RENEWABLE DIESEL FUEL EFFECTS ON EXHAUST EMISSIONS FROM A TIER 3 GE ES44C4 LOCOMOTIVE

Agreement No. 19ISD009

FINAL REPORT

SwRI® Project No. 03.25756

Prepared for:
California Air Resources Board
Industrial Strategies Division (Fuels)
P.O. Box 2815
1001 I Street
Sacramento, CA 95812

Prepared by:
Christopher Stoos, Sr. Research Engineer
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San Antonio, TX 78238

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Prepared by:	**Reviewed by:**
Christopher Stoos, Sr. Research Engineer **Locomotive Technology Center** **Design & Development Dept.**	**Steven G. Fritz, Manager** **Locomotive Technology Center** **Design & Development Dept.**

POWERTRAIN ENGINEERING DIVISION

Disclaimer

The statements and conclusions in this Report are those of the contractor and not necessarily those of the California Air Resources Board. The mention of commercial products, their source, or their use in connection with material reported herein is not to be construed as actual or implied endorsement of such products.

Acknowledgement

Acknowledge the SwRI Locomotive Technology Center team of Southwest Research Institute.

Funding for the Biodiesel blends tested as part of this project was provided by BNSF Railway and Union Pacific Railroad. BNSF Railway also provided the test locomotive, BNSF 7934.

The Renewable Energy Group (REG) donated the neat Biodiesel (B100) used for the biodiesel blend tests at no cost to the project.

This Report was submitted in fulfillment of ARB Agreement #19ISD009 for "Renewable Diesel Fuel Effects on Exhaust Emissions from a Tier 3 GE ES44C4 Locomotive" by Southwest Research Institute under the sponsorship of the California Air Resources Board. Work was completed as of June 17, 2020. Ms. Danielle Magadia, Air Resources Engineer, was the ARB Project Manager overseeing this work.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

This report documents the effects of renewable diesel on locomotive exhaust emissions. A total of nine emissions tests were conducted on a 4500 horsepower (HP) US EPA Tier 3 GE ES44C4 locomotive using five different fuels or fuel blends. A randomized test matrix was used to determine the test order of the first eight emissions tests, consisting of duplicate testing for each of four specified fuel blends. A ninth test was added using fuel that met US EPA Certification fuel standards for a baseline reference. Testing was conducted using the following fuel and fuel blends:

100% CARB Diesel
100% Renewable Diesel
50% CARB Diesel / 50% Renewable Diesel
50% CARB Diesel / 30% Renewable Diesel / 20% Biodiesel
100% US EPA Certification Diesel

The exhaust emission and fuel consumption results from this testing provide a better understanding of the effects that various fuels and fuel mixtures have on locomotive emissions and fuel consumption.

EXECUTIVE SUMMARY

Background

California's Low Carbon Fuel Standard is designed to decrease the carbon intensity of California's transportation fuel pool and provide an increasing range of low-carbon and renewable alternatives, which reduce petroleum dependency and achieve air quality benefits. It is important to understand the effects these fuels have on vehicle emissions and fuel consumption. To determine how renewable diesel affects locomotive emissions, locomotive exhaust emissions testing was completed on various fuels and fuel mixtures at the Southwest Research Institute's (SwRI) Locomotive Technology Center (LTC) in June 2020.

Methods

Testing was conducted at the SwRI LTC on a 4,500 HP US EPA Tier 3 GE ES44C4 locomotive, which was provided for testing by BNSF Railway.

The original CARB-funded project plan called for duplicate testing of CARB diesel, 100% Renewable Diesel, and a 50/50 blend of the two fuels. Based on interest from Union Pacific Railroad (UP), and BNSF Railway (BNSF), a blend of 50% CARB diesel, 30% Renewable, and 20% Biodiesel, was added to the test plan, with funding for the extra fuel blends and locomotive tests covered by UP and BNSF.

The commercially available base fuels were acquired and mixed by SwRI into the required blends for testing. The resulting fuels and fuel blends were then analyzed to determine their properties and to verify that the fuel mixtures were correct. Once the fuel analysis results were completed and approved, locomotive emissions testing began. Emissions testing was completed according to Federal Test Procedure (FTP) as defined in Title 40 of the Code of Federal Regulations (CFR), Part 1065 and Part 1033.

Carbon Intensity (CI) for the base fuels were provided by CARB and take into account the supplier and associated feed stock for the fuels. A total of eight planned FTPs were conducted in a randomized test matrix, with duplicate tests conducted on each of the first four fuel or fuel blends. One additional test was added using EPA Certification Diesel fuel as defined in 40 CFR Part 1065.703 Table 1. This test was performed by SwRI to provide a baseline for the test results back to EPA certification levels, and for baseline fuel comparisons. Table ES-1 contains the test order, the fuel blends utilized in this testing, and the CI for each test fuel.

Each test was completed using the same measurement equipment and was run at similar ambient temperatures to minimize the effects that temperature has on locomotive emissions and fuel consumption. No locomotive power deration was noted on any of the fuels tested in this project.

Results

The average results for each fuel blend over the EPA Linehaul cycle is shown in Tables ES-2.

TABLE ES-1. TEST FUELS, TEST ORDER, AND CARBON INTENSITY

Test #	Test Date	Test Fuel	Designation	Carbon Intensity, gCO_2e/MJ
1	6/4/2020	100% CARB Diesel	C100	100.45
2	6/5/2020	50% CARB Diesel / 30% Renewable Diesel / 20% Biodiesel	C50R30B20	67.9
3	6/8/2020	100% Renewable Diesel	R100	35.7
4	6/9/2020	50% CARB Diesel / 50% Renewable Diesel	C50R50	69.7
5	6/10/2020	100% Renewable Diesel	R100	35.7
6	6/11/2020	50% CARB Diesel / 50% Renewable Diesel	C50R50	69.7
7	6/12/2020	50% CARB Diesel / 30% Renewable Diesel / 20% Biodiesel	C50R30B20	67.9
8	6/15/2020	100% CARB Diesel	C100	100.45
9	6/17/2020	US EPA Cert Diesel	Cert	-

TABLE ES-2. AVERAGE EPA LINEHAUL CYCLE RESULTS

Test Fuel	BSFC	Vol Fuel Consumption	BSHC	BSCO	$BSNO_x$	$BSCH_4$	BSPM	$BSCO_2$
	[lb/hp-hr]	[gal/MW-hr]	[g/hp-hr]	[g/hp-hr]	[g/hp-hr]	[g/hp-hr]	[g/hp-hr]	[g/hp-hr]
US EPA Tier 3/FEL Limits	*NS*	*NS*	*0.300*	*1.50*	*4.80*	*NS*	*0.090*	*NS*
Cert	0.369	70.0	0.065	0.23	5.29	0.001	0.030	536.8
C100	0.363	69.5	0.068	0.23	4.87	0.001	0.031	521.5
C50R30B20	0.367	72.0	0.057	0.19	4.88	0.001	0.021	515.2
C50R50	0.358	70.8	0.060	0.21	4.74	0.001	0.025	512.7
R100	0.352	72.1	0.051	0.20	4.65	0.001	0.021	501.0

NS = No Standard

Discussion

Over the Linehaul cycle, as the percentage of Renewable Diesel increased in the fuel blends, reductions were seen in emissions of Particulate Matter (PM), Oxides of Nitrogen (NO_x), and Carbon Dioxide (CO_2). Brake Specific Fuel consumption (BSFC) on a mass basis also showed a decreasing trend with increased Renewable fuel content. However, due to the lower density of the Renewable Diesel, volumetric fuel consumption generally got worse with increases in Renewable Diesel content.

Testing showed notable reduction in PM emissions when using the C50R30B20, C50/R50, and R100 fuel blends, compared to the other fuel mixtures tested. The increased NO_x emissions generally seen when operating on biodiesel were offset by the NO_x reductions in the renewable diesel, making the C50R30B20 fuel blend essentially NO_x neutral with the C100 fuel.

Similar trends in locomotive emissions were noted over the EPA Switch cycle, though the differences were more notable as the Renewable Diesel's impact was more pronounced at the lower load points. The following report provides further details on the results of this testing.

1.0 INTRODUCTION

The information detailed in the following report is the result of emissions testing performed for the California Air Resources Board (CARB), BNSF Railway Company (BNSF), and Union Pacific Railroad (UPRR) by Southwest Research Institute (SwRI).

The emissions testing was performed at the SwRI Locomotive Technology Center (LTC) in San Antonio, Texas.

This report includes the description of the locomotive tested, the test equipment and test fuels used, the procedures followed, and the results of the emissions testing. These topics are discussed in more detail in the following sections of the report.

2.0 TECHNICAL APPROACH

2.1 Test Engine

FIGURE 1. TEST LOCOMOTIVE, BNSF 7934

Testing was performed using BNSF 7934, a 4500 HP Tier 3 GE ES44C4 locomotive. BNSF provided the locomotive for testing and made arrangements to move it to San Antonio. The Tier 3 GEVO engines are equipped with high pressure common rail (HPCR) fuel injection systems.

The details of the test locomotive are listed in Table 1. The EPA useful life for this locomotive engine is 33,750 MW-hrs, and BNSF 7934 had accumulated 21,852 MW-hrs at the time of testing, or roughly 65 percent.

TABLE 1. TEST LOCOMOTIVE DETAILS

Road Number	BNSF 7934
Manufacturer	GE
Model	ES44C4
EPA Tier	3
Loco Build Date	12/2014
Engine Build Date	11/2014
Engine Model	GEVO12LDC12
Engine SN	G442140997
Locomotive SN	63016
Lifetime MW-hrs	21,852
Lifetime Mileage	625,296

2.2 Test Fuels

The original CARB-funded project plan called for duplicate testing of CARB diesel, 100% Renewable Diesel, and a 50/50 blend of the two fuels. Based on interest from Union Pacific Railroad (UP), and BNSF Railway (BNSF), a blend of 50% CARB diesel, 30% Renewable, and 20% Biodiesel, was added to the test plan, with funding for the extra fuel blends and locomotive tests covered by UP and BNSF.

Procurement of the CARB diesel fuel turned out to be very challenging, as the goal was to obtain commercially available fuel from California, but before it was blended with either Biodiesel or Renewable Diesel. Ultimately, SwRI procured 2,500 gallons of CARB diesel fuel from the PBF Energy refinery in Martinez, California.

Renewable Diesel was purchased from Renewable Energy Group, Inc. (REG), and was produced at their Geismar, Louisiana biorefinery. This plant uses a wide variety of feedstocks to produce approximately 75 million gallons of high-quality renewable diesel, renewable naphtha, and renewable autogas annually. The largest feedstock components at the time the test fuel was produced were likely animal fat (mostly beef tallow), used cooking oil (UCO), and distillers corn oil (DCO). The most conservative approach for the Renewable Diesel carbon intensity (CI) would be to assume it was made from 100% animal fat. SwRI purchased 2,200 gallons of Renewable Diesel from REG.

Biodiesel was donated to the project by REG, and was produced at the Albert Lea, Minnesota plant from a mixture of DCO and UCO. The REG Albert Lea plant has been in operation since 2005 with numerous upgrades over the years, including the addition of a distillation unit for the biodiesel product in 2014. The original nameplate production volume for the plant was 30 MMGPY but its current operating volume is more than 40 MMGPY. The exact CI of the biodiesel depends on the feedstock mix at the time (per CARB methodology), but it generally less than 30 gCO_2/MJ. The

most conservative approach would be to assume it is made from 100% DCO. REG provided 240 gallons of B100 to SwRI for this project.

The bulk CARB Diesel and Renewable were delivered to SwRI and transferred into temporary 4,000-gallon diesel tanks shown in Figure 2, that were steam-cleaned prior to use. The Neat Biodiesel was provided in its own 330-gallon shipping tote. Before blending, detailed fuel analyses of each fuel were performed by SwRI to make sure the fuels were as expected. Specifically, we wanted to ensure that the CARB diesel did not contain any Biodiesel or Renewable Diesel, and that the Renewable Diesel and Biodiesel were nearly 100 percent Bio Carbon, per ASTM D6866-20, using radiocarbon analysis.

FIGURE 2. FUEL STORAGE TANKS

Fuel analyses results are summarized in Table 1. All fuel property testing was completed at SwRI, with the exception of ASTM D6866-20 Bio-Carbon analysis, which was performed by Beta Analytic Testing Laboratory in Glenvar Heights, Florida. The ASTM D6866-20 results for the base fuels showed that the CARB diesel (C100) was 0.6 percent Bio Carbon, the Renewable Diesel (R100) was 100 percent Bio Carbon, and the Biodiesel (B100) was 95.7 percent Bio Carbon. REG reported that the small level (4.3 percent) of non-Bio Carbon was from the methanol used to convert the fat/oil into FAME (fatty acid methyl esters) and was an expected result. SwRI provided test results for the base fuels to CARB for review and approval prior to blending. SwRI received CARB approval to blend, and the 550-gallon stainless steel totes shown in Figure 2 were used for blending and storage of blended fuels.

Two fuel blends were prepared; a 50/50 volume mix of C100 and R100 (assigned a test code of C50/R50), and a blend of 50 percent C100, 30 percent R100, and 20 percent B100, and assigned the code C50/R30/B20.

