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Railroad Energy Intensity and Criteria Air Pollutant Emissions

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A tiered emission factors table was developed by Argonne National Laboratory to populate its Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) model for pollutants emissions, as well as to calculate energy intensities for passenger and freight rail applications. The rail module within the GREET® model was updated with data developed in this study to enable the evaluation of energy use, greenhouse gas emissions, and criteria air pollutant emissions by rail transport on a life-cycle basis.

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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)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
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)

MASS - WEIGHT (APPROXIMATE)

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

VOLUME (APPROXIMATE)

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)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

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)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
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)

TEMPERATURE (EXACT)

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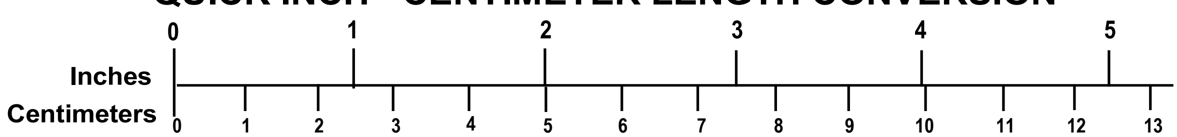
QUICK INCH - CENTIMETER LENGTH CONVERSION



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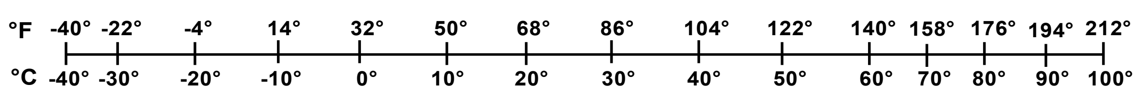

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Executive Summary

From June 30, 2014, to March 20, 2016, the Argonne National Laboratory (Argonne) was contracted by the Federal Railroad Administration (FRA) to update Argonne's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model to include a rail module. Argonne was also tasked to use that module to evaluate the life-cycle cost of using of compressed natural gas, liquefied natural gas or dimethyl ether as possible alternative locomotive fuels from an energy and emissions perspective. The study fully evaluated energy and emission impacts of advanced vehicle technologies, including new transportation fuels, the fuel cycle from wells to wheels, and the vehicle cycle through material recovery and vehicle disposal. With sponsorship from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE), Argonne developed GREET® in 1996 as a full life-cycle model that allowed researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis.

Although the rail mode is known to be very energy efficient, little information is widely available about the energy intensity of individual railroad operations. Railroads use internal combustion engines to power their locomotives, but information related to locomotive emissions standards and in-use emissions is scattered in various publications.

Argonne examined the annual reports for Class I railroads, commonly known as R-1 reports, from six major railroad companies: Burlington Northern Santa Fe Railway (BNSF), CSX Transportation (CSX), Kansas City Southern Railway (KCS), Norfolk Southern Corporation (NS), SOO Line Railroad (SOO), and Union Pacific Railroad (UP). Data were collected on line-haul and switching operations, including annual diesel gallons used and ton-miles of freight movement.

The data for line-haul and switching operations were combined to develop an energy intensity (Btu/ton-mile) factor, which was based on the weighted average of ton-miles of shipments by each company. The aggregate freight movement energy intensity in 2014 was calculated at 270 Btu/ton-mile. The distribution of energy intensity between companies was in the range of 229 to 310 Btu/ton-mile. The Argonne team also extracted data from the Amtrak 2014 report on diesel gallons used, actual train miles, and passenger-miles activities by month. The data were aggregated to calculate gallons of diesel used per passenger-mile for 2014. Electricity use data from Amtrak's Northeast Corridor were extracted to separate diesel and electricity use per passenger-mile. This yielded an average energy intensity of 1,788 Btu/passenger-mile for diesel trains and 960 Btu/passenger-mile for electric trains.

Argonne extracted emissions data for hydrocarbons (HC), oxides of nitrogen (NO_X), carbon monoxide (CO), and particulate matter (PM) using the U.S. Environmental Protection Agency's (EPA) tier standards for Tiers 0 through 4 (covering years 1973 to 2015). Argonne also collected emissions data from a California Air Resources Board (CARB) report for Tier 0. The CARB report provided actual emissions from two companies (UP and BNSF), which covered three engines from each company.

The emission factors and the brake specific fuel consumption (BSFC) were reported for each throttle notch operation, were aggregated based on the time spent in each notch, and used to evaluate emissions and BSFC for the entire duty cycle of operation. An emission factors table by tier was developed to populate Argonne's GREET® model for pollutants emissions, along with the calculated energy intensities for passenger and freight rail applications. The rail module within the GREET® model was updated with data developed in this study to enable the evaluation of energy use, greenhouse gas emissions, and criteria air pollutant emissions by rail transport on a life-cycle basis.

