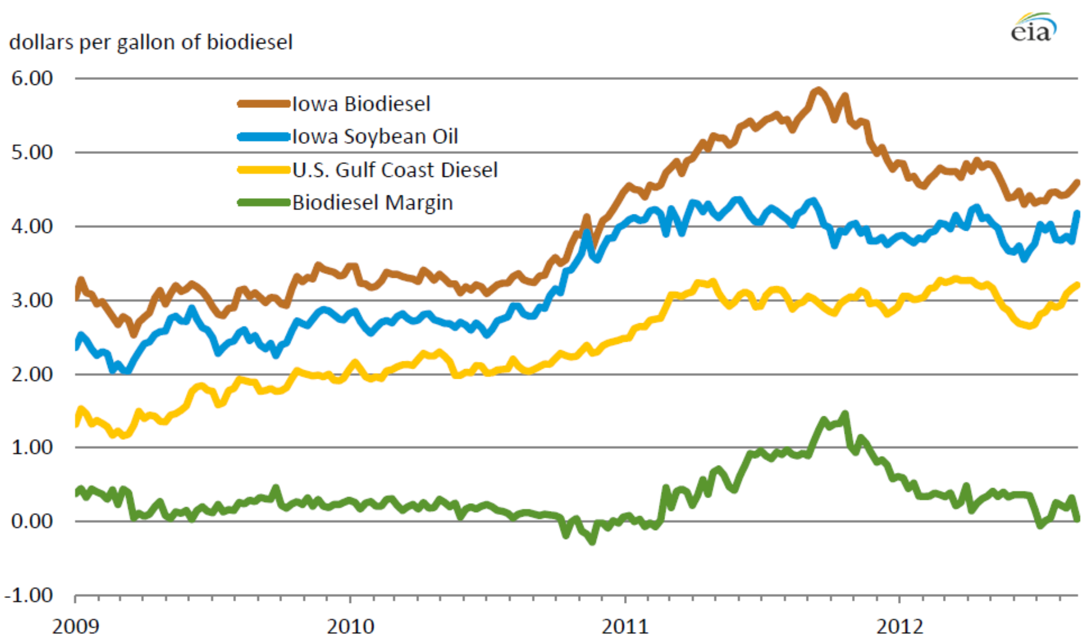


Figure 34. Cost Data for Biodiesel Produced from Iowan Source, 2009–2012

When comparing the cost of No. 2 diesel fuel (yellow trend line) during the same time frame, diesel fuel was approximately $2.00 less than biodiesel. It was more economical for the Class I railroads, the largest consumer of diesel fuel in the rail industry, to use diesel fuel rather than biodiesel fuel.

[14] "Biofuel Issues and Trends", U.S. Energy Information Administration, U.S. Department of Energy, October 2012

The derived public benefit from the use of biodiesel in the railroad industry can be realized in lower greenhouse gas emissions, particularly CO, HC, and possibly PM. However, use of high blends of biodiesel, such as 20 percent or more, can result in a higher concentration of NOx emissions. NOx emissions adversely affect the atmosphere of the earth over long periods of time. Therefore, the derived public benefit from the use of B20 and higher blends of biodiesel is minimal when considering all the emissions, especially NOx, associated with the use of the fuel. Additionally, emissions treatment equipment would be needed to reduce the NOx, thereby increasing the overall costs associated with using biodiesel fuel.

In conclusion, FRA research initiatives focusing on biodiesel as an alternative fuel for rail transportation show that it is feasible to operate locomotive engines on a 20 percent blend of biodiesel with minimal effects on performance. However, additional research is needed to understand the long term effects of biodiesel on locomotive engines. Additional research is also needed to determine performance in colder environments. An increase in domestic production of biofuels such as biodiesel could result in biodiesel fuel cost reductions, thereby providing further incentive to encourage the use of B20 biodiesel as an alternative fuel for rail transportation.

6. REFERENCES

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Appendix A. Fuel Specifications and Analysis Results

A.1 Biodiesel Intercity Passenger Rail Revenue Service Test Fuel and Oil Sample Specifications and Analyses Results

Table A1. ASTM D-975 ULSD DIESEL FUEL SPECIFICATION

TEST	DESCRIPTION	ASTM	SPECIFICATION	UNITS
1	API Gravity	D-287	30 min	
2	Distillation	D-86		
	Initial Boiling Point		345 typical	°F
	10% Recovered Volume		420 typical	°F
	50% Recovered Volume		500 typical	°F
	90% Recovered Volume		540 min / 640 max	°F
	Final Boiling Point		670 typical	°F
	Total Recovered Volume		98.0 min	Volume %
3	Cetane Index	D-976	40 min	
4	Water and Sediment	D-1796	0.0500 max	Volume %
5	Sulfur Content	D-5453	15 max	ppm
6	Viscosity @ 40 °C	D-445	1–9 min / 4.1 max	cSt
7	Cloud Point	D-2500	Report	°F
8	Flash Point	D-93	126 min	°F
9	Lubricity by HFRR	D-6079	520 ma	microns