Fuels were blended on a volumetric basis, using a volumetric flowmeter dispensing nozzle and cross-checked with fuel level strapping charts for the 550-gallon totes. After the appropriate amount of each fuel was added to each tote, they were mechanically mixed with a propeller-type mixer powered by an air motor for 30-minutes each. Samples were then drawn from the blended and mixed totes for blended fuel analyses. These results are also given in Table 2, along with properties of the current batch of EPA Certification Diesel fuel (as defined in 40 CFR Part 1065.703 Table 1). The fuel properties were also used to verify that the fuel mixtures used in testing were correctly blended. SwRI sent the fuel analysis results table, now updated with the blended test fuel results, to CARB for review and approval to proceed with testing. CARB approved the blended fuel results, and SwRI then proceeded with BNSF Railway to coordinate delivery to the test locomotive.

TABLE 2. TEST FUEL PROPERTIES

ASTM			C100	B100	R100	C50/R50 A	C50 R30 B20 A	EPA Cert.
Procedure	Property	Units						
D240G	BTUHeat	BTU/lb	19,792	17,186	20,297	20,020	19,560	19,652
D240N	BTUHeat	BTU/lb	18,534	16,090	18,922	18,702	18,270	18,445
	HHV	BTU/gal	137,800	126,562	132,296	134,897	132,760	138,103
HHV % change from C100			***	-8.2%	-4.0%	-2.1%	-3.7%	0.2%
	LHV	BTU/gal	129,041	118,491	123,334	126,016	124,004	129,621
LHV % change from C100			***	-8.2%	-4.4%	-2.3%	-3.9%	0.4%
D4052	API@60F		37.94	28.69	49.49	43.58	42.31	36.40
	SPGr@60F		0.835	0.883	0.782	0.808	0.814	0.843
	Dens@15C	g/ml	0.835	0.883	0.782	0.808	0.814	0.842
	density	lb/gal	7.0	7.4	6.5	6.7	6.8	7.0
D445 40c	Viscosty	cSt	2.2	4.1	3.1	2.6	2.8	2.3
D4629	Nitrogen	ppm	21.7	<1.0	<1.0			ND
	Nitmass	mass %	0.0022	0.0001	0.0000			ND
D4737A	Cetane Index		45.3	NA	95.5	66.6	69.2	46.1
D4737B	Cetane Index		45.1	NA	79.9	61.7	64.3	ND
D5186	Total Aromatics	Mass%	9.1	NA	0.2	5.0	3.3	29.8
	Mono Arom	Mass%	8.6	NA	0.2	4.6	3.2	22.8
	Poly Arom	Mass%	0.5	NA	ND	0.4	0.1	7.0
D5291 CH	Carbon	wt%	85.92	76.96	84.96	85.90	83.96	86.46
	Hydrogen	wt%	13.80	12.01	15.07	14.44	14.14	13.12
	Oxygen	wt%	0.28	11.03	-0.03	-0.34	1.90	0.42
	H/C		1.95	1.89	2.15	2.00	2.01	1.81
D5453	Sulfur	ppm	2.2	1.6	<0.5	0.9	0.7	8.1
D613	Cetane Number		48.1	51.9	>74.8	64.5	69.5	44.6
D86	PCorrIBP	degF	338.1	NA	287.8	334.0	344.7	333.0
	PCorrFBP	degF	663.2	NA	611.8	631.5	653.4	653.0
	PCorrD05	degF	373.6	NA	461.4	390.7	409.0	382.0
	PCorrD10	degF	383.3	NA	502.6	411.7	440.1	399.3
	PCorrD15	degF	392.9	NA	522.4	430.3	464.0	412.5
	PCorrD20	degF	401.4	NA	533.0	445.4	483.8	425.3
	PCorrD30	degF	419.6	NA	543.2	474.2	514.7	446.8
	PCorrD40	degF	438.0	NA	548.8	499.3	537.0	466.8
	PCorrD50	degF	456.9	NA	553.5	520.7	552.7	485.6
	PCorrD60	degF	477.8	NA	556.9	537.4	564.9	505.5
	PCorrD70	degF	502.6	NA	560.7	550.8	575.7	527.8
	PCorrD80	degF	534.6	NA	565.5	562.6	588.2	554.6
	PCorrD90	degF	583.3	NA	572.5	578.7	609.2	595.4
	PCorrD95	degF	628.1	NA	585.9	606.7	632.6	632.5
	UCorRcvd	mL	98.3	NA	97.6	97.3	97.9	97.8
	UCorLoss	mL	0.4	NA	1.1	1.1	0.6	0.9
D93	Flash	degF	145.0	353.0	133.0	137.0	143.0	153.0
D976	Cetane Index		44.4	NA	77.5	63.2	64.3	46.2
EN14078	FAME	volume %	0.3	100.0	<0.1	<0.1	19.5	0.1
D6866-20	% Bio Carbon	volume %	0.6	95.7	100	48.21	67 / 57 / 48	ND

The carbon intensity (CI) of the base fuels and fuel blends are summarized in Figure 3. The CI for the base fuels were provided by CARB and take into account the supplier and associated feed stock for the fuels[1].

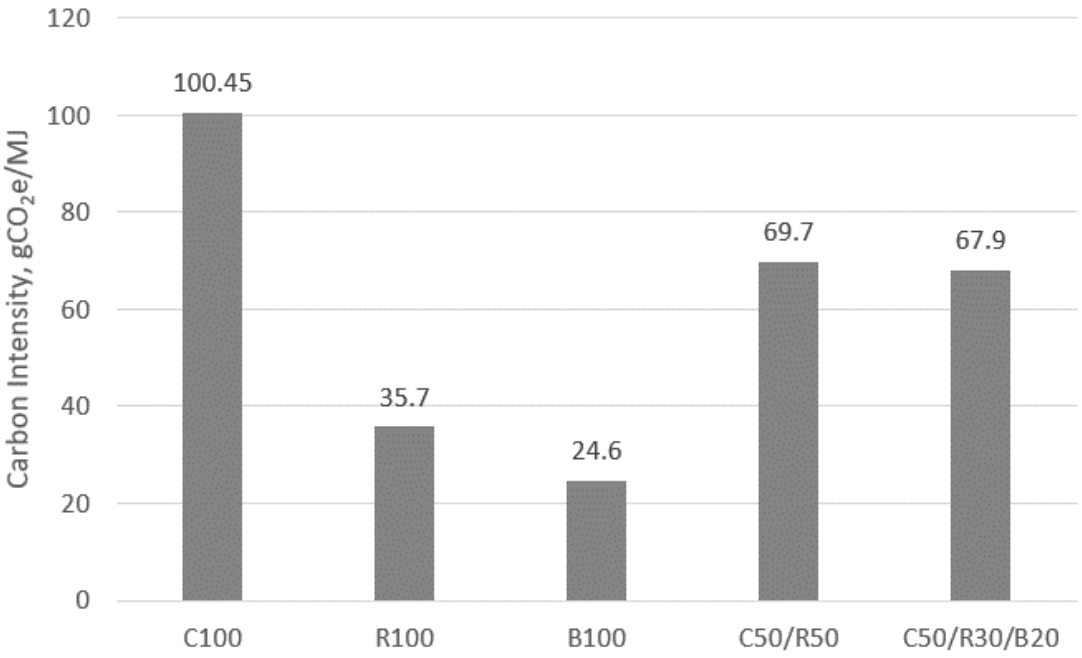

FIGURE 3. CARBON INTENSITY OF THE LOCOMOTIVE TEST FUELS

2.3 Instrumentation and Data Acquisition

All emissions testing was performed at the SwRI Locomotive Technology Center. All tests were conducted using the measurement equipment described below.

2.3.1 Fuel Measurements

Diesel fuel consumption was measured on a mass basis. The mass measuring device used by SwRI is a Micro Motion® CMF-25. Before testing, the Micro-Motion calibration was verified and compared to a calibrated scale. The Micro-Motion measures the makeup fuel supplied to a closed loop system, which is kept at a constant pressure that supplies fuel to the locomotive lift pump.

The SwRI fuel cart is equipped with heat exchangers and a chilled water system to regulate the fuel supply temperature to the locomotive at a target of 27°C (±6°C). The fuel supply temperature is measured at the outlet of the fuel cart, just after the heat exchanger.

[1] CARB LCFS Pathway Table https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/current-pathways_all.xlsx

2.3.2 Power Measurements

Traction power is measured on the direct current (DC) electrical bus within the locomotive. Voltage was measured directly, and current was measured using a DaniSense DS5000 current transformer. The output of the DaniSense and the voltage were sent to a Yokogawa WT3000E power analyzer.

Accessory power was measured at 3-phase AC output of thee auxiliary alternator. It was measured using a pair of current transducers, direct voltage measurements, and the Yokogawa WT3000E Power Analyzer.

Gross power was calculated using alternator efficiencies provided to SwRI by WABTEC.

2.3.3 Emissions Measurements

Gaseous emissions were sampled from within an exhaust stack extension using a Horiba MEXA7100 emissions bench. A heated line was used to transfer the raw exhaust sample to the emission instruments for analysis. Measured gaseous emissions included hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), oxides of nitrogen (NO_X), and methane (CH_4). Measurements were taken for each discrete mode listed in the EPA locomotive duty cycles.

Total hydrocarbon concentration in the raw exhaust was determined using a Horiba heated flame ionization detector (HFID), calibrated on propane. NO_X concentration in the raw exhaust was measured with a heated chemiluminescent detector (HCLD). NO_X correction factors for ambient air humidity were applied as specified by EPA in 40CFR1065.670. Concentrations of CO and CO_2 in the raw exhaust were determined by non-dispersive infrared (NDIR) instruments, and O_2 concentrations were measured using a magneto-pneumatic analyzer. Raw exhaust methane (CH_4) concentration was measured using a non-methane cutter (NMC) and a dedicated heated flame ionization detector (NMC-HFID) as outlined in 40CFR1065.365(d).

Particulate emissions were measured at each test point with a Sierra Instruments BG-3 Particulate Partial-Flow Sampling System. This “mini-dilution tunnel” device employs a partial flow dilution technique that can be characterized as the “split then dilute” technique, in which a portion of the raw locomotive exhaust is “split” from the total flow and mixed with filtered air in a micro dilution tunnel.

The Sierra BG-3 sampling system used a single ended probe facing upstream in the exhaust to extract a fraction of the raw exhaust. The diluted exhaust was then pulled through a Sierra Heat-Pak before being routed through a single 47 mm diameter TX40 sample filter. The Sierra Heat-Pak is a heated enclosure (target temperature of 47°C) that contains a stainless-steel cyclonic separator and a residence chamber. This is an optional BG-3 accessory offered by Sierra Instruments as a tool for sampling under 40CFR1065 criteria. The BG-3 measured the dilution air flow using a laminar flow element (LFE), and the total dilute sample was measured by a positive displacement roots meter. The difference between the two measurements is defined as the raw

exhaust sample volume, which was used along with the filter mass increase and the calculated engine exhaust flow rate to calculate the PM mass emission rate of the locomotive.

2.4 Common Test Parameters

During testing, the locomotive was provided with compressed air from an outside source, such that the air compressor remained unloaded throughout the test. All auxiliary cab loads (such as headlights, cab lights, and air conditioners) were turned off. The same measurement devices were used during each test. The locomotive was self-loaded on its own grids.

2.5 Test Sequence

Upon delivery to SwRI, the locomotive was subject to an inbound inspection for obvious mechanical or electrical problems. This inspection also consisted of recording part numbers and serial numbers for key components (including photographs of the EPA compliance sticker and EPA Engine Compliance tag).

Testing was done in accordance with the Federal Test Protocol (FTP), as defined by the Code of Federal Regulations (CFR), Title 40, Part 1065 and Part 1033. A single FTP was run each day, targeting similar ambient temperature conditions. In total, 9 individual tests were run over the course of this project.

The test order of the first eight tests was generated randomly using Microsoft Excel. The order and the date that each test was completed are listed in Table 3. FTP 9, which was run on US EPA Certification Diesel, was not originally included in the test matrix and was therefore not included in the randomized test matrix. It was added to the end of the project as a reference point, to put the other tests into a common context.

TABLE 3. TEST FUELS AND TEST ORDER

Test #	Test Date	Test Fuel	Designation
1	6/4/2020	100% CARB Diesel	C100
2	6/5/2020	50% CARB Diesel / 30% Renewable Diesel / 20% Biodiesel	C50R30B20
3	6/8/2020	100% Renewable Diesel	R100
4	6/9/2020	50% CARB Diesel / 50% Renewable Diesel	C50R50
5	6/10/2020	100% Renewable Diesel	R100
6	6/11/2020	50% CARB Diesel / 50% Renewable Diesel	C50R50
7	6/12/2020	50% CARB Diesel / 30% Renewable Diesel / 20% Biodiesel	C50R30B20
8	6/15/2020	100% CARB Diesel	C100
9	6/17/2020	US EPA Cert Diesel	Cert

SwRI utilizes a closed loop system for fuel measurement and temperature control. It is not possible to fully drain this system when switching fuels due to issues with air entering the system so testing was performed on the system before this project began to determine the time necessary to fully

purge the remaining fuel in the system. This was completed right at 2 minutes. When switching fuels during this project, an extra minute was added to that purge time to make certain that all previous fuel was purged from the system before the next test began.

2.6 Duty-Cycle Weighting Factors

The US EPA Linehaul and Switch duty-cycles were used to determine the fuel consumption values reported in this project. Table 4 lists the EPA Linehaul duty-cycle weighting factors, and Table 5 lists the EPA Switch duty-cycle.