1. Introduction

The Federal Railroad Administration contracted the Argonne National Laboratory (Argonne) to assess the energy efficiency and emissions of current rail transportation, and to evaluate the environmental benefits of alternative fuels as potential replacement fuels for diesel locomotive engines by updating Argonne's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model from June 30, 2014, to March 20, 2016.

1.1 Background

Although rail is known to be energy-efficient compared to other transportation modes, not much data is widely available on the energy intensity of individual railroad operations for freight and passenger transport. Like light-duty vehicles and heavy trucks, locomotives use internal combustion engines for power. However, information about locomotive emissions standards and in-use emissions has been scattered throughout various publications.

1.2 Objectives

The objectives of this study were to develop energy intensity and emission factors for various railroad applications (namely freight and passenger transport), and to evaluate the potential environmental benefits of switching on a life-cycle basis from petroleum diesel to alternative fuels, such as natural gas and dimethyl ether (DME).

1.3 Overall Approach

First, Argonne collected data on annual fuel use, freight- and passenger-miles, and pollutant emissions from publicly available sources. Next, the data were used to populate the rail module within the GREET® model for the evaluation of energy use, greenhouse gas (GHG) emissions, and criteria pollutant emissions during rail operation, also known as pump-to-wheels (PTW). Then, the GREET® model was used to calculate the well-to-pump (WTP) upstream fuel production and transportation energy use (by primary energy resource, e.g., petroleum, natural gas, and biomass) and emissions (by category, e.g., GHG and criteria air pollutants). Finally, the WTP and PTW energy use and emissions are combined to calculate the well-to-wheels (WTW) energy use and emissions associated with various fuels and rail operations.

1.4 Scope

The scope of this study covers both freight and passenger rail transport, as well as examining diesel, natural gas, DME, and electricity as energy sources powering freight and passenger locomotives. The scope of the environmental benefits covers the life cycle of the fuel WTW.

1.5 Organization of the Report

Section 1 serves as the introduction.

Section 2 provides a summary of Class I freight hauling railroad energy consumption and revenue ton-miles, and presents estimates for resulting energy intensity for each Class I railroad.

Section 3 presents U.S. Environmental Protection Agency (EPA) locomotive criteria pollutant standards, as well as computed implications for Class I railroads in terms of emissions per million Btu. An analysis of the results of the locomotive emissions tests performed by the Association of American Railroads (AAR) is presented, along with computed resulting in-use emissions rates for Class I railroads. For intercity passenger rail service, an analysis of energy use and passenger-miles to compute energy intensity is presented, as are analysis results. For future values, historical data were analyzed and historical locomotive retirement rates were used to estimate the composition of future locomotive fleets by EPA tier. Estimated future energy intensity and emissions rates were presented.

Section 4 summarizes the results of the analysis of railroad energy intensity, locomotive emission standards, and AAR in-use emissions tests.

Appendix A discusses alternative fuels for locomotives.

Appendix B discusses the rail module in the GREET® model.[1]

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[1] Argonne National Laboratory. (2014). *GREET® Model: The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model*. Argonne National Laboratory: Argonne, IL. Available at: http://greet.es.anl.gov/.

2. Railroad Energy Intensity

In this section, we examine the energy intensity of current and future freight and intercity passenger rail operations. Freight rail data are collected on (1) total ton-miles of freight movement and (2) annual diesel use for line-haul and switching operations. The passenger rail data are based on annual diesel fuel and electricity use, number of passengers transported, and number of train miles travelled as reported by Amtrak. The projections for future energy intensities up to 2040 are based on *Annual Energy Outlook* (AEO) projections by the U.S. Department of Energy's Energy Information Administration (EIA).

2.1 Freight Rail Energy Intensity

A large majority of freight (in terms of ton-miles) is transported by Class I railroads. In 2014, there were six Class I railroads in the United States: (1) Burlington Northern Santa Fe Railway (BNSF), (2) CSX Transportation (CSX), (3) Kansas City Southern Railway (KCS), (4) Norfolk Southern Corporation (NS), (5) SOO Line Railroad (SOO), and (6) Union Pacific Railroad (UP).

Each Class I railroad company files its annual report with the Surface Transportation Board (STB). These reports include fuel use by line-haul and switching operations, and revenue ton-miles (Surface Transportation Board, 2015). Table 1 summarizes these data and the resulting energy intensities for the six Class I railroads and the combined values for all Class I railroads for 2014.