Table A2. ASTM D6751, B100 BIODIESEL FUEL SPECIFICATIONS

TEST	DESCRIPTION	ASTM	SPECIFICATION	UNITS
1	Flash Point	D-93	130 min	°C
2	Water and Sediment	D-2709	0.0500 max	Volume %
3	Kinematic Viscosity@ 40 °C	D-445	1.9-6.0	cSt
4	Sulfated Ash	D-874	0.020 max	Weight %
5	Sulfur	D-5453	15 max	ppm
6	Copper Strip Corrosion	D-130	No. 3 max	Rating
7	Cetane Index	D-976	47 min	
8	Cloud Point	D-2500	Report	°C
9	Carbon Residue	D-4530	0.0050 max	Weight %
10	Acid Number	D-664	0.50 max	Mg KOH/g
11	Free Glycerin	D-6584	0.020 ma	Volume %
12	Total Glycerin	D-6584	0.240 max	Volume %
13	Phosphorous	D-4951	0.0010 max	Weight %
14	Distillation Temperature	D-1160	360 max	°C
15	Calcium and Magnesium	EN14538	5 max	ppm
16	Sodium and Potassium	EN14538	5 max	ppm
17	Oxidation Stability	EN14112	3 min	Hours

Table A3. ASTM D7476, B6-B20 BIODIESEL FUEL SPECIFICATIONS

TEST	DESCRIPTION	ASTM	SPECIFICATION	UNITS
1	Flash Point	D-93	52 minimum	°C
2	Water and Sediment	D-2709	0.0500 maximum	Volume %
3	Kinematic Viscosity @ 40 °C	D-445	1.9-4.1	cSt
4	Ash content	D-482	0.01 maximum	Weight %
5	Sulfur	D-5453	15 maximum	ppm
6	Copper Strip Corrosion	D-130	No. 3 maximum	Rating
7	Centane Index	D-976	40 minimum	
8	Cloud Point	D-2500	Report	°C
9	Carbon Residue 10%	D-524	0.3500	Weight %
10	Aromaticity	D-1319	35 maximum	Volume %
11	Acid Number	D-664	0.3 maximum	Mg/KOH
12	Free Glycerin	D-6584	Report	Volume %
13	Total Glycerin	D-6584	Report	Volume %
14	Distillation Temperature 90%	D-86	343 maximum	°C
15	Biodiesel Content	D-7371	6-20	Volume %
16	Oxidation Stability	EN14112	6 minimum	Hours
17	Lubricity	D-6070	520 maximum	Microns

Table A4. ANA LABORATORIES B100 BASELINE SAMPLE INITIAL TEST RESULTS

	Description	ASTM	Spec.	Results	Units
1)	Flash Point	D-93	130 min	165	°C
2)	Water and Sediment	D-2709	0.0500 max	<0.0150	vol %
3)	Kinematic Viscosity @40C	D-445	1.9-6.0	4.62	cSt
4)	Sulfated Ash	D-482	0.020 max	0.001	wt %
5)	Sulfur	D-5453	15 max	0.0005	ppm
6)	Copper Strip Corrosion	D-130	No. 3 max	1a	rating
7)	Cetane Index	D-976	47 min	60.3	
8)	Cloud Point	D-2500	Report	17	°C
9)	Carbon Residue	D-524	0.0050 max	0.0031	wt %
11)	Acid Number	D-664	0.50 max	0.30	mg KOH/g
12)	Free Glycerin	D-6584	0.020 max	0.23	vol %
13)	Total Glycerin	D-6584	0.240 max	0.250	vol %
14)	Phosphorous	D-4951	0.0010 max	<0.0001	wt %
14)	Distillation Temp 90%	D-86	343 max	341	°C
15)	Calcium and Magnesium	EN14538	5 max	<1	ppm
16)	Sodium and Potassium	EN14538	5 max	<1	ppm
17)	Oxidations and Stability	EN14112	3 min	>10	hours

Table A5. ANA LABORATORY B100 BASELINE SAMPLE RETEST RESULTS

Test	Description	ASTM	Spec.	Results	Units
1)	Flash Point	D-93	130 min	146	°C
2)	Water and Sediment	D-2709	0.0500 max	0.0100	vol %
3)	Kinematic Viscosity @ 40 °C	D-445	1.9-6.0	4.67	cSt
4)	Sulfated Ash	D-482	0.020 max	0.001	wt %
5)	Sulfur	D-5453	15 max	0.0007	ppm
6)	Copper Strip Corrosion	D-130	No. 3 max	1a	rating
7)	Cetane Index	D-976	47 min	59.1	
8)	Cloud Point	D-2500	Report	17	°C
9)	Carbon Residue	D-524	0.0050 max	0.049	wt %
11)	Acid Number	D-664	0.50 max	0.28	mg KOH/g
12)	Free Glycerin	D-6584	0.020 max	0.00	vol %
13)	Total Glycerin	D-6584	0.240 max	0.00	vol %
14)	Phosphorous	D-4951	0.0010 max	<0.0001	wt %
14)	Distillation Temperature 90%	D-86	360 max	331	°C
15)	Calcium and Magnesium	EN14538	5 max	<1	ppm
16)	Sodium and Potassium	EN14538	5 max	<1	ppm
17)	Oxidations and Stability	EN14112	3 min	>10	hours