TABLE 4. LINEHAUL DUTY-CYCLE WEIGHTING FACTORS

Locomotive Notch	**Weighting factor, %**
Notch 8	16.2
Notch 7	3.0
Notch 6	3.9
Notch 5	3.8
Notch 4	4.4
Notch 3	5.2
Notch 2	6.5
Notch 1	6.5
DB-2 (580 RPM)	12.5
Idle (300 RPM)	38.0
Total	**100.0**

TABLE 5. SWITCH DUTY-CYCLE WEIGHTING FACTORS

Locomotive Notch	**Weighting factor, %**
Notch 8	0.8
Notch 7	0.2
Notch 6	1.5
Notch 5	3.6
Notch 4	3.6
Notch 3	5.8
Notch 2	12.3
Notch 1	12.4
DB-2 (580 RPM)	-
Idle (300 RPM)	59.8
Total	**100.0**

3.0 TEST RESULTS

This section includes emissions and fuel consumption results from all testing performed. Detailed test summaries are given in Appendix A of this report.

3.1 Test Conditions

Ambient conditions have some influence on locomotive emissions, smoke opacity, and fuel consumption. To minimize the impact of these effects, similar ambient temperatures were targeted for each test. Engine intake air temperature, intake air humidity, and barometric pressure throughout each test are shown in Figures 4-6 below.

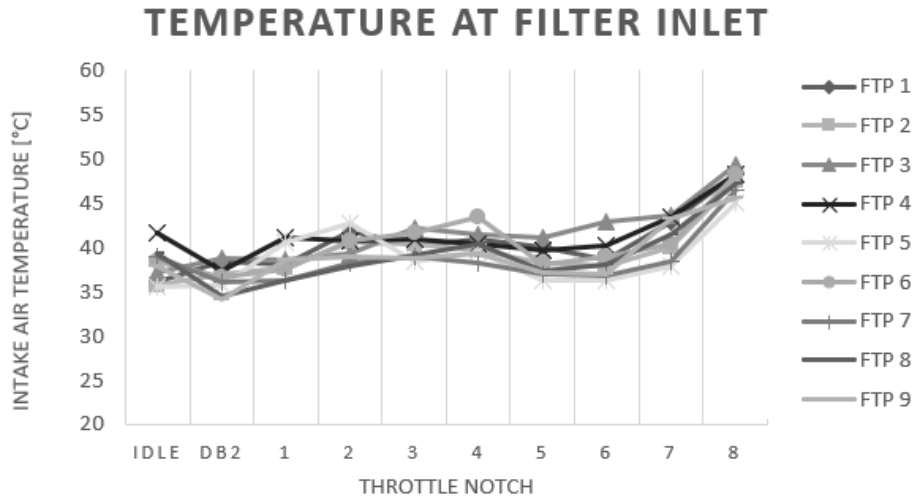

FIGURE 4. INTAKE AIR TEMPERATURES AT AIR FILTER INLET DURING EACH TEST

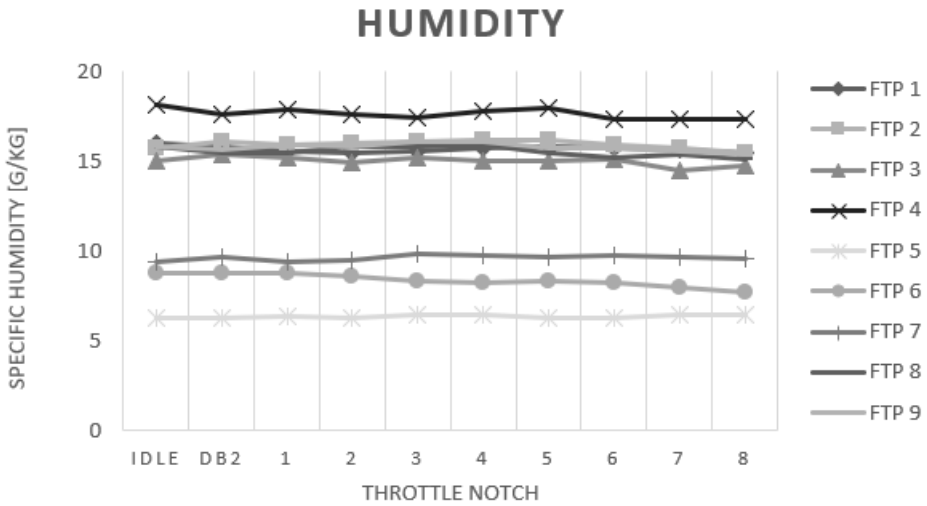

FIGURE 5. INTAKE AIR HUMIDITY DURING EACH TEST

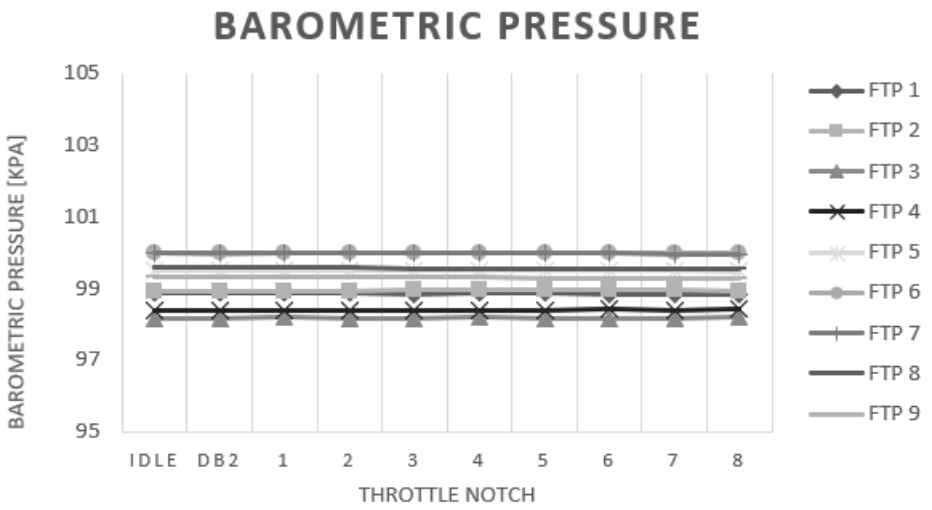

FIGURE 6. BAROMETRIC PRESSURE DURING EACH TEST

While similar ambient temperatures and barometric pressure were seen during each test, humidity changes did occur. There was slightly higher humidity for FTP 4, and notably lower humidity for FTPs 5-7. Note that, while humidity has a large effect on NOx emissions, correction factors for ambient humidity are specified in 40 CFR Part 1065. All NOx reported herein are corrected for ambient humidity.

3.2 Duty Cycle Weighted Emissions Results

The duty cycle results for each test run over the linehaul and switch cycles are listed in Tables 6 and 7, respectively. The average emissions test results for each fuel mixture are show in Tables 8 and 9.

TABLE 6. LINEHAUL CYCLE EMISSIONS RESULTS

Test #	Test Fuel	BSHC [g/hp-hr]	BSCO [g/hp-hr]	BSNO$_x$ [g/hp-hr]	BSCH4 [g/hp-hr]	BSPM [g/hp-hr]	BSCO$_2$ [g/hp-hr]
1	C100	0.068	0.24	4.85	0.000	0.033	521.3
2	C50R30B20	0.056	0.20	4.87	0.001	0.023	515.0
3	R100	0.051	0.21	4.58	0.001	0.024	504.1
4	C50R50	0.061	0.22	4.68	0.001	0.027	513.4
5	R100	0.051	0.18	4.72	0.001	0.018	497.9
6	C50R50	0.060	0.19	4.79	0.001	0.022	512.1
7	C50R30B20	0.058	0.18	4.89	0.001	0.020	515.4
8	C100	0.068	0.23	4.89	0.001	0.028	521.8
9	Cert	0.065	0.23	5.29	0.001	0.030	536.8

TABLE 7. SWITCH CYCLE EMISSIONS RESULTS

Test #	Test Fuel	BSHC [g/hp-hr]	BSCO [g/hp-hr]	BSNOx [g/hp-hr]	BSCH4 [g/hp-hr]	BSPM [g/hp-hr]	BSCO2 [g/hp-hr]
1	C100	0.092	0.34	6.84	0.001	0.047	557.1
2	C50R30B20	0.073	0.28	6.70	0.002	0.030	550.1
3	R100	0.059	0.31	6.22	0.002	0.029	540.0
4	C50R50	0.077	0.33	6.44	0.002	0.033	553.4
5	R100	0.061	0.26	6.45	0.002	0.023	536.4
6	C50R50	0.077	0.29	6.55	0.002	0.029	549.7
7	C50R30B20	0.076	0.26	6.76	0.002	0.028	551.9
8	C100	0.092	0.34	6.88	0.002	0.035	562.7
9	Cert	0.096	0.35	7.60	0.002	0.041	597.7

TABLE 8. AVERAGE LINEHAUL CYCLE EMISSIONS RESULTS

Test Fuel	BSHC [g/hp-hr]	BSCO [g/hp-hr]	BSNOx [g/hp-hr]	BSCH4 [g/hp-hr]	BSPM [g/hp-hr]	BSCO2 [g/hp-hr]
Cert	0.065	0.23	5.29	0.001	0.030	536.8
C100	0.068	0.23	4.87	0.001	0.031	521.5
C50R30B20	0.057	0.19	4.88	0.001	0.021	515.2
C50R50	0.060	0.21	4.74	0.001	0.025	512.7
R100	0.051	0.20	4.65	0.001	0.021	501.0

TABLE 9. AVERAGE SWITCH CYCLE EMISSIONS RESULTS

Test Fuel	BSHC [g/hp-hr]	BSCO [g/hp-hr]	BSNOx [g/hp-hr]	BSCH4 [g/hp-hr]	BSPM [g/hp-hr]	BSCO2 [g/hp-hr]
Cert	0.096	0.35	7.60	0.002	0.041	597.7
C100	0.092	0.34	6.86	0.002	0.041	559.9
C50R30B20	0.075	0.27	6.73	0.002	0.029	551.0
C50R50	0.077	0.31	6.49	0.002	0.031	551.5
R100	0.060	0.29	6.33	0.002	0.026	538.2

Using the test on the US EPA Certification fuel (Cert) as the baseline, Table 10 shows the percent change for each emission. Negative numbers imply a reduction from the baseline in the given emission, while a positive number is an increase.

TABLE 10. PERCENT CHANGE FROM BASELINE - LINEHAUL

Test Fuel	BSHC [% change]	BSCO [% change]	BSNOx [% change]	BSCH4 [% change]	BSPM [% change]	BSCO2 [% change]
Cert	-	-	-	-	-	-
C100	3.9%	1.0%	-8.0%	-8.9%	1.5%	-2.8%
C50R30B20	-12.5%	-19.6%	-7.8%	-3.4%	-29.2%	-4.0%
C50R50	-8.1%	-10.6%	-10.5%	-4.2%	-18.1%	-4.5%
R100	-21.6%	-15.6%	-12.1%	4.5%	-30.4%	-6.7%

TABLE 11. PERCENT CHANGE FROM BASELINE - SWITCH

Test Fuel	BSHC [% change]	BSCO [% change]	BSNOx [% change]	BSCH4 [% change]	BSPM [% change]	BSCO2 [% change]
Cert	-	-	-	-	-	-
C100	-4.0%	-3.7%	-9.7%	-7.8%	-0.9%	-6.3%
C50R30B20	-22.0%	-23.0%	-11.4%	-5.1%	-29.5%	-7.8%
C50R50	-19.9%	-12.5%	-14.5%	-3.6%	-24.2%	-7.7%
R100	-37.0%	-19.0%	-16.6%	7.4%	-35.9%	-10.0%

3.3 Duty Cycle Weighted Fuel Consumption Results

The fuel consumption results for each test are listed below in Table 10. Fuel consumption results are displayed in brake specific fuel consumption (BSFC), which is a mass-based value. In addition, a volumetric fuel consumption was also calculated based off the density of each fuel mixture, expressed in gallons per Megawatt-hour (gal/MW-hr). Average fuel consumption results for each fuel blend are in Table 12.

TABLE 12. FUEL CONSUMPTION RESULTS

		Line Haul Cycle		Switch Cycle	
Test #	Test Fuel	BSFC [lb/hp-hr]	Volumetric Fuel Cons. [gal/MW-hr]	BSFC [lb/hp-hr]	Volumetric Fuel Cons. [gal/MW-hr]
1	C100	0.363	69.5	0.387	74.1
2	C50R30B20	0.367	72.0	0.391	76.8
3	R100	0.355	72.6	0.379	77.6
4	C50R50	0.358	70.9	0.385	76.3
5	R100	0.350	71.6	0.376	77.0
6	C50R50	0.357	70.7	0.383	75.7
7	C50R30B20	0.367	72.1	0.392	77.0
8	C100	0.363	69.5	0.391	74.8
9	Cert	0.369	70.0	0.410	77.8

TABLE 13. AVERAGE FUEL CONSUMPTION RESULTS

	Line Haul Cycle		Switch Cycle	
Test Fuel	BSFC [lb/hp-hr]	Volumetric Fuel Cons. [gal/MW-hr]	BSFC [lb/hp-hr]	Volumetric Fuel Cons. [gal/MW-hr]
Cert	0.369	70.0	0.410	77.8
C100	0.363	69.5	0.389	74.5
C50R30B20	0.367	72.0	0.392	76.9
C50R50	0.358	70.8	0.384	76.0
R100	0.352	72.1	0.378	77.3

3.4 Emissions Trends

Some overall emissions trends were noted during this testing. In general, as the fraction of renewable diesel was increased, overall emissions trended downward.