Table 1. Class I Railroad Energy Use, Revenue Ton-Miles, and Energy Intensity in 2014

	Diesel Fuel Use (gallons)					
Railroad Company	**Line-haul**	**Switching**	**Total**	**Revenue Ton-Miles (million)**	**Btu per Revenue Ton-Mile[a]**	**Revenue Ton-Mile /Gallon**
BNSF	1,389,787,439	54,299,412	1,444,086,851	711,321	261	493
CSX	461,650,090	45,657,701	507,307,791	245,212	266	483
KCS	68,417,838	3,570,093	71,987,931	33,826	273	470
NS	463,454,201	30,547,002	494,001,203	205,020	310	415
SOO	68,663,230	2,437,292	71,100,522	39,856	229	561
UP	1,021,942,292	136,957,434	1,158,899,726	549,629	271	474
Total	3,473,915,090	273,468,934	3,747,384,024	1,784,865	270	476

[a] Based on lower heating value (LHV) of diesel as 128,488 Btu/gallon.
Source: STB (2015)

Class I railroad energy intensity, in terms of Btu per ton-mile (Btu/ton-mile), ranged from 229 to 310 in 2014, and the average for all Class I railroads was 270. The most efficient railroad consumed only 85 percent of the average energy per ton-mile, and the lease efficient railroad consumed 115 percent of the average.

Two railroads, BNSF and UP, accounted for 70.7 percent of total revenue ton-miles. These two railroads also accounted for 69.4 percent of line-haul energy and 70 percent of switching energy. BNSF ranked number one for revenue ton-miles (39.9 percent) and line-haul energy (40 percent), but ranked second in switching energy (19.9 percent). UP ranked second for revenue ton-miles (30.8 percent) and line-haul energy (29.4 percent), but ranked first for switching energy (50.1 percent). KCS and SOO were the bottom two rankings in 2014, accounting for 4.1 percent of revenue ton-miles, 4 percent of line-haul energy, and 2.2 percent of switching energy. KCS carried the fewest ton-miles (1.9 percent vs. 2.2 percent for SOO) and consumed slightly less line-haul energy (1.97 percent vs. 1.98 percent for SOO), but consumed more switching energy (1.3 percent vs. 0.9 percent for SOO).

2.1.1 Future Freight Rail Energy Intensity

The average energy intensity of Class I railroads is used in the GREET® model. We recommend that the 2014 energy intensity (270 Btu/ton-mile) be used for 2015. For estimating future energy intensities up to 2040, we used the AEO projections by the EIA. In the "Freight Transportation Energy Use" table of the 2015 AEO, the EIA projects a steady decline in rail energy intensity. It projects rail energy intensity to decline by a factor of 0.9642 every 5 years during the period 2015 to 2040 (Sieminski, A., 2015). Thus, the rail freight would be 260 Btu/ton-mile in 2020, 251 in 2025, 242 in 2030, 233 in 2035, and 225 in 2040. These energy intensity values are based on the LHV of diesel fuel.

2.2 Passenger Rail Energy Intensity

Intercity passenger rail operations are carried out by the National Railroad Passenger Corporation, better known by its registered service mark "Amtrak." Amtrak publishes monthly performance reports that contain performance data for the month and cumulative performance data for the year-to-date (YTD). Amtrak uses its fiscal year (FY), October to September, for the YTD data.

Amtrak served 30.921 million passengers for 6,654.53 million passenger-miles (PM) during the year ending September 2014 (Amtrak, 2014). It operated 37.999 million train-miles. The average rate of diesel fuel consumption was 2.3 gallons per train-mile. Multiplying these two numbers yields 87.4 million gallons of diesel use. However, both these numbers have been rounded to the desired significant digits, thus the estimate may not be exact.

Table 4–26 of the 2015 National Transportation Statistics (NTS), which is published by the Bureau of Transportation Statistics (BTS), lists Amtrak diesel use in 2013 as 66,036,326 gallons and electricity use as 525,127,185 kWh (Bureau of Transportation Statistics, 2015). Although these energy use numbers represent calendar year (CY) use, they can be used for computing passenger rail energy intensity. Also, they represent actual energy use.

Amtrak operated 38.167 million train-miles in FY13 (Amtrak, 2013) as compared to 37.999 million train-miles in FY14, resulting in 168,000 fewer train-miles in FY14. These 168,000 train-miles represent a 4.4 percent decrease. The rate of diesel use, diesel gallons per train-mile, increased from 2.2 in FY13 to 2.3 in FY14, a 4.5 percent increase. The net change in diesel fuel consumption is estimated as -0.44 percent. The estimated diesel use in FY14 is 65,745,653 gallons.