Table A6. ANA LABORATORY B20 BASELINE INITIAL SAMPLE TEST RESULTS

Test	Description	ASTM	Spec.	Results	Units
1)	Flash Point	D-93	52 min	72	°C
2)	Water and Sediment	D-2709	0.0500 max	<0.0010	Vol %
3)	Kinematic Viscosity @ 40 °C	D-445	1.9-4.1	3.19	cSt
4)	Ash Content	D-482	0.01 max	0.003	wt %
5)	Sulfur	D-5453	15 max	9	ppm
6)	Copper Strip Corrosion	D-130	No. 3 max	1a	rating
7)	Cetane Index	D-976	40 min	45.6	
8)	Cloud Point	D-2500	Report	-6	°C
9)	Carbon Residue 10%	D-524	0.3500 max	0.1010	wt %
10)	Aromaticity	D-1319	35 max	46.6	vol %
11)	Acid Number	D-664	0.3 max	0.12	mg KOH/g
12)	Free Glycerin	D-6584	Report	0.07	vol %
13)	Total Glycerin	D-6584	Report	0.07	vol %
14)	Distillation Temperature 90%	D-86	343 max	336	°C
15)	Biodiesel Content	D-7371	6-20	17.4	vol %
16)	Oxidation Stability	EN14112	6 min	>10	Hours
17)	Lubricity	D-6079	520 max	207	microns

Table A7. ANA LABORATORY B20 BASELINE SAMPLE RETEST RESULTS

Test	Description	ASTM	Spec.	Results	Units
1)	Flash Point	D-93	52 min	74	°C
2)	Water and Sediment	D-2709	0.0500 max	<0.0010	Vol %
3)	Kinematic Viscosity @ 40 °C	D-445	1.9-4.1	3.14	cSt
4)	Ash Content	D-482	0.01 max	0.003	wt %
5)	Sulfur	D-5453	15 max	9	ppm
6)	Copper Strip Corrosion	D-130	No. 3 max	1a	rating
7)	Cetane Index	D-976	40 min	53.3	
8)	Cloud Point	D-2500	Report	-7	°C
9)	Carbon Residue 10%	D-524	0.3500 max	0.040	wt %
10)	Aromaticity	D-1319	35 max	31	vol %
11)	Acid Number	D-664	0.3 max	0.19	mg KOH/g
12)	Free Glycerin	D-6584	Report	0.0	vol %
13)	Total Glycerin	D-6584	Report	0.0	vol %
14)	Distillation Temperature 90%	D-86	343 max	331	°C
15)	Biodiesel Content	D-7371	6-20	20	vol %
16)	Oxidation Stability	EN14112	6 min	>10	Hours
17)	Lubricity	D-6079	520 max	195	microns

A.2 Locomotive Emissions of Various Blends of Biodiesel – Results of Fuel Blends

Table A8. Analysis Results of Fuel Blends (CARB5, EPA5, CARB20, EPA20)

		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

A.3 NCSU Locomotive Biofuel Study – Fuel Characterization

Table A9. Literature and Measured Fuel Properties for ULSD Fuel

Properties	Unit	Literature-Based Estimates*	ULSD SwRI Obtained 7/6/2013	SwRI Obtained 9/3/2013	SwRI Obtained 10/22/2013
ASTM D130 Copper Corrosion					
Copper Corrosion	rating	N/A	1A	1A	1A
ASTM D240 Gross Heat of Combustion					
Gross Heat	BTU/lb	19386	19690	19598	19690
Gross Heat	MJ/Kg	45.092	45.800	45.584	45.798
Gross Heat	Cal/g	10777	10939	10888	10939
ASTM D240 Net Heat of Combustion					
Net Heat	BTU/lb	18176	18470	18374	18568
Net Heat	Mj/Kg	42.278	42.962	42.738	43.190
Net Heat	Cal/g	10105	10261	10208	10316
ASTM D2500 Cloud Point					
Cloud Point	°C	-35 to 5	-11.1	-12.0	-11.0
ASTM D2622 Sulfur by WDXRF					
Sulfur	ppm	≤ 15	12.1	11.0	9.3
ASTM D4052 API, Density, Specific Gravity					
API	°	N/A	36.7	36.5	36.7
Specific Gravity @60°F		0.850	0.8413	0.8422	0.8414
Density @15°C	g/ml	0.8501	0.8409	0.8417	0.8409
ASTM D5291 Carbon Hydrogen Nitrogen					
Carbon	wt%	87.00	86.71	86.80	86.71
Hydrogen	wt%	13.00	13.37	13.41	12.29
Nitrogen	wt%	N/A	0.03	0.02	0.02
ASTM D613 Cetane Number					
Cetane	No.	40 to 55	48.9	46.7	46.1
ASTM D93 Flash Point					
Flash Point	°C	60 to 80	65.0	63.0	65.0
BioDiesel Content by IR					
Biodiesel	vol%	0.0	N/A	N/A	N/A
ASTM D6079 Lubricity					
Wear Scar Diameter	µm	N/A	405	220	462
Major Axis	mm	N/A	0.445	0.261	0.511
Minor Axis	mm	N/A	0.364	0.178	0.413
Scar Description		N/A	EAO**	EAO**	EAO**
ASTM D445 Kinematic Viscosity					
Viscosity	cSt	1.30 to 4.10	2.552	2.492	2.449
ASTM D86 Distillation					
Initial Boiling Point	°F	180 to 340	331.7	330.0	334.9
10% Recovered	°F	N/A	404.0	400.9	396.7
50% Recovered	°F	N/A	504.6	507.0	500.6
90% Recovered	°F	N/A	621.3	622.0	621.6
Final Boiling Point	°F	N/A	662.2	656.3	663.0
Recovered	%	N/A	97.4	97.0	97.1
Residue	%	N/A	1.2	1.4	1.4
Loss	%	N/A	1.4	1.6	1.5