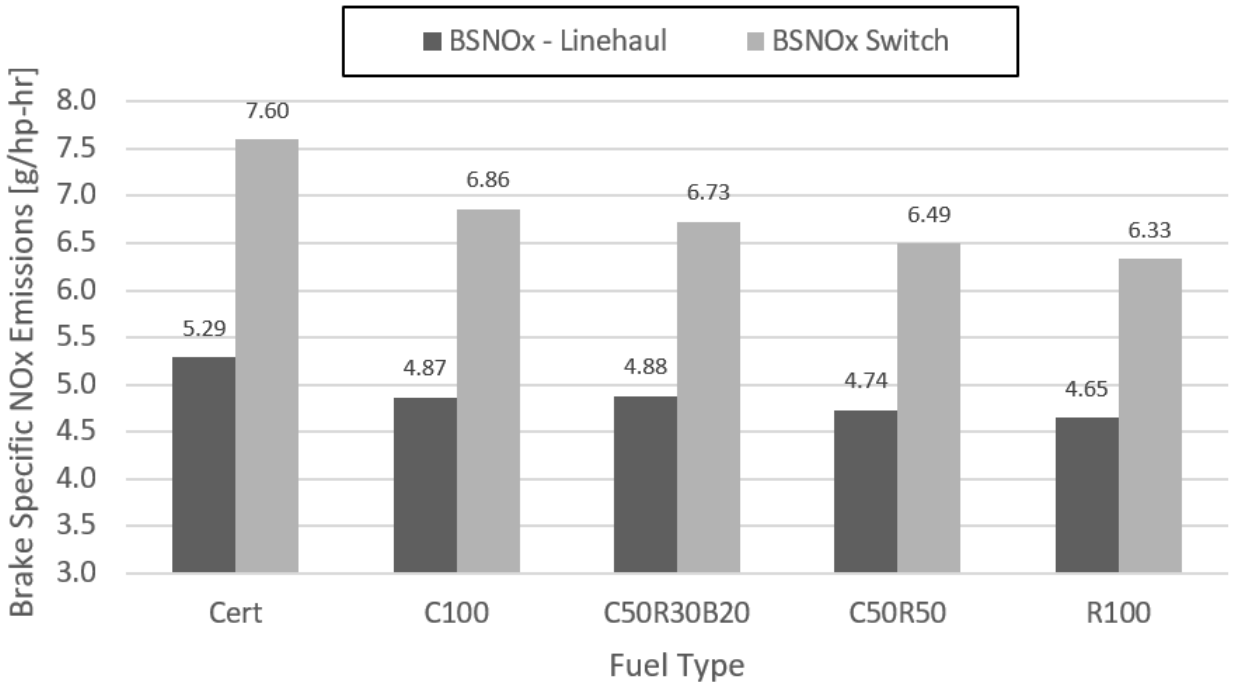

FIGURE 7. BRAKE SPECIFIC NOx AVERAGE BY FUEL TYPE

Figure 7 shows the average brake specific NOx emissions for each fuel type. NOx trended slightly lower as the percentage of renewable diesel increased, showing a 2.7% decrease in NOx from the C100 average with the C50R50 blend, and a 4.4% reduction using R100. EPA Cert diesel had NOx emissions that were 8.7% higher than the C100 average. The C50R30B20 fuel blend showed NOx equivalence with C100, implying that the NOx reduction from the renewable diesel balanced the NOx increase that is often associated with Biodiesel.

Particulate matter emissions for both EPA Cert Diesel and C100 were essentially equivalent over the linehaul and switch cycles. Over the linehaul cycle C50R50 and R100 showed reductions in PM of 19.3% and 31.4%, respectively. The C50R30B20 mixture also showed a 30.3% reduction in PM. Figure 8 shows the brake specific PM emissions averages for each test fuel.

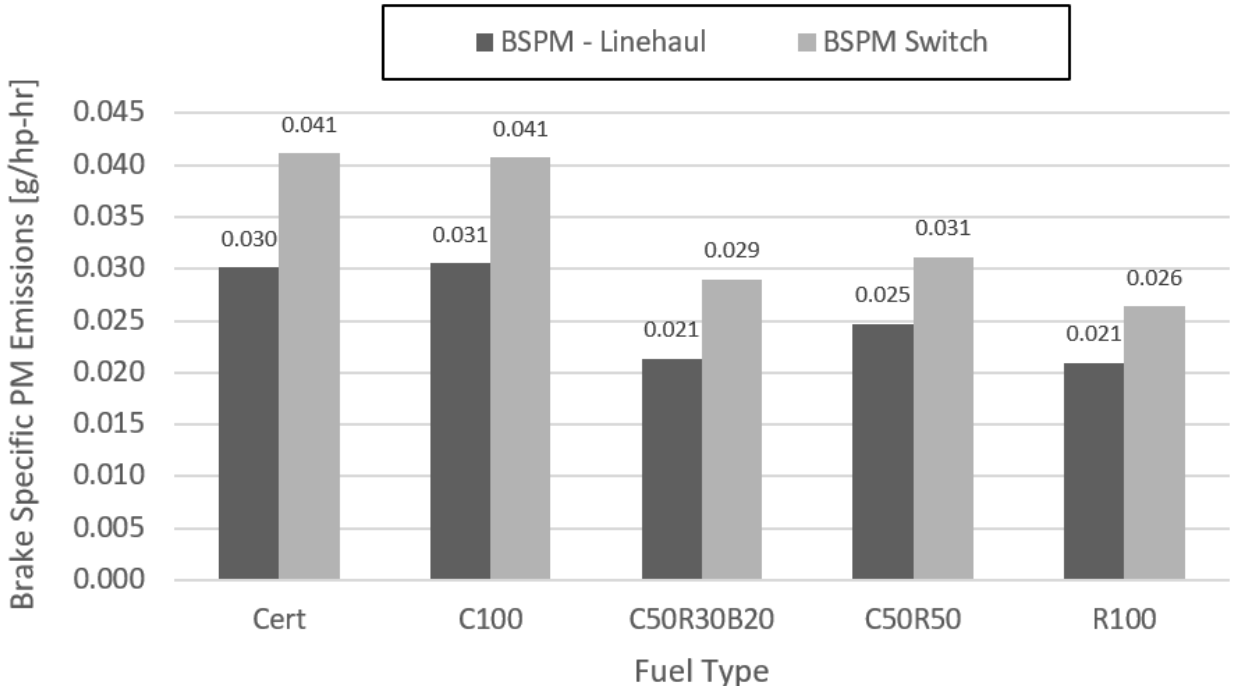

FIGURE 8. BRAKE SPECIFIC PM AVERAGE BY FUEL TYPE

As seen in Figures 9-11, other regulated emissions showed similar trends to those discussed above. Reductions in CO2, CO, and HC were seen as the as the percentage of renewable diesel in the fuel was increased.

Overall, renewable diesel showed reductions in all regulated locomotive emissions with reductions generally increasing as the percentage of renewable diesel increased. The addition of biodiesel in the C50R30B20 mixture did not decrease BSNOx emissions compared to C100, but showed larger decreases in PM, HC, and CO emissions.