Amtrak's rail service in the Northeast Corridor (NEC) uses electricity. From the September 2014 and 2013 monthly performance reports, we estimated passenger-miles in this corridor. In FY14, the NEC's fully allocated contribution was $482.2 million, and the per passenger-mile value was $0.25. The FY13 values were $364.1 million total and $0.195 per passenger-mile. These data provided FY14 NEC passenger-miles as 1,928,800,000 and FY13 passenger-miles as

1,867,179,487, a 3.3 percent increase in FY14. The estimated electricity use in FY14 is 542,456,382 kWh.

In summary, during FY14, Amtrak passenger service covered 6,654,530.000 passenger-miles, of which 1,928,800,000 were by trains that used electricity. The remaining 4,725,730,000 passenger-miles were covered by diesel-powered trains.

Argonne's GREET® model uses diesel's LHV of 128,488 Btu/gallon and treats 1 kWh as equivalent to 3,412.14 Btu. The estimated 65,745,766 gallons of diesel contains 8,447,528 million Btu, and the estimated 542,456,382 kWh of electricity is equivalent to 1,850,941 million Btu. Amtrak's FY14 energy intensity values are estimated as 1,788 Btu/PM for diesel trains and 960 Btu/PM for electric trains. The estimated combined passenger-mile weighted value is 1,548 Btu/PM.

2.2.1 Future Passenger Energy Intensity

We also examined trends in passenger rail energy intensity by using the historical passenger-mile and energy use data from Table 4-26 of the NTS (Bureau of Transportation Statistics, 2015). Figure 1 shows the trend in passenger rail energy intensity for the period of 2000 to 2014. Except for 2009, the energy intensity declined steadily from 2000 to 2012, but increased slightly during 2013 and 2014. For future energy intensity values, we recommend that the 2014 value (1,548 Btu/PM) be used for 2015. A decline of 1 percent every 5 years would give an energy intensity of 1,533 Btu/PM in 2020, 1,517 in 2025, 1,502 in 2030, 1,487 in 2035, and 1,472 in 2040.

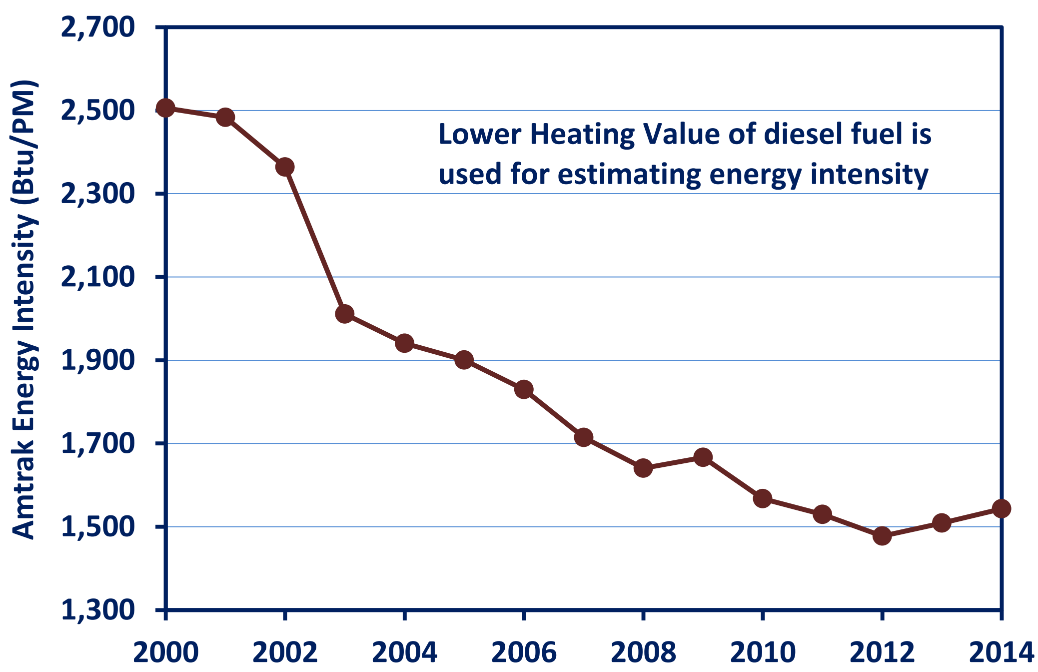

Figure 1. Trend in Passenger Rail Energy Intensity

2.2.2 Passenger Rail Load Factor

An important aspect of passenger rail service is its load factor. The load factor is the ratio of passenger-miles to seats miles, usually reported as a percentage. Amtrak's monthly performance reports provide these data for each month in 2015. [2]