Table A10. Literature and Measured Fuel Properties for B10 Biodiesel Fuel

		B10 Biodiesel	
		Literature-Based Estimate	SwRI Measured *Obtained 9/10/2013
Properties	**Unit**		
ASTM D130 Copper Corrosion			
Copper Corrosion	rating	N/A	1A
ASTM D240 Gross Heat of Combustion			
Gross Heat	BTU/lb	19188	19491
Gross Heat	MJ/Kg	44.630	45.336
Gross Heat	Cal/g	10667	10828
ASTM D240 Net Heat of Combustion			
Net Heat	BTU/lb	17977	18279
Net Heat	Mj/Kg	41.815	42.517
Net Heat	Cal/g	9994	10155
ASTM D2500 Cloud Point			
Cloud Point	°C	-31.8 to 6	-11.1
ASTM D2622 Sulfur by WDXRF			
Sulfur	ppm	≤ 15.9	8
ASTM D4052 API, Density, Specific Gravity			
API	°	N/A	36.6
Specific Gravity @60°F		0.853	0.8416
Density @15°C	g/ml	0.8525	0.8411
ASTM D5291 Carbon Hydrogen Nitrogen			
Carbon	wt%	86.00	85.72
Hydrogen	wt%	12.90	13.29
Nitrogen	wt%	N/A	0.20
ASTM D613 Cetane Number			
Cetane	No.	40.8 to 56	49.0
ASTM D93 Flash Point			
Flash Point	°C	64 to 89	
61.0			
BioDiesel Content by IR			
Biodiesel	vol%	10.0	
6.6			
ASTM D6079 Lubricity			
Wear Scar Diameter	µm	N/A	265
Major Axis	mm	N/A	0.297
Minor Axis	mm	N/A	0.233
Scar Description		N/A	EAO**
ASTM D445 Kinematic Viscosity			
Viscosity	cSt	1.57 to 4.29	2.510
ASTM D86 Distillation			
Initial Boiling Point	°F	194 to 341	333.5
10% Recovered	°F	N/A	398.9
50% Recovered	°F	N/A	510.3
90% Recovered	°F	N/A	624.9
Final Boiling Point	°F	N/A	660.0
Recovered	%	N/A	97.9
Residue	%	N/A	1.3
Loss	%	N/A	0.8

Table A11. Literature and Measured Fuel Properties for B40 Biodiesel Fuel

Properties	Unit	B40 Biodiesel Literature-Based Estimates*	SwRI Measured Obtained 10/21/2013
ASTM D130 Copper Corrosion			
Copper Corrosion	rating	N/A	1A
ASTM D240 Gross Heat of Combustion			
Gross Heat	BTU/lb	18593	18636
Gross Heat	MJ/Kg	43.247	43.347
Gross Heat	Cal/g	10336	10353
ASTM D240 Net Heat of Combustion			
Net Heat	BTU/lb	17381	17481
Net Heat	Mj/Kg	40.428	40.661
Net Heat	Cal/g	9662	9711.7
ASTM D2500 Cloud Point			
Cloud Point	°C	-22.2 to 9	-4.8
ASTM D2622 Sulfur by WDXRF			
Sulfur	ppm	≤ 18.6	7.6
ASTM D4052 API, Density, Specific Gravity			
API	°	N/A	33.0
Specific Gravity @60°F		0.862	0.8599
Density @15°C	g/ml	0.8596	0.8595
ASTM D5291 Carbon Hydrogen Nitrogen			
Carbon	wt%	83.00	82.79
Hydrogen	wt%	12.60	12.66
Nitrogen	wt%	N/A	0.16
ASTM D613 Cetane Number			
Cetane	No.	43.2 to 59	48.6
ASTM D93 Flash Point			
Flash Point	°C	76 to 116	70.0
BioDiesel Content by IR			
Biodiesel	vol%	40.0	39.3
ASTM D6079 Lubricity			
Wear Scar Diameter	µm	N/A	161
Major Axis	mm	N/A	0.188
Minor Axis	mm	N/A	0.134
Scar Description		N/A	EAO**
ASTM D445 Kinematic Viscosity			
Viscosity	cSt	2.38 to 4.86	2.952
ASTM D86 Distillation			
Initial Boiling Point	°F	234 to 344	347.6
10% Recovered	°F	N/A	427.1
50% Recovered	°F	N/A	587.5
90% Recovered	°F	N/A	641.9
Final Boiling Point	°F	N/A	670.1
Recovered	%	N/A	98.6
Residue	%	N/A	0.8
Loss	%	N/A	0.6