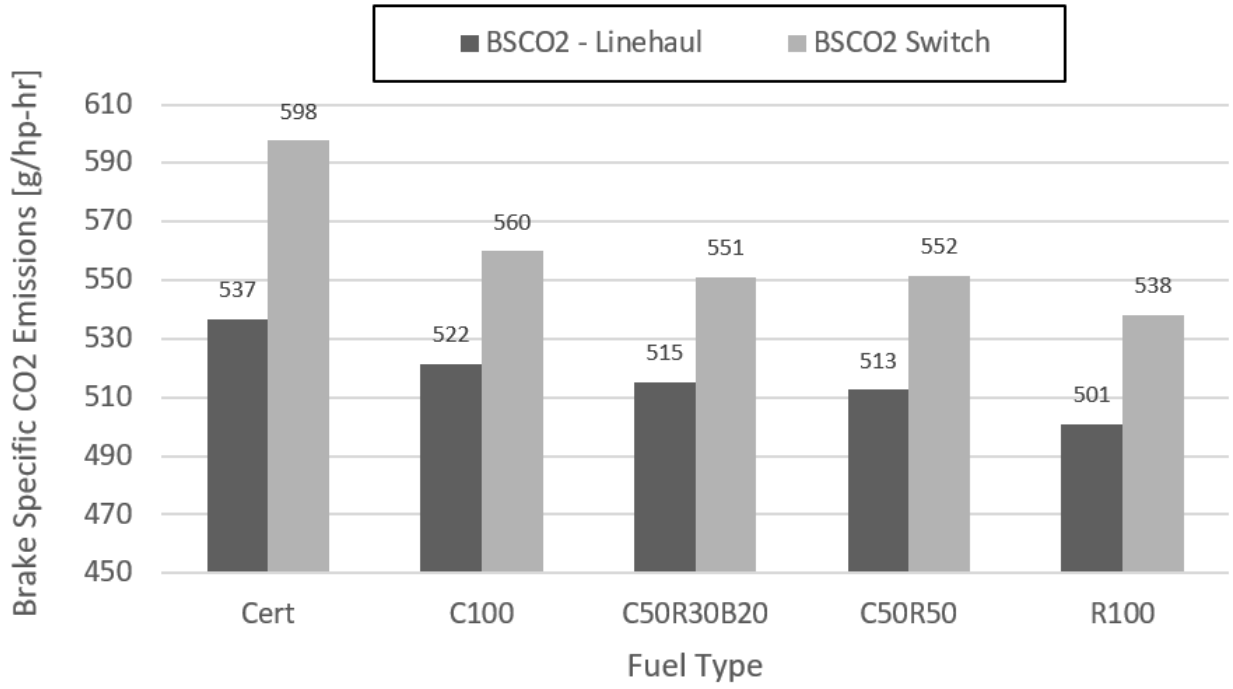

FIGURE 9. BRAKE SPECIFIC CO2 AVERAGE BY FUEL TYPE

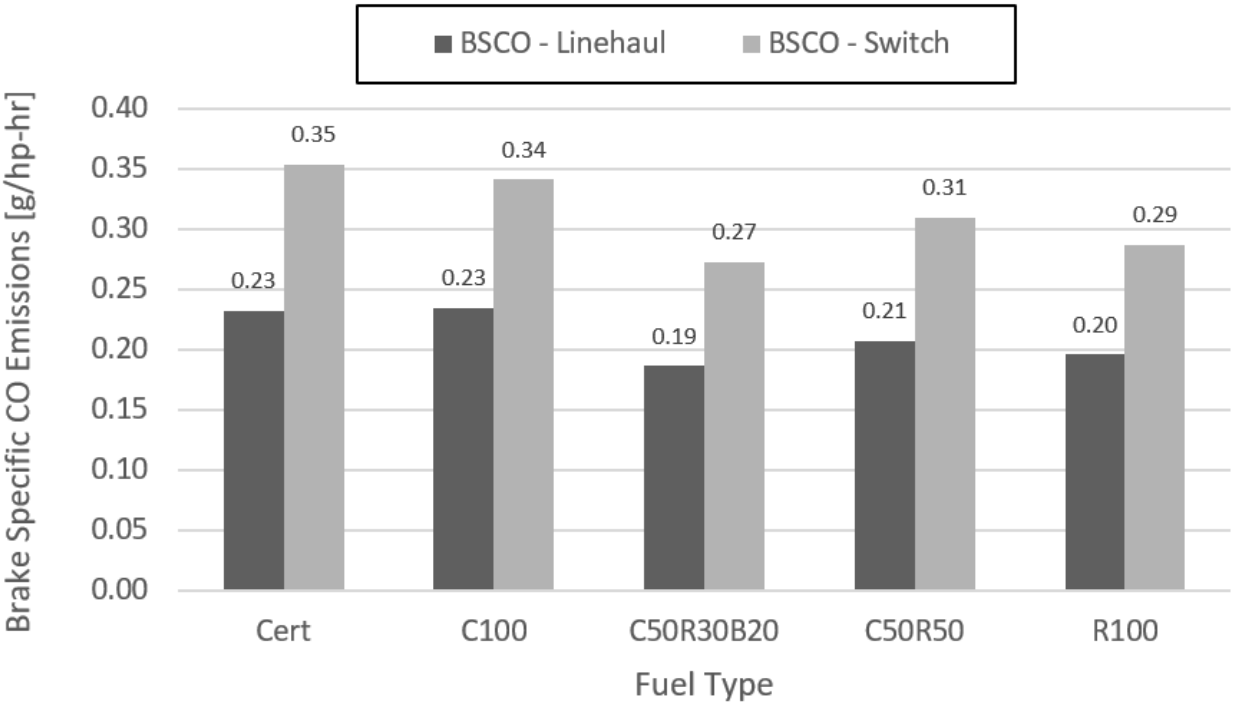

FIGURE 10. BRAKE SPECIFIC CO AVERAGE BY FUEL TYPE

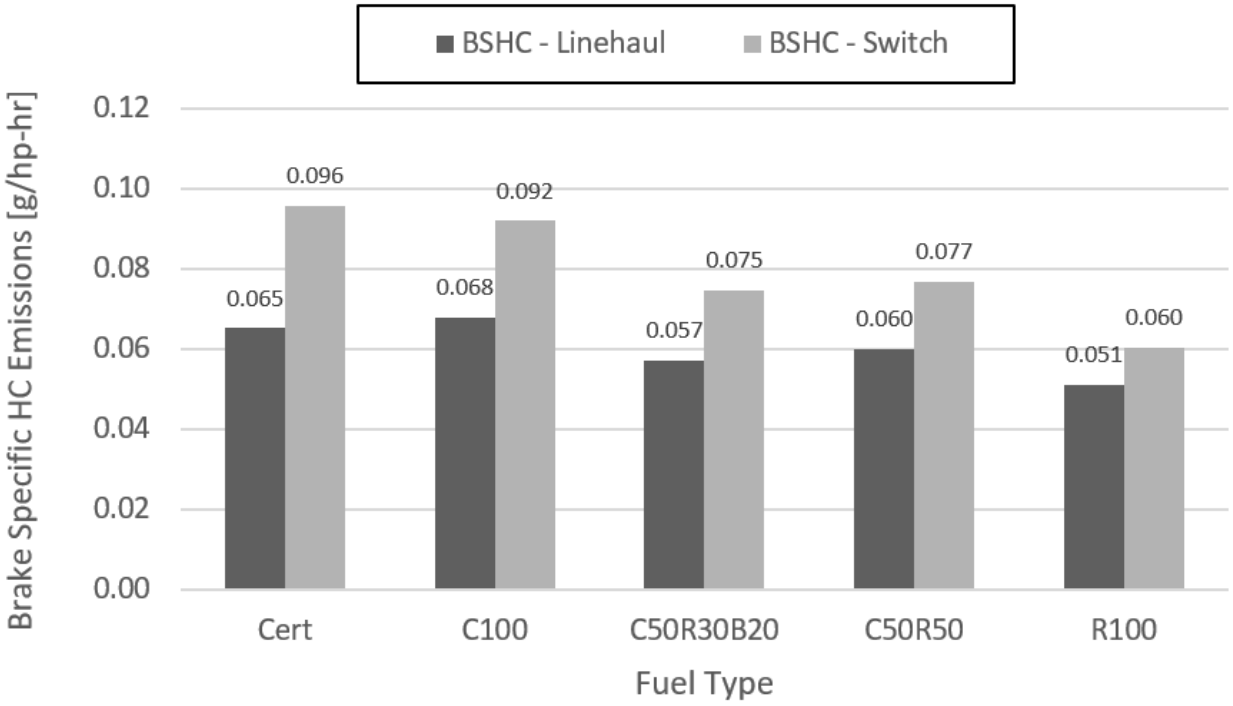

FIGURE 11. BRAKE SPECIFIC HC AVERAGE BY FUEL TYPE

The various fuel blends had very limited effect on locomotive smoke opacity. The average smoke opacity results for each fuel blend are shown in Figure 12. Overall, the locomotive was well below the allowable smoke opacity limits on each test fuel.

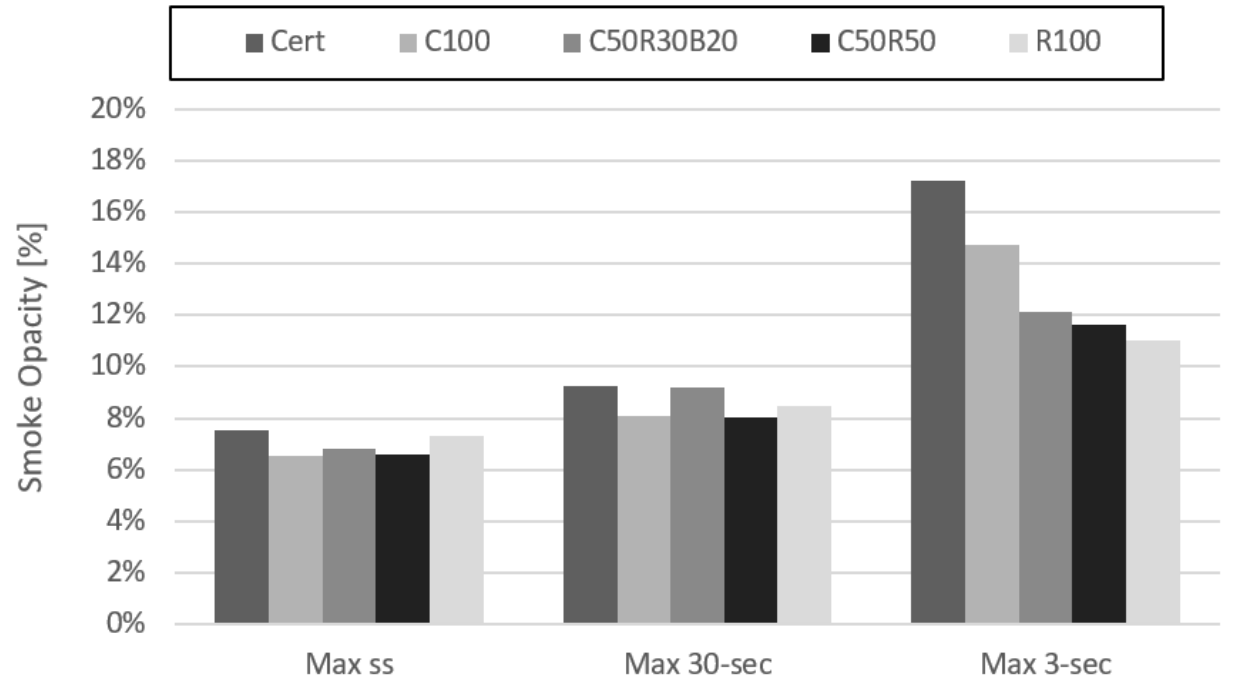

FIGURE 12. SMOKE OPACITY AVERAGE BY FUEL TYPE

REFERENCES

List of inventions and copyrighted materials produced
Glossary of Terms, Abbreviations, and Symbols

AAR – Association of American Railroads
AC – Alternating Current
BSFC – Brake Specific Fuel Consumption
C100 – 100% CARB Diesel
C50R30B20 – 50% CARB Diesel, 30% Renewable Diesel, 20% Biodiesel
C50R50 – 50% CARB Diesel, 50% Renewable Diesel
CARB – California Air Resources Board
CH4 – Methane
CO – Carbon Monoxide
CO2 – Carbon Dioxide
DC – Direct Current
EPA – Environmental Protection Agency
HC – Hydrocarbons
hp – Horsepower
lb – Pounds mass
MW – Megawatt
NOx – Oxides of Nitrogen
PM – Particulate Matter
R100 – 100% Renewable Diesel

APPENDICES

BNSF 7934 - T3 GE ES44C4
Test #: FTP 1
HDT Run #: 000852
Date: 6/4/2020
Fuel: C100

Notch	Gross HP	obs Fuel Rate (lb/hr)	HC (g/hr)	CO (g/hr)	Corr. NOx (g/hr)	CH4 (g/hr)	PM (g/hr)	CO2 (g/hr)	BSFC lb/hp-hr)
IDLE	8.8	20.5	14.0	21.7	854.8	0.9	9.3	30,418	2.338
DB2	19.8	45.0	38.2	129.2	871.6	1.5	11.6	66,005	2.276
1	284.0	106.5	36.2	94.1	2,596.3	0.0	21.7	153,759	0.375
2	573.7	198.4	59.8	114.4	5,035.8	0.0	20.9	285,381	0.346
3	1,194.8	454.8	110.6	346.9	6,226.2	0.0	38.0	652,713	0.381
4	1,683.3	615.8	82.5	845.9	7,710.6	0.0	47.4	882,365	0.366
5	2,267.4	824.3	97.2	1,009.2	9,314.1	0.0	74.5	1,182,052	0.364
6	2,995.3	1,046.5	135.6	567.8	13,220.5	0.0	42.6	1,502,036	0.349
7	3,676.8	1,284.6	182.2	447.8	16,855.1	0.0	47.3	1,844,713	0.349
8	4,383.8	1,533.3	265.7	792.4	18,202.4	0.0	139.7	2,201,831	0.350

Smoke		
Max ss	lax 30-se	Max 3-sec
7%	8%	16%

EPA Switcher Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	59.8%	5.2	12.3	8.4	13.0	511.2	0.5	5.5	18,190
DB2	0.0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
1	12.4%	35.2	13.2	4.5	11.7	321.9	0.0	2.7	19,066
2	12.3%	70.6	24.4	7.4	14.1	619.4	0.0	2.6	35,102
3	5.8%	69.3	26.4	6.4	20.1	361.1	0.0	2.2	37,857
4	3.6%	60.6	22.2	3.0	30.5	277.6	0.0	1.7	31,765
5	3.6%	81.6	29.7	3.5	36.3	335.3	0.0	2.7	42,554
6	1.5%	44.9	15.7	2.0	8.5	138.3	0.0	0.6	22,531
7	0.2%	7.4	2.6	0.4	0.9	33.7	0.0	0.1	3,689
8	0.8%	35.1	12.3	2.1	6.3	145.6	0.0	1.1	17,615
sum =	100.0%	409.9	158.6	37.6	141.4	2804.2	0.5	19.2	228369
			0.387	**0.09**	**0.3**	**6.8**	**0.0**	**0.047**	**557**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Modal Brake-Specific Emissions

Notch	HC (g/hp-hr)	CO (g/hp-hr)	Corr. NOx (g/hp-hr)	PM (g/hp-hr)	CO2 (g/hp-hr)
IDLE	1.60	2.47	97.47	1.06	3,469
DB2	1.93	6.54	44.12	0.58	3,341
1	0.13	0.33	9.14	0.08	541
2	0.10	0.20	8.78	0.04	497
3	0.09	0.29	5.21	0.03	546
4	0.05	0.50	4.58	0.03	524
5	0.04	0.45	4.11	0.03	521
6	0.05	0.19	4.41	0.01	501
7	0.05	0.12	4.58	0.01	502
8	0.06	0.18	4.15	0.03	502

EPA Freight Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	38.0%	3.3	7.8	5.3	8.2	324.8	0.3	3.5	11,559
DB2	12.5%	2.5	5.6	4.8	16.1	108.9	0.2	1.4	8,251
1	6.5%	18.5	6.9	2.4	6.1	168.8	0.0	1.4	9,994
2	6.5%	37.3	12.9	3.9	7.4	327.3	0.0	1.4	18,550
3	5.2%	62.1	23.7	5.8	18.0	323.8	0.0	2.0	33,941
4	4.4%	74.1	27.1	3.6	37.2	339.3	0.0	2.1	38,824
5	3.8%	86.2	31.3	3.7	38.4	353.9	0.0	2.8	44,918
6	3.9%	116.8	40.8	5.3	22.1	515.6	0.0	1.7	58,579
7	3.0%	110.3	38.5	5.5	13.4	505.7	0.0	1.4	55,341
8	16.2%	710.2	248.4	43.0	128.4	2948.8	0.0	22.6	356,697
sum =	100.0%	1221.2	443.0	83.2	295.5	5916.9	0.5	40.3	636654
			0.363	**0.07**	**0.2**	**4.8**	**0.00**	**0.033**	**521**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Fuel-Specific Emissions

Notch	HC (g/lb fuel)	CO (g/lb fuel)	Corr. NOx (g/lb fuel)	PM (g/lb fuel)	CO2 (g/lb fuel)
IDLE	0.68	1.06	41.69	0.45	1,484
DB2	0.85	2.87	19.38	0.26	1,468
1	0.34	0.88	24.38	0.20	1,444
2	0.30	0.58	25.38	0.11	1,438
3	0.24	0.76	13.69	0.08	1,435
4	0.13	1.37	12.52	0.08	1,433
5	0.12	1.22	11.30	0.09	1,434
6	0.13	0.54	12.63	0.04	1,435
7	0.14	0.35	13.12	0.04	1,436
8	0.17	0.52	11.87	0.09	1,436

BNSF 7934 - T3 GE ES44C4
Test #: FTP 2
HDT Run #: 000853
Date: 6/5/2020
Fuel: C50R30B20

Notch	Gross HP	obs Fuel Rate (lb/hr)	HC (g/hr)	CO (g/hr)	Corr. NOx (g/hr)	CH4 (g/hr)	PM (g/hr)	CO2 (g/hr)	BSFC lb/hp-hr)
IDLE	8.4	20.1	10.1	16.8	702.0	1.0	2.9	29,065	2.374
DB2	19.8	45.9	28.3	88.2	655.4	1.9	11.6	65,995	2.314
1	283.8	106.9	28.8	78.2	2,196.2	0.1	21.3	150,944	0.377
2	573.9	202.2	44.5	109.7	5,205.6	0.0	17.9	284,279	0.352
3	1,196.9	460.3	94.5	246.4	6,658.4	0.0	30.4	645,797	0.385
4	1,684.5	623.2	74.8	710.6	8,123.7	0.0	28.6	873,172	0.370
5	2,269.6	835.6	84.9	839.3	9,624.5	0.0	45.9	1,171,497	0.368
6	2,995.8	1,062.2	114.8	480.1	13,743.2	0.0	28.9	1,490,182	0.355
7	3,678.4	1,299.2	151.1	375.4	17,367.9	0.0	35.1	1,823,825	0.353
8	4,385.7	1,549.0	223.3	643.5	18,464.0	0.0	98.4	2,174,551	0.353

Smoke		
Max ss	lax 30-se	lax 3-sec
6%	8%	13%

EPA Switcher Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	59.8%	5.1	12.0	6.0	10.0	419.8	0.6	1.7	17,381
DB2	0.0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
1	12.4%	35.2	13.3	3.6	9.7	272.3	0.0	2.6	18,717
2	12.3%	70.6	24.9	5.5	13.5	640.3	0.0	2.2	34,966
3	5.8%	69.4	26.7	5.5	14.3	386.2	0.0	1.8	37,456
4	3.6%	60.6	22.4	2.7	25.6	292.5	0.0	1.0	31,434
5	3.6%	81.7	30.1	3.1	30.2	346.5	0.0	1.7	42,174
6	1.5%	44.9	15.9	1.7	7.2	206.1	0.0	0.4	22,353
7	0.2%	7.4	2.6	0.3	0.8	34.7	0.0	0.1	3,648
8	0.8%	35.1	12.4	1.8	5.1	147.7	0.0	0.8	17,396
sum =	100.0%	410.0	160.3	30.1	116.4	2746.1	0.6	12.3	225525
			0.391	**0.07**	**0.3**	**6.7**	**0.0**	**0.030**	**550**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Modal Brake-Specific Emissions

Notch	HC (g/hp-hr)	CO (g/hp-hr)	Corr. NOx (g/hp-hr)	PM (g/hp-hr)	CO2 (g/hp-hr)
IDLE	1.20	1.99	83.08	0.34	3,440
DB2	1.43	4.45	33.07	0.59	3,330
1	0.10	0.28	7.74	0.08	532
2	0.08	0.19	9.07	0.03	495
3	0.08	0.21	5.56	0.03	540
4	0.04	0.42	4.82	0.02	518
5	0.04	0.37	4.24	0.02	516
6	0.04	0.16	4.59	0.01	497
7	0.04	0.10	4.72	0.01	496
8	0.05	0.15	4.21	0.02	496

EPA Freight Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	38.0%	3.2	7.6	3.8	6.4	266.8	0.4	1.1	11,045
DB2	12.5%	2.5	5.7	3.5	11.0	81.9	0.2	1.5	8,249
1	6.5%	18.4	7.0	1.9	5.1	142.8	0.0	1.4	9,811
2	6.5%	37.3	13.1	2.9	7.1	338.4	0.0	1.2	18,478
3	5.2%	62.2	23.9	4.9	12.8	346.2	0.0	1.6	33,581
4	4.4%	74.1	27.4	3.3	31.3	357.4	0.0	1.3	38,420
5	3.8%	86.2	31.8	3.2	31.9	365.7	0.0	1.7	44,517
6	3.9%	116.8	41.4	4.5	18.7	536.0	0.0	1.1	58,117
7	3.0%	110.4	39.0	4.5	11.3	521.0	0.0	1.1	54,715
8	16.2%	710.5	250.9	36.2	104.3	2391.2	0.0	15.9	352,277
sum =	100.0%	1221.7	447.9	68.8	239.8	5347.4	0.6	27.8	629211
			0.367	**0.06**	**0.2**	**4.9**	**0.00**	**0.023**	**515**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Fuel-Specific Emissions

Notch	HC (g/lb fuel)	CO (g/lb fuel)	Corr. NOx (g/lb fuel)	PM (g/lb fuel)	CO2 (g/lb fuel)
IDLE	0.50	0.84	34.99	0.14	1,449
DB2	0.62	1.92	14.29	0.25	1,439
1	0.27	0.73	20.54	0.20	1,412
2	0.22	0.54	25.75	0.09	1,406
3	0.21	0.54	14.46	0.07	1,403
4	0.12	1.14	13.03	0.05	1,401
5	0.10	1.00	11.52	0.05	1,402
6	0.11	0.45	12.94	0.03	1,403
7	0.12	0.29	13.37	0.03	1,404
8	0.14	0.42	11.92	0.06	1,404

BNSF 7934 - T3 GE ES44C4
Test #: FTP 3
HDT Run #: 000854
Date: 6/8/2020
Fuel: R100

Notch	Gross HP	obs Fuel Rate (lb/hr)	HC (g/hr)	CO (g/hr)	Corr. NOx (g/hr)	CH4 (g/hr)	PM (g/hr)	CO2 (g/hr)	BSFC lb/hp-hr)
IDLE	7.9	20.7	7.6	15.0	587.7	1.3	3.2	30,517	2.618
DB2	21.7	46.5	21.3	75.2	502.3	2.1	21.4	67,762	2.146
1	283.6	104.3	20.2	75.2	2,073.3	0.2	17.2	148,934	0.368
2	572.3	193.6	34.2	121.6	4,759.0	0.0	16.1	275,315	0.338
3	1,194.6	441.6	78.9	267.5	6,447.2	0.0	31.3	626,643	0.370
4	1,682.4	597.9	64.3	768.1	7,781.4	0.0	30.2	847,332	0.355
5	2,265.1	803.8	73.3	1,040.6	9,130.3	0.0	50.7	1,139,828	0.355
6	2,993.5	1,024.9	100.1	510.5	13,042.0	0.0	28.3	1,454,805	0.342
7	3,670.0	1,252.0	140.8	392.7	16,601.6	0.0	32.9	1,777,941	0.341
8	4,380.8	1,496.1	218.7	705.9	17,467.0	0.0	99.1	2,124,752	0.342

Smoke		
Max ss	lax 30-se	lax 3-sec
6%	7%	10%

EPA Switcher Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	59.8%	4.7	12.4	4.5	9.0	351.4	0.8	1.9	18,249
DB2	0.0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
1	12.4%	35.2	12.9	2.5	9.3	257.1	0.0	2.1	18,468
2	12.3%	70.4	23.8	4.2	15.0	585.4	0.0	2.0	33,864
3	5.8%	69.3	25.6	4.6	15.5	373.9	0.0	1.8	36,345
4	3.6%	60.6	21.5	2.3	27.7	280.1	0.0	1.1	30,504
5	3.6%	81.5	28.9	2.6	37.5	328.7	0.0	1.8	41,034
6	1.5%	44.9	15.4	1.5	7.7	195.6	0.0	0.4	21,822
7	0.2%	7.3	2.5	0.3	0.8	33.2	0.0	0.1	3,556
8	0.8%	35.0	12.0	1.7	5.6	139.7	0.0	0.8	16,938
sum =	100.0%	409.0	155.1	24.3	128.0	2545.2	0.8	12.0	220840
			0.379	**0.06**	**0.3**	**6.2**	**0.0**	**0.029**	**540**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Modal Brake-Specific Emissions

Notch	HC (g/hp-hr)	CO (g/hp-hr)	Corr. NOx (g/hp-hr)	PM (g/hp-hr)	CO2 (g/hp-hr)
IDLE	0.96	1.90	74.23	0.40	3,855
DB2	0.98	3.47	23.17	0.99	3,126
1	0.07	0.27	7.31	0.06	525
2	0.06	0.21	8.32	0.03	481
3	0.07	0.22	5.40	0.03	525
4	0.04	0.46	4.63	0.02	504
5	0.03	0.46	4.03	0.02	503
6	0.03	0.17	4.36	0.01	486
7	0.04	0.11	4.52	0.01	484
8	0.05	0.16	3.99	0.02	485

EPA Freight Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	38.0%	3.0	7.9	2.9	5.7	223.3	0.5	1.2	11,596
DB2	12.5%	2.7	5.8	2.7	9.4	62.8	0.3	2.7	8,470
1	6.5%	18.4	6.8	1.3	4.9	134.8	0.0	1.1	9,681
2	6.5%	37.2	12.6	2.2	7.9	309.3	0.0	1.0	17,895
3	5.2%	62.1	23.0	4.1	13.9	335.3	0.0	1.6	32,585
4	4.4%	74.0	26.3	2.8	33.8	342.4	0.0	1.3	37,283
5	3.8%	86.1	30.5	2.8	39.5	347.0	0.0	1.9	43,313
6	3.3%	116.7	40.0	3.9	19.9	508.6	0.0	1.1	56,737
7	3.0%	110.1	37.6	4.2	11.8	498.0	0.0	1.0	53,338
8	16.2%	709.7	242.4	35.4	114.4	2829.7	0.0	16.1	344,210
sum =	100.0%	1220.1	432.8	62.4	261.2	5591.1	0.8	29.1	615110
			0.355	**0.05**	**0.2**	**4.6**	**0.00**	**0.024**	**504**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Fuel-Specific Emissions

Notch	HC (g/lb fuel)	CO (g/lb fuel)	Corr. NOx (g/lb fuel)	PM (g/lb fuel)	CO2 (g/lb fuel)
IDLE	0.37	0.73	28.36	0.15	1,473
DB2	0.46	1.62	10.80	0.46	1,457
1	0.19	0.72	19.88	0.16	1,428
2	0.18	0.63	24.59	0.08	1,422
3	0.18	0.61	14.60	0.07	1,419
4	0.11	1.28	13.01	0.05	1,417
5	0.09	1.29	11.36	0.06	1,418
6	0.10	0.50	12.72	0.03	1,419
7	0.11	0.31	13.26	0.03	1,420
8	0.15	0.47	11.68	0.07	1,420

BNSF 7934 - T3 GE ES44C4
Test #: FTP 4
HDT Run #: 000855
Date: 6/9/2020
Fuel: C50R50

Notch	Gross HP	obs Fuel Rate (lb/hr)	HC (g/hr)	CO (g/hr)	Corr. NOx (g/hr)	CH4 (g/hr)	PM (g/hr)	CO2 (g/hr)	BSFC lb/hp-hr)
IDLE	7.2	20.7	11.1	18.2	636.5	1.2	3.2	30,849	2.890
DB2	21.0	47.0	29.4	79.3	540.1	1.9	15.0	68,873	2.234
1	282.9	106.5	29.1	79.0	2,194.8	0.1	17.3	153,304	0.376
2	570.4	196.9	47.5	119.6	4,962.9	0.0	17.3	282,346	0.345
3	1,194.1	450.4	93.9	281.0	6,510.3	0.0	34.0	644,366	0.377
4	1,681.1	609.6	70.7	868.7	7,792.6	0.0	41.5	870,619	0.363
5	2,263.3	813.3	86.1	1,061.3	9,235.3	0.0	66.2	1,162,168	0.359
6	2,991.0	1,035.3	118.4	553.4	13,135.6	0.0	40.4	1,480,846	0.346
7	3,675.4	1,264.3	159.0	405.8	16,783.2	0.0	37.1	1,809,493	0.344
8	4,381.1	1,506.9	248.7	699.0	17,838.5	0.0	118.8	2,156,796	0.344

Smoke		
Max ss	lax 30-se	Max 3-sec
7%	9%	13%

EPA Switcher Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	59.8%	4.3	12.4	6.6	10.9	380.6	0.7	1.9	18,448
DB2	0.0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
1	12.4%	35.1	13.2	3.6	9.8	272.2	0.0	2.1	19,010
2	12.3%	70.2	24.2	5.8	14.7	610.4	0.0	2.1	34,729
3	5.8%	69.3	26.1	5.4	16.3	377.6	0.0	2.0	37,373
4	3.6%	60.5	21.9	2.5	31.3	280.5	0.0	1.5	31,342
5	3.6%	81.5	29.3	3.1	38.2	332.5	0.0	2.4	41,838
6	1.5%	44.9	15.5	1.8	8.3	197.0	0.0	0.6	22,213
7	0.2%	7.4	2.5	0.3	0.8	33.6	0.0	0.1	3,619
8	0.8%	35.0	12.1	2.0	5.6	142.7	0.0	1.0	17,254
sum =	100.0%	408.0	157.3	31.3	135.9	2627.1	0.7	13.6	225826
			0.385	**0.08**	**0.3**	**6.4**	**0.0**	**0.033**	**553**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Modal Brake-Specific Emissions

Notch	HC (g/hp-hr)	CO (g/hp-hr)	Corr. NOx (g/hp-hr)	PM (g/hp-hr)	CO2 (g/hp-hr)
IDLE	1.55	2.54	88.77	0.44	4,303
DB2	1.40	3.77	25.69	0.71	3,276
1	0.10	0.28	7.76	0.06	542
2	0.08	0.21	8.70	0.03	495
3	0.08	0.24	5.45	0.03	540
4	0.04	0.52	4.64	0.02	518
5	0.04	0.47	4.08	0.03	513
6	0.04	0.19	4.39	0.01	495
7	0.04	0.11	4.57	0.01	492
8	0.06	0.16	4.07	0.03	492

EPA Freight Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	38.0%	2.7	7.9	4.2	6.9	241.9	0.4	1.2	11,723
DB2	12.5%	2.6	5.9	3.7	9.9	67.5	0.2	1.9	8,609
1	6.5%	18.4	6.9	1.9	5.1	142.7	0.0	1.1	9,965
2	6.5%	37.1	12.8	3.1	7.8	322.6	0.0	1.1	18,352
3	5.2%	62.1	23.4	4.9	14.6	338.5	0.0	1.8	33,507
4	4.4%	74.0	26.8	3.1	38.2	342.9	0.0	1.8	38,307
5	3.8%	86.0	30.9	3.3	40.3	350.9	0.0	2.5	44,162
6	3.9%	116.6	40.4	4.6	21.6	512.3	0.0	1.6	57,753
7	3.0%	110.3	37.9	4.8	12.2	503.5	0.0	1.1	54,285
8	16.2%	709.7	244.1	40.3	113.2	2889.8	0.0	19.3	349,401
sum =	100.0%	1219.5	437.0	73.8	269.9	5712.6	0.7	33.4	626065
			0.358	**0.06**	**0.2**	**4.7**	**0.00**	**0.027**	**513**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Fuel-Specific Emissions

Notch	HC (g/lb fuel)	CO (g/lb fuel)	Corr. NOx (g/lb fuel)	PM (g/lb fuel)	CO2 (g/lb fuel)
IDLE	0.54	0.88	30.71	0.15	1,489
DB2	0.63	1.69	11.50	0.32	1,467
1	0.27	0.74	20.61	0.16	1,440
2	0.24	0.61	25.21	0.09	1,434
3	0.21	0.62	14.45	0.08	1,431
4	0.12	1.43	12.78	0.07	1,428
5	0.11	1.30	11.36	0.08	1,429
6	0.11	0.53	12.69	0.04	1,430
7	0.13	0.32	13.27	0.03	1,431
8	0.17	0.46	11.84	0.08	1,431