Table A12. Literature and Measured Fuel Properties for B40 Biodiesel Fuel

		B60 Biodiesel	
		Literature-Based Estimates*	SwRI Measured Obtained 8/12/2013
Properties	**Unit**		
ASTM D130 Copper Corrosion			
Copper Corrosion	rating	N/A	1A
ASTM D240 Gross Heat of Combustion			
Gross Heat	BTU/lb	18196	18091
Gross Heat	MJ/Kg	42.324	42.080
Gross Heat	Cal/g	10116	10051
ASTM D240 Net Heat of Combustion			
Net Heat	BTU/lb	16983	16955
Net Heat	Mj/Kg	39.503	39.437
Net Heat	Cal/g	9441	9419.4
ASTM D2500 Cloud Point			
Cloud Point	°C	-15.8 to 11	-4.2
ASTM D2622 Sulfur by WDXRF			
Sulfur	ppm	≤ 20.4	5.9
ASTM D4052 API, Density, Specific Gravity			
API	°	N/A	31.7
Specific Gravity @60°F		0.868	0.8672
Density @15°C	g/ml	0.8644	0.8667
ASTM D5291 Carbon Hydrogen Nitrogen			
Carbon	wt%	81.00	80.64
Hydrogen	wt%	12.40	12.46
Nitrogen	wt%	N/A	0.14
ASTM D613 Cetane Number			
Cetane	No.	44.8 to 61	48.8
ASTM D93 Flash Point			
Flash Point	°C	84 to 134	
73.0			
BioDiesel Content by IR			
Biodiesel	vol%	60.0	
55.6			
ASTM D6079 Lubricity			
Wear Scar Diameter	µm	N/A	159
Major Axis	mm	N/A	0.189
Minor Axis	mm	N/A	0.129
Scar Description		N/A	EAO**
ASTM D445 Kinematic Viscosity			
Viscosity	cSt	2.92 to 5.24	3.352
ASTM D86 Distillation			
Initial Boiling Point	°F	261 to 346	343.5
10% Recovered	°F	N/A	469.7
50% Recovered	°F	N/A	616.8
90% Recovered	°F	N/A	644.5
Final Boiling Point	°F	N/A	674.0
Recovered	%	N/A	98.7
Residue	%	N/A	0.7
Loss	%	N/A	0.6