BNSF 7934 - T3 GE ES44C4
Test #: FTP 5
HDT Run #: 000856
Date: 6/10/2020
Fuel: R100

Notch	Gross HP	obs Fuel Rate (lb/hr)	HC (g/hr)	CO (g/hr)	Corr. NOx (g/hr)	CH4 (g/hr)	PM (g/hr)	CO2 (g/hr)	BSFC lb/hp-hr)
IDLE	8.3	20.3	7.2	14.0	611.6	1.1	2.4	29,924	2.449
DB2	18.8	45.0	19.5	70.1	486.2	1.8	16.2	65,529	2.397
1	282.9	103.2	20.1	70.7	2,165.2	0.0	15.3	147,455	0.365
2	572.2	194.4	36.4	115.5	4,946.8	0.0	13.9	276,684	0.340
3	1,135.6	440.7	81.8	235.0	6,665.3	0.3	24.7	625,646	0.369
4	1,682.9	595.5	71.8	581.7	8,029.8	0.0	22.4	844,275	0.354
5	2,267.0	797.9	81.8	803.9	9,475.2	0.0	37.0	1,131,831	0.352
6	2,997.7	1,016.8	108.2	438.5	13,411.2	0.0	20.7	1,443,510	0.339
7	3,679.2	1,242.3	144.5	337.7	16,946.8	0.0	26.1	1,764,709	0.338
8	4,387.5	1,473.8	216.0	590.0	18,011.5	0.0	74.1	2,093,643	0.336

Smoke		
Max ss	lax 30-se	Max 3-sec
8%	10%	12%

EPA Switcher Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	59.8%	5.0	12.1	4.3	8.4	365.7	0.7	1.4	17,895
DB2	0.0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
1	12.4%	35.1	12.8	2.5	8.8	268.5	0.0	1.9	18,284
2	12.3%	70.4	23.9	4.5	14.2	608.5	0.0	1.7	34,032
3	5.8%	69.3	25.6	4.7	13.6	386.6	0.0	1.4	36,287
4	3.6%	60.6	21.4	2.6	20.9	289.1	0.0	0.8	30,394
5	3.6%	81.6	28.7	2.9	28.9	341.1	0.0	1.3	40,746
6	1.5%	45.0	15.3	1.6	6.6	201.2	0.0	0.3	21,653
7	0.2%	7.4	2.5	0.3	0.7	33.9	0.0	0.1	3,529
8	0.8%	35.1	11.8	1.7	4.7	144.1	0.0	0.6	16,749
sum =	100.0%	409.4	154.1	25.2	106.8	2638.6	0.7	9.5	219570
			0.376	**0.06**	**0.3**	**6.4**	**0.0**	**0.023**	**536**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Modal Brake-Specific Emissions

Notch	HC (g/hp-hr)	CO (g/hp-hr)	Corr. NOx (g/hp-hr)	PM (g/hp-hr)	CO2 (g/hp-hr)
IDLE	0.86	1.69	73.84	0.29	3,613
DB2	1.04	3.74	25.91	0.86	3,492
1	0.07	0.25	7.65	0.05	521
2	0.06	0.20	8.65	0.02	484
3	0.07	0.20	5.57	0.02	523
4	0.04	0.35	4.77	0.01	502
5	0.04	0.35	4.18	0.02	499
6	0.04	0.15	4.47	0.01	482
7	0.04	0.09	4.61	0.01	480
8	0.05	0.13	4.11	0.02	477

EPA Freight Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	38.0%	3.1	7.7	2.7	5.3	232.4	0.4	0.9	11,371
DB2	12.5%	2.3	5.6	2.4	8.8	60.8	0.2	2.0	8,191
1	6.5%	18.4	6.7	1.3	4.6	140.7	0.0	1.0	9,585
2	6.5%	37.2	12.6	2.4	7.5	321.5	0.0	0.9	17,984
3	5.2%	62.2	22.9	4.3	12.2	346.6	0.0	1.3	32,534
4	4.4%	74.0	26.2	3.2	25.6	353.3	0.0	1.0	37,148
5	3.8%	86.1	30.3	3.1	30.5	360.1	0.0	1.4	43,010
6	3.9%	116.9	39.7	4.2	17.1	523.0	0.0	0.8	56,237
7	3.0%	110.4	37.3	4.3	10.1	508.4	0.0	0.8	52,941
8	16.2%	710.8	238.8	35.0	95.6	2917.9	0.0	12.0	339,170
sum =	100.0%	1221.5	427.8	62.9	217.4	5764.7	0.7	22.1	608231
			0.350	**0.05**	**0.2**	**4.7**	**0.00**	**0.018**	**498**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Fuel-Specific Emissions

Notch	HC (g/lb fuel)	CO (g/lb fuel)	Corr. NOx (g/lb fuel)	PM (g/lb fuel)	CO2 (g/lb fuel)
IDLE	0.35	0.69	30.15	0.12	1,475
DB2	0.43	1.56	10.81	0.36	1,457
1	0.19	0.69	20.99	0.15	1,429
2	0.19	0.59	25.44	0.07	1,423
3	0.19	0.53	15.12	0.06	1,420
4	0.12	0.98	13.48	0.04	1,418
5	0.10	1.01	11.88	0.05	1,419
6	0.11	0.43	13.19	0.02	1,420
7	0.12	0.27	13.64	0.02	1,421
8	0.15	0.40	12.22	0.05	1,421

BNSF 7934 - T3 GE ES44C4
Test #: FTP 6
HDT Run #: 000857
Date: 6/11/2020
Fuel: C50R50

Notch	Gross HP	obs Fuel Rate (lb/hr)	HC (g/hr)	CO (g/hr)	Corr. NOx (g/hr)	CH4 (g/hr)	PM (g/hr)	CO2 (g/hr)	BSFC lb/hp-hr)
IDLE	8.2	20.7	10.6	17.3	661.2	1.1	2.8	30,867	2.540
DB2	20.2	45.9	27.4	74.3	538.3	1.7	11.9	67,370	2.274
1	283.3	105.4	29.7	78.7	2,154.0	0.0	17.5	151,633	0.372
2	571.7	196.0	47.0	114.5	4,998.1	0.0	16.5	280,938	0.343
3	1,193.9	447.3	97.1	248.5	6,708.3	0.0	31.2	639,974	0.375
4	1,683.3	605.2	79.4	670.7	8,023.6	0.0	32.1	864,625	0.360
5	2,265.3	810.4	90.8	875.2	9,469.3	0.0	48.8	1,158,464	0.358
6	2,992.6	1,033.7	119.3	492.7	13,465.4	0.0	27.1	1,479,009	0.345
7	3,677.2	1,262.1	159.3	365.2	17,083.8	0.0	30.7	1,806,571	0.343
8	4,384.5	1,507.5	240.6	630.2	18,268.7	0.0	93.7	2,158,130	0.344

Smoke		
Max ss	lax 30-se	lax 3-sec
6%	7%	11%

EPA Switcher Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	59.8%	4.9	12.4	6.3	10.4	395.4	0.6	1.7	18,459
DB2	0.0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
1	12.4%	35.1	13.1	3.7	9.8	267.1	0.0	2.2	18,802
2	12.3%	70.3	24.1	5.8	14.1	614.8	0.0	2.0	34,555
3	5.8%	69.2	25.9	5.6	14.4	389.1	0.0	1.8	37,118
4	3.6%	60.6	21.8	2.9	24.1	288.8	0.0	1.2	31,127
5	3.6%	81.6	29.2	3.3	31.5	340.9	0.0	1.8	41,705
6	1.5%	44.9	15.5	1.8	7.4	202.0	0.0	0.4	22,185
7	0.2%	7.4	2.5	0.3	0.7	34.2	0.0	0.1	3,613
8	0.8%	35.1	12.1	1.9	5.0	146.1	0.0	0.7	17,265
sum =	100.0%	409.0	156.6	31.6	117.4	2678.4	0.6	11.8	224829
			0.383	**0.08**	**0.3**	**6.5**	**0.0**	**0.029**	**550**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Modal Brake-Specific Emissions

Notch	HC (g/hp-hr)	CO (g/hp-hr)	Corr. NOx (g/hp-hr)	PM (g/hp-hr)	CO2 (g/hp-hr)
IDLE	1.30	2.12	81.03	0.34	3,783
DB2	1.36	3.68	26.69	0.59	3,340
1	0.10	0.28	7.60	0.06	535
2	0.08	0.20	8.74	0.03	491
3	0.08	0.21	5.62	0.03	536
4	0.05	0.40	4.77	0.02	514
5	0.04	0.39	4.18	0.02	511
6	0.04	0.16	4.50	0.01	494
7	0.04	0.10	4.65	0.01	491
8	0.05	0.14	4.17	0.02	492

EPA Freight Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	38.0%	3.1	7.9	4.0	6.6	251.3	0.4	1.1	11,730
DB2	12.5%	2.5	5.7	3.4	9.3	67.3	0.2	1.5	8,421
1	6.5%	18.4	6.8	1.9	5.1	140.0	0.0	1.1	9,856
2	6.5%	37.2	12.7	3.1	7.4	324.9	0.0	1.1	18,261
3	5.2%	62.1	23.3	5.0	12.9	348.8	0.0	1.6	33,279
4	4.4%	74.1	26.6	3.5	29.5	353.0	0.0	1.4	38,044
5	3.8%	86.1	30.8	3.5	33.3	359.8	0.0	1.9	44,022
6	3.9%	116.7	40.3	4.7	19.2	525.2	0.0	1.1	57,681
7	3.0%	110.3	37.9	4.8	11.0	512.5	0.0	0.9	54,197
8	16.2%	710.3	244.2	39.0	102.1	2959.5	0.0	15.2	349,617
sum =	100.0%	1220.7	436.3	72.8	236.4	5842.3	0.6	26.8	625107
			0.357	**0.06**	**0.2**	**4.8**	**0.00**	**0.022**	**512**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Fuel-Specific Emissions

Notch	HC (g/lb fuel)	CO (g/lb fuel)	Corr. NOx (g/lb fuel)	PM (g/lb fuel)	CO2 (g/lb fuel)
IDLE	0.51	0.84	31.91	0.14	1,489
DB2	0.60	1.62	11.74	0.26	1,469
1	0.28	0.75	20.44	0.17	1,439
2	0.24	0.58	25.50	0.08	1,433
3	0.22	0.56	15.00	0.07	1,431
4	0.13	1.11	13.26	0.05	1,429
5	0.11	1.08	11.68	0.06	1,429
6	0.12	0.48	13.03	0.03	1,431
7	0.13	0.29	13.54	0.02	1,431
8	0.16	0.42	12.12	0.06	1,432

BNSF 7934 - T3 GE ES44C4
Test #: FTP 7
HDT Run #: 000858
Date: 6/12/2020
Fuel: C50R30B20

Notch	Gross HP	obs Fuel Rate (lb/hr)	HC (g/hr)	CO (g/hr)	Corr. NOx (g/hr)	CH4 (g/hr)	PM (g/hr)	CO2 (g/hr)	BSFC lb/hp-hr)
IDLE	8.0	20.5	10.0	16.4	689.2	1.2	2.8	29,693	2.560
DB2	19.3	46.5	28.1	82.7	615.8	2.0	13.0	66,989	2.405
1	283.1	108.0	28.9	79.3	2,172.7	0.1	21.3	152,472	0.382
2	571.9	201.7	45.4	111.3	5,179.4	0.0	18.1	283,749	0.353
3	1,193.5	460.3	94.7	228.7	6,881.2	0.0	27.4	645,818	0.386
4	1,681.7	623.0	83.1	598.4	8,314.5	0.0	24.5	873,059	0.370
5	2,266.0	829.6	97.7	746.4	9,848.7	0.0	37.8	1,163,181	0.366
6	2,993.0	1,059.3	124.6	436.5	13,905.1	0.0	25.3	1,486,498	0.354
7	3,677.9	1,295.2	160.3	346.1	17,473.3	0.0	28.2	1,818,125	0.352
8	4,384.0	1,549.0	227.7	573.3	18,417.0	0.0	81.8	2,174,620	0.353

Smoke		
Max ss	lax 30-se	Max 3-sec
7%	11%	11%

EPA Switcher Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	59.8%	4.8	12.3	6.0	9.8	412.2	0.7	1.6	17,756
DB2	0.0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
1	12.4%	35.1	13.4	3.6	9.8	269.4	0.0	2.6	18,906
2	12.3%	70.3	24.8	5.6	13.7	637.1	0.0	2.2	34,901
3	5.8%	69.2	26.7	5.5	13.3	399.1	0.0	1.6	37,457
4	3.6%	60.5	22.4	3.0	21.5	299.3	0.0	0.9	31,430
5	3.6%	81.6	29.9	3.5	26.9	354.6	0.0	1.4	41,875
6	1.5%	44.9	15.9	1.9	6.5	208.6	0.0	0.4	22,297
7	0.2%	7.4	2.6	0.3	0.7	34.9	0.0	0.1	3,636
8	0.8%	35.1	12.4	1.8	4.6	147.3	0.0	0.7	17,397
sum =	100.0%	408.9	160.3	31.1	106.8	2762.5	0.7	11.4	225657
			0.392	**0.08**	**0.3**	**6.8**	**0.0**	**0.028**	**552**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Modal Brake-Specific Emissions

Notch	HC (g/hp-hr)	CO (g/hp-hr)	Corr. NOx (g/hp-hr)	PM (g/hp-hr)	CO2 (g/hp-hr)
IDLE	1.24	2.05	86.07	0.34	3,708
DB2	1.45	4.28	31.83	0.67	3,463
1	0.10	0.28	7.68	0.08	539
2	0.08	0.19	9.06	0.03	496
3	0.08	0.19	5.77	0.02	541
4	0.05	0.36	4.94	0.01	519
5	0.04	0.33	4.35	0.02	513
6	0.04	0.15	4.65	0.01	497
7	0.04	0.09	4.75	0.01	494
8	0.05	0.13	4.20	0.02	496

EPA Freight Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	38.0%	3.0	7.8	3.8	6.2	261.9	0.4	1.0	11,283
DB2	12.5%	2.4	5.8	3.5	10.3	77.0	0.2	1.6	8,374
1	6.5%	18.4	7.0	1.9	5.2	141.2	0.0	1.4	9,911
2	6.5%	37.2	13.1	3.0	7.2	336.7	0.0	1.2	18,444
3	5.2%	62.1	23.9	4.9	11.9	357.8	0.0	1.4	33,583
4	4.4%	74.0	27.4	3.7	26.3	365.8	0.0	1.1	38,415
5	3.8%	86.1	31.5	3.7	28.4	374.3	0.0	1.4	44,201
6	3.9%	116.7	41.3	4.9	17.0	542.3	0.0	1.0	57,973
7	3.0%	110.3	38.9	4.8	10.4	524.2	0.0	0.8	54,544
8	16.2%	710.2	250.9	36.9	92.9	2383.5	0.0	13.2	352,288
sum =	100.0%	1220.5	447.7	71.0	215.8	5964.7	0.7	24.3	629015
			0.367	**0.06**	**0.2**	**4.9**	**0.00**	**0.020**	**515**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Fuel-Specific Emissions

Notch	HC (g/lb fuel)	CO (g/lb fuel)	Corr. NOx (g/lb fuel)	PM (g/lb fuel)	CO2 (g/lb fuel)
IDLE	0.49	0.80	33.62	0.13	1,448
DB2	0.60	1.78	13.24	0.28	1,440
1	0.27	0.73	20.11	0.20	1,411
2	0.23	0.55	25.68	0.09	1,407
3	0.21	0.50	14.95	0.06	1,403
4	0.13	0.96	13.35	0.04	1,401
5	0.12	0.90	11.87	0.05	1,402
6	0.12	0.41	13.13	0.02	1,403
7	0.12	0.27	13.49	0.02	1,404
8	0.15	0.37	11.89	0.05	1,404

BNSF 7934 - T3 GE ES44C4
Test #: FTP 8
HDT Run #: 000859
Date: 6/15/2020
Fuel: C100

Notch	Gross HP	obs Fuel Rate (lb/hr)	HC (g/hr)	CO (g/hr)	Corr. NOx (g/hr)	CH4 (g/hr)	PM (g/hr)	CO2 (g/hr)	BSFC lb/hp-hr)
IDLE	7.6	21.6	14.4	23.4	835.2	1.3	3.2	32,198	2.833
DB2	21.8	46.7	35.8	106.2	823.3	2.0	12.0	68,827	2.149
1	281.6	107.6	35.0	93.6	2,544.9	0.1	18.9	155,330	0.382
2	571.6	198.9	59.3	111.4	5,083.7	0.0	18.9	286,154	0.348
3	1,132.5	456.1	108.2	321.1	6,443.8	0.0	34.9	654,512	0.383
4	1,679.7	617.1	84.2	823.8	7,780.2	0.0	43.0	884,504	0.367
5	2,264.7	821.2	102.2	984.4	9,315.7	0.0	65.1	1,177,996	0.363
6	2,990.1	1,045.9	135.5	544.1	13,172.1	0.0	33.7	1,501,517	0.350
7	3,671.2	1,284.2	179.8	419.9	16,911.8	0.0	40.2	1,844,490	0.350
8	4,381.9	1,526.5	263.1	725.0	18,455.4	0.0	125.7	2,192,678	0.348

Smoke		
Max ss	lax 30-se	lax 3-sec
6%	8%	13%

EPA Switcher Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	59.8%	4.6	12.9	8.6	14.0	499.5	0.8	1.9	19,255
DB2	0.0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
1	12.4%	34.9	13.3	4.3	11.6	315.6	0.0	2.3	19,261
2	12.3%	70.3	24.5	7.3	13.7	625.3	0.0	2.3	35,197
3	5.8%	69.2	26.5	6.3	18.6	373.7	0.0	2.0	37,962
4	3.6%	60.5	22.2	3.0	29.7	280.1	0.0	1.5	31,842
5	3.6%	81.5	29.6	3.7	35.4	335.4	0.0	2.3	42,408
6	1.5%	44.9	15.7	2.0	8.2	197.6	0.0	0.5	22,523
7	0.2%	7.3	2.6	0.4	0.8	33.8	0.0	0.1	3,689
8	0.8%	35.1	12.2	2.1	5.8	147.6	0.0	1.0	17,541
sum =	100.0%	408.2	159.4	37.7	137.8	2808.6	0.8	14.1	229677
			0.391	**0.09**	**0.3**	**6.9**	**0.0**	**0.035**	**563**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Modal Brake-Specific Emissions

Notch	HC (g/hp-hr)	CO (g/hp-hr)	Corr. NOx (g/hp-hr)	PM (g/hp-hr)	CO2 (g/hp-hr)
IDLE	1.89	3.07	109.51	0.42	4,222
DB2	1.64	4.88	37.85	0.55	3,164
1	0.12	0.33	9.04	0.07	552
2	0.10	0.19	8.89	0.03	501
3	0.09	0.27	5.40	0.03	549
4	0.05	0.49	4.63	0.03	527
5	0.05	0.43	4.11	0.03	520
6	0.05	0.18	4.41	0.01	502
7	0.05	0.11	4.61	0.01	502
8	0.06	0.17	4.21	0.03	500

EPA Freight Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	38.0%	2.9	8.2	5.5	8.9	317.4	0.5	1.2	12,235
DB2	12.5%	2.7	5.8	4.5	13.3	102.9	0.2	1.5	8,603
1	6.5%	18.3	7.0	2.3	6.1	165.4	0.0	1.2	10,096
2	6.5%	37.2	12.9	3.9	7.2	330.4	0.0	1.2	18,600
3	5.2%	62.0	23.7	5.6	16.7	335.1	0.0	1.8	34,035
4	4.4%	73.9	27.2	3.7	36.2	342.3	0.0	1.9	38,918
5	3.8%	86.1	31.2	3.9	37.4	354.0	0.0	2.5	44,764
6	3.9%	116.6	40.8	5.3	21.2	513.7	0.0	1.3	58,559
7	3.0%	110.1	38.5	5.4	12.6	507.4	0.0	1.2	55,335
8	16.2%	709.9	247.3	42.6	117.4	2989.8	0.0	20.4	355,214
sum =	100.0%	1219.7	442.7	82.6	277.1	5958.4	0.7	34.2	636360
			0.363	**0.07**	**0.2**	**4.9**	**0.00**	**0.028**	**522**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Fuel-Specific Emissions

Notch	HC (g/lb fuel)	CO (g/lb fuel)	Corr. NOx (g/lb fuel)	PM (g/lb fuel)	CO2 (g/lb fuel)
IDLE	0.67	1.08	38.66	0.15	1,490
DB2	0.77	2.27	17.61	0.26	1,473
1	0.33	0.87	23.65	0.18	1,444
2	0.30	0.56	25.56	0.10	1,439
3	0.24	0.70	14.13	0.08	1,435
4	0.14	1.33	12.61	0.07	1,433
5	0.12	1.20	11.34	0.08	1,434
6	0.13	0.52	12.59	0.03	1,436
7	0.14	0.33	13.17	0.03	1,436
8	0.17	0.47	12.09	0.08	1,436

BNSF 7934 - T3 GE ES44C4
Test #: FTP 9
HDT Run #: 000860
Date: 6/17/2020
Fuel: ULSD Cert Fuel

Note: The locomotive experienced a high oil temperature de-rate 5.5 minutes into N8. Power, fuel rate, and gaseous emissions were averaged for the first 5 minutes before the derate occurred, but PM ran for an additional 30 seconds. The g/hr value shown is based on the BSPM value of the entire sample, multiplied by the HP of the 5 minutes shown.

Notch	Gross HP	obs Fuel Rate (lb/hr)	HC (g/hr)	CO (g/hr)	Corr. NOx (g/hr)	CH4 (g/hr)	PM (g/hr)	CO2 (g/hr)	BSFC lb/hp-hr)
IDLE	7.7	21.2	13.9	21.6	899.8	1.1	3.4	31,936	2.758
DB2	21.9	46.7	37.1	121.8	926.4	2.0	12.8	69,670	2.132
1	252.4	108.0	37.2	92.4	2,694.8	0.1	26.1	157,649	0.428
2	538.2	200.4	58.4	112.3	5,427.5	0.0	22.6	291,708	0.372
3	1,122.6	459.4	112.4	339.0	6,637.9	0.0	37.3	667,149	0.409
4	1,626.1	622.6	86.4	858.2	8,107.1	0.0	47.1	903,252	0.383
5	2,198.3	830.0	97.8	963.0	9,678.4	0.0	68.3	1,205,128	0.378
6	2,907.7	1,052.5	130.9	545.6	13,840.3	0.0	41.0	1,529,588	0.362
7	3,601.3	1,292.8	167.7	438.9	17,832.8	0.0	50.8	1,879,621	0.359
8	4,372.2	1,519.6	239.8	711.5	19,860.5	0.0	125.6	2,209,708	0.348

Smoke		
Max ss	lax 30-se	Max 3-sec
8%	9%	17%

EPA Switcher Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	59.8%	4.6	12.7	8.3	12.9	538.1	0.7	2.0	19,098
DB2	0.0%	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
1	12.4%	31.3	13.4	4.6	11.5	334.1	0.0	3.2	19,549
2	12.3%	66.2	24.6	7.2	13.8	667.6	0.0	2.8	35,880
3	5.8%	65.1	26.6	6.5	19.7	385.0	0.0	2.2	38,695
4	3.6%	58.5	22.4	3.1	30.9	291.9	0.0	1.7	32,517
5	3.6%	79.1	29.9	3.5	34.9	348.4	0.0	2.5	43,385
6	1.5%	43.6	15.8	2.0	8.2	207.6	0.0	0.6	22,944
7	0.2%	7.2	2.6	0.3	0.9	35.7	0.0	0.1	3,759
8	0.8%	35.0	12.2	1.9	5.7	158.9	0.0	1.0	17,678
sum =	100.0%	390.7	160.2	37.5	138.4	2967.3	0.7	16.1	233503
			0.410	**0.10**	**0.4**	**7.6**	**0.0**	**0.041**	**598**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Modal Brake-Specific Emissions

Notch	HC (g/hp-hr)	CO (g/hp-hr)	Corr. NOx (g/hp-hr)	PM (g/hp-hr)	CO2 (g/hp-hr)
IDLE	1.81	2.82	117.28	0.44	4,162
DB2	1.69	5.56	42.26	0.58	3,178
1	0.15	0.37	10.68	0.10	625
2	0.11	0.21	10.08	0.04	542
3	0.10	0.30	5.91	0.03	594
4	0.05	0.53	4.99	0.03	555
5	0.04	0.44	4.40	0.03	548
6	0.05	0.19	4.76	0.01	526
7	0.05	0.12	4.95	0.01	522
8	0.05	0.16	4.54	0.03	505

EPA Freight Duty Cycle Weighted Results

Notch	WF	w-BHP	obs w-Fuel w-(lb/hr)	w-HC w-(g/hr)	w-CO w-(g/hr)	w-NOx w-(g/hr)	w-CH4 w-(g/hr)	w-PM w-(g/hr)	w-CO2 w-(g/hr)
IDLE	38.0%	2.9	8.0	5.3	8.2	341.9	0.4	1.3	12,136
DB2	12.5%	2.7	5.8	4.6	15.2	115.8	0.3	1.6	8,709
1	6.5%	16.4	7.0	2.4	6.0	175.2	0.0	1.7	10,247
2	6.5%	35.0	13.0	3.8	7.3	352.8	0.0	1.5	18,961
3	5.2%	58.4	23.9	5.8	17.6	345.2	0.0	1.9	34,692
4	4.4%	71.5	27.4	3.8	37.8	356.7	0.0	2.1	39,743
5	3.8%	83.5	31.5	3.7	36.8	367.8	0.0	2.6	45,795
6	3.9%	113.4	41.0	5.1	21.3	539.8	0.0	1.6	59,654
7	3.0%	108.0	38.8	5.0	13.2	535.0	0.0	1.5	56,389
8	16.2%	708.3	246.2	38.9	115.3	3217.4	0.0	20.4	357,973
sum =	100.0%	1200.2	442.8	78.5	278.7	6347.5	0.7	36.1	644298
			0.369	**0.07**	**0.2**	**5.3**	**0.00**	**0.030**	**537**
			obs bsfc	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)	(g/hp-hr)

Fuel-Specific Emissions

Notch	HC (g/lb fuel)	CO (g/lb fuel)	Corr. NOx (g/lb fuel)	PM (g/lb fuel)	CO2 (g/lb fuel)
IDLE	0.66	1.02	42.52	0.16	1,509
DB2	0.79	2.61	19.82	0.27	1,491
1	0.34	0.86	24.95	0.24	1,459
2	0.29	0.56	27.08	0.11	1,456
3	0.24	0.74	14.45	0.08	1,452
4	0.14	1.38	13.02	0.08	1,451
5	0.12	1.17	11.66	0.08	1,452
6	0.12	0.52	13.15	0.04	1,453
7	0.13	0.34	13.79	0.04	1,454
8	0.16	0.47	13.07	0.08	1,454