Appendix B. Emissions Data

B.1 Biodiesel Intercity Passenger Rail Revenue Service Test – Emissions Results

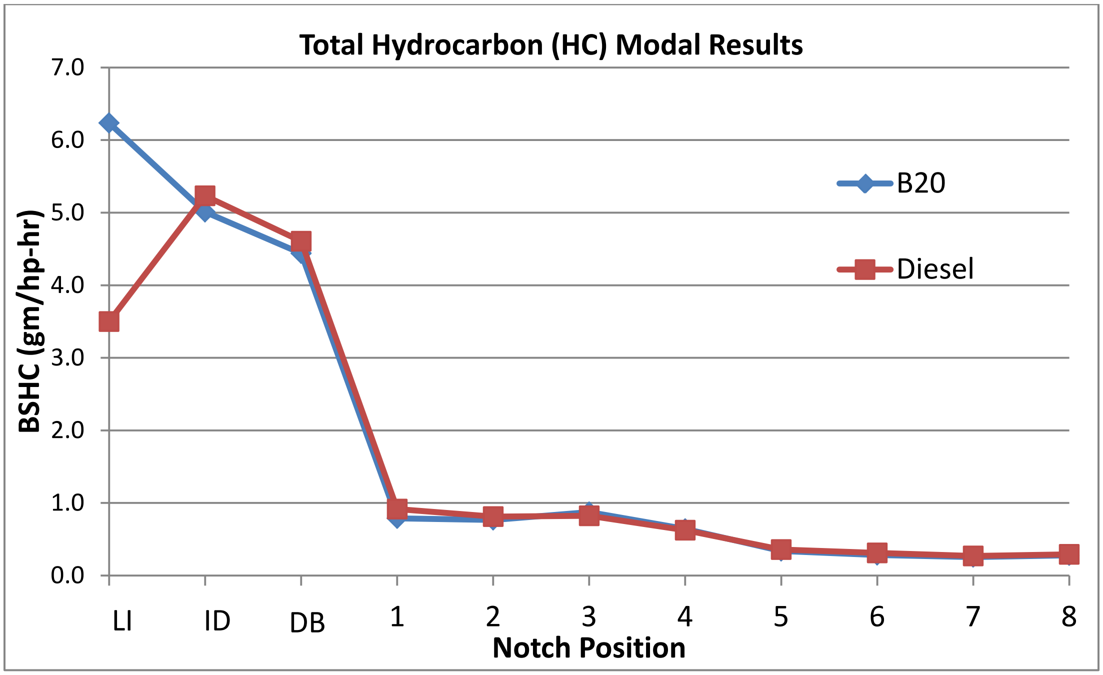

Figure B1. Total Hydrocarbon (HC) Emissions Test Results

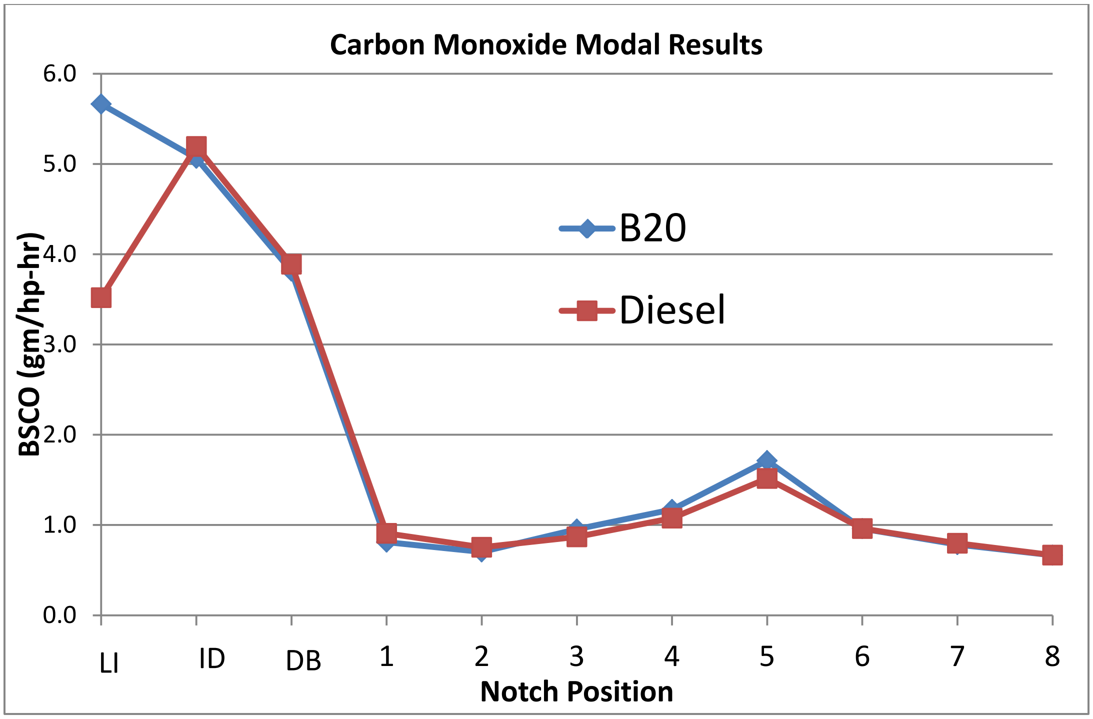

Figure B2. Carbon Monoxide (CO) Emissions Test Results

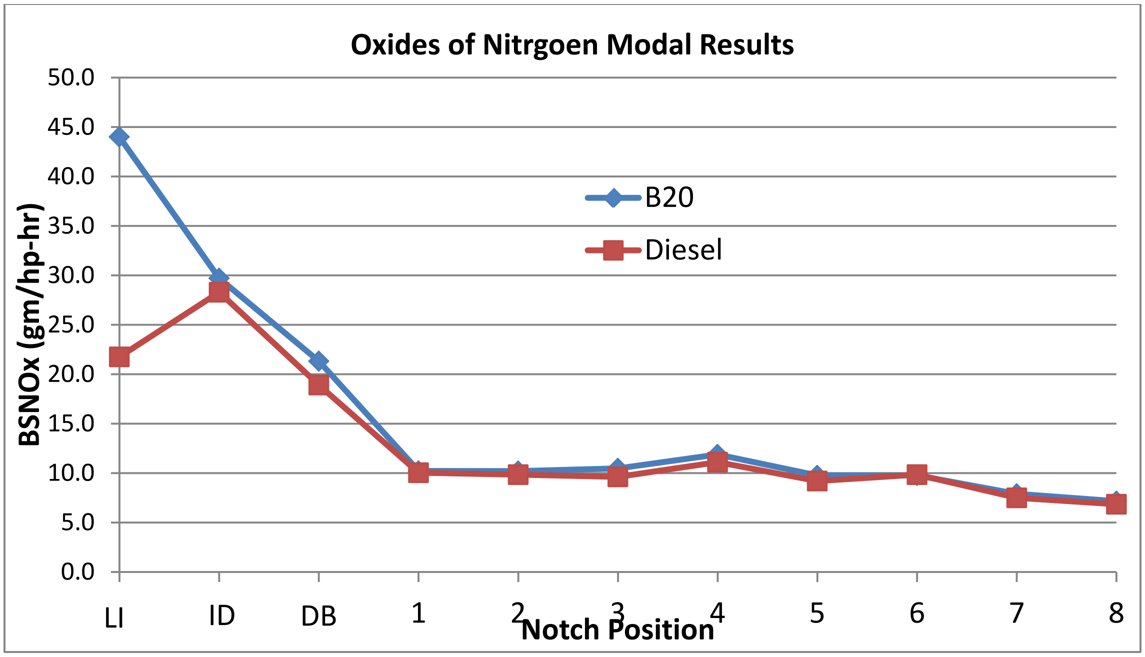

Figure B3. Oxides of Nitrogen (NOx) Emissions Test Results

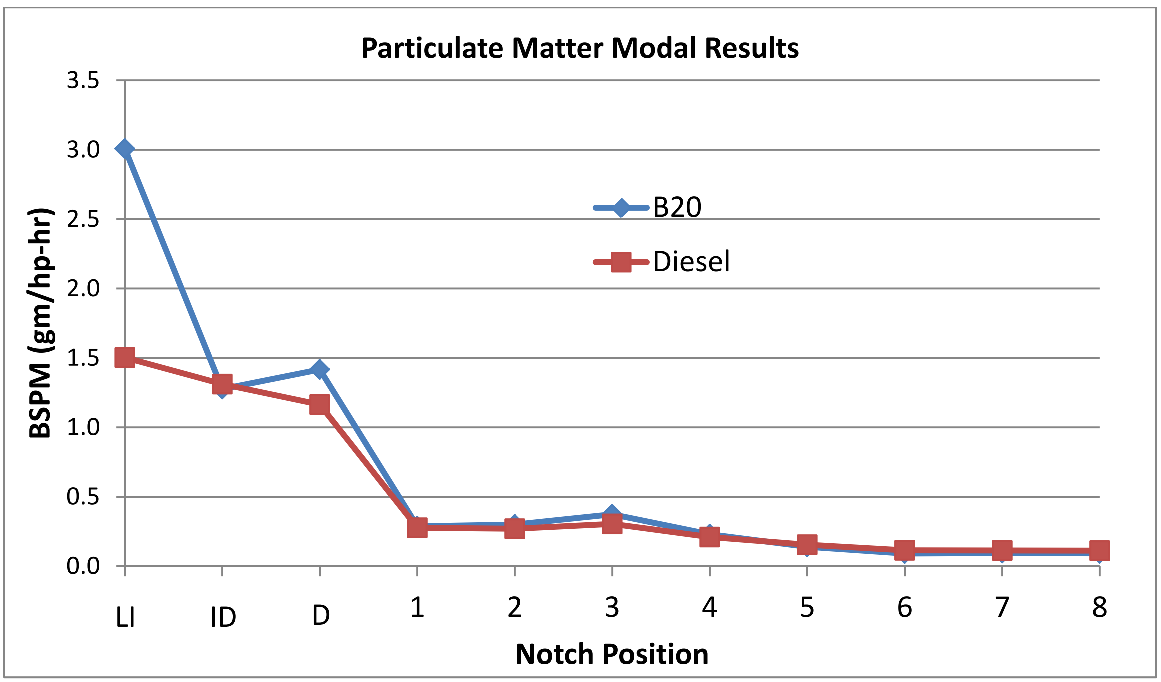

Figure B4. Particulate Matter (PM) Emissions Test Results

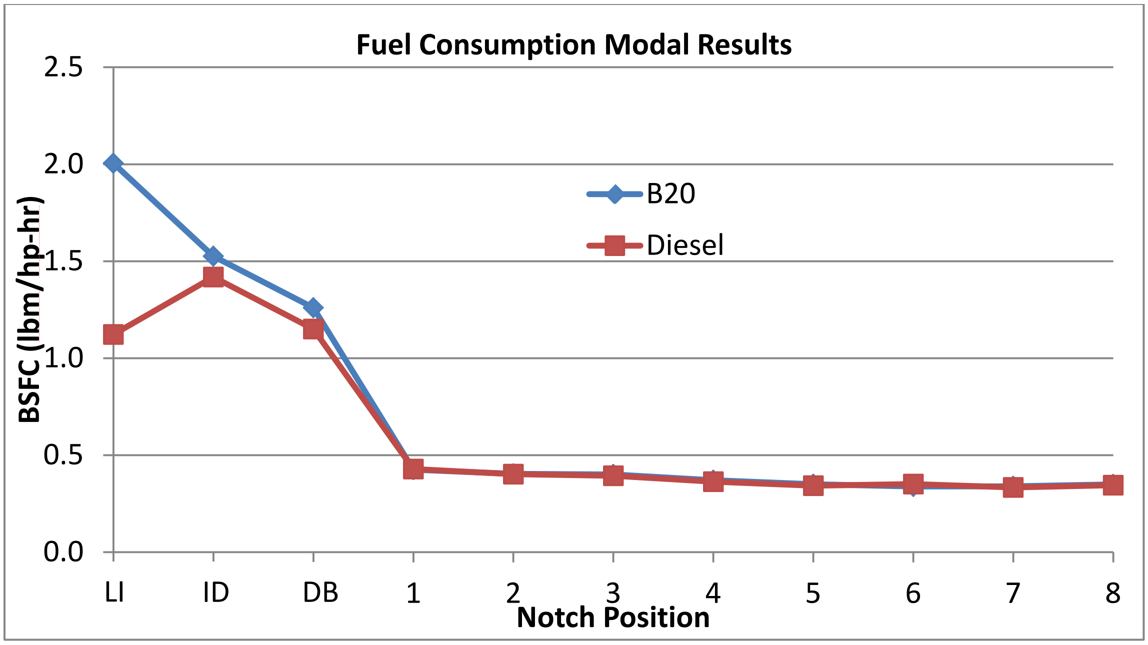

Figure B5. Fuel Consumption of Engine #500

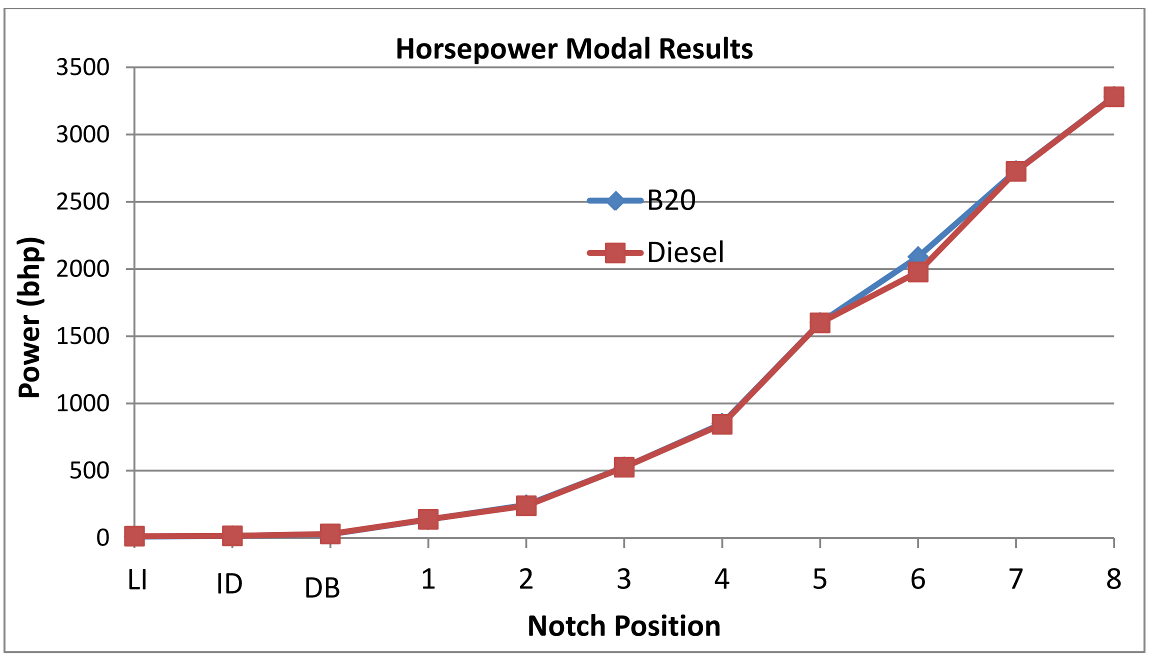

Figure B6. Engine #500 Powering Performance

Appendix C. Certificate of Analysis - AGP

AGP
Ag Processing Inc

Certificate of Analysis

Vendor Details:	Company Name:	Ag Processing Inc	Customer:	SOUTHWEST RESEAR 23690
				SAN ANTONIO TX
	Manufacturing Address:	900 Lower Lake		
		St. Joseph, MO	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

Abbreviations and Acronyms

AAR	Association of American Railroads
Amtrak	National Railroad Passenger Corporation
AN	Acid Number
ASTM	American Society for Testing and Materials
B5	Blend of 5 percent pure biodiesel and 95 percent petrodiesel
B10	Blend of 10 percent pure biodiesel and 80 percent petrodiesel
B20	Blend of 20 percent pure biodiesel and 80 percent petrodiesel
B40	Blend of 40 percent pure biodiesel and 80 percent petrodiesel
B60	Blend of 60 percent pure biodiesel and 80 percent petrodiesel
B80	Blend of 80 percent pure biodiesel and 80 percent petrodiesel
B100	100 percent pure biodiesel
BHP	Brake Horse Power
BN	Base Number
BNSF	BNSF Railway
BTU	British Thermal Unit
CARB	California Air Resource Board
CARB0	Pure CARB Diesel Fuel
CARB5	Blend of 5 % Pure Biodiesel Fuel and 95 % CARB Diesel Fuel
CARB20	Blend of 20 % Pure Biodiesel Fuel and 80 % CARB Diesel Fuel
cBSFC	Corrected Brake Specific Fuel consumption
CFR	Code of Federal Regulations
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COA	Certificate of Analysis
DOT	Department of Transportation
EMD	Electro-Motive Diesel
EPA0	EPA Certification Fuel
EPA5	Blend of 5% pure biodiesel and 95% EPA Certification Fuel
EPA20	Blend of 20% pure biodiesel and 80% EPA Certification Fuel
FRA	Federal Railroad Administration
FTP	Federal Test Procedure

GE	General Electric
HFLD	Heated Flame Ionization Detector
HCLD	Heated Chemi-Luminescent Detector
HP	Horse Power
LMOA	Locomotive Maintenance Officers Association
HC	Hydrocarbon
NOx	Oxides of Nitrogen
NCSU	North Carolina State University
O_2	Oxygen
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
PRIIA	Passenger Rail Investment and Improvement Act of 2008
Rail E3	Rail Energy, Environment, and Engine Technology Research
RFQ	Request for Quote
SAE	Society of Automotive Engineers
SWRI	Southwest Research Institute
ULSD	Ultra Low Sulfur Diesel