Figure 2 shows the month to month variations in Amtrak's load factor for the period January 2003 to December 2014. The data show that the load factor is highest during the summer months and is the lowest during the first 2 months of a CY. The highest load factor of 63.6 percent was achieved in August 2011, while the lowest load factor of 39 percent was experienced in January 2007.

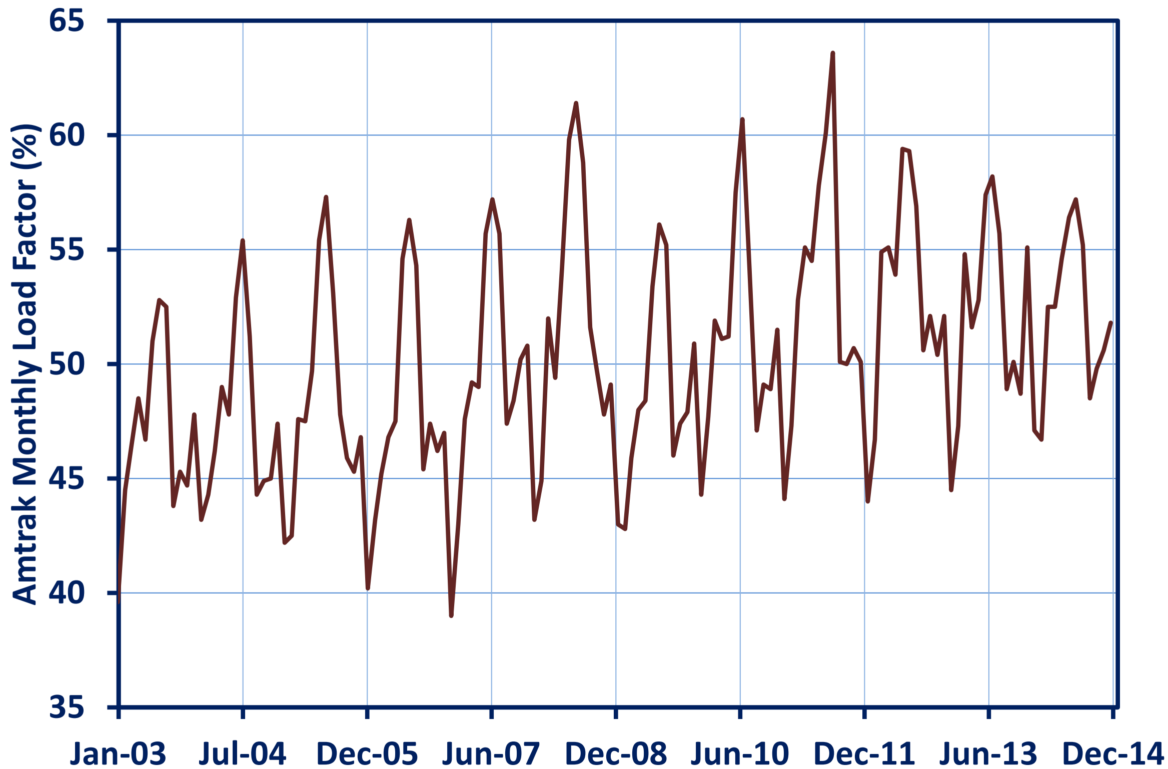

Figure 2. Month-to-Month Variations in Amtrak's Load Factor

We also examined the average annual load factors for CYs 2003 through 2014. These values were computed as the sum of passenger-miles divided by the sum of seat miles served during the year. Figure 3 shows the trend in average annual load factors from 2003 to 2014. Except for 2 years, the average annual load factor showed an upward trend during the first 10 years, as can be seen in the figure. The average annual load factor declined a little in 2013 and remained almost flat in 2014. It appears that the load factor would stabilize in the 52 percent to 55 percent range. We recommend that a load factor of 52 percent be used for 2015, increasing by 0.5 percent every 5 years. The resulting load factor values would be 52.5 percent in 2020, 53 percent in 2020, 53.5 percent in 2030, 54 percent in 2035, and 54.5 percent in 2040.

[2] Amtrak's monthly performance reports are no longer available. Contact Amtrak for report information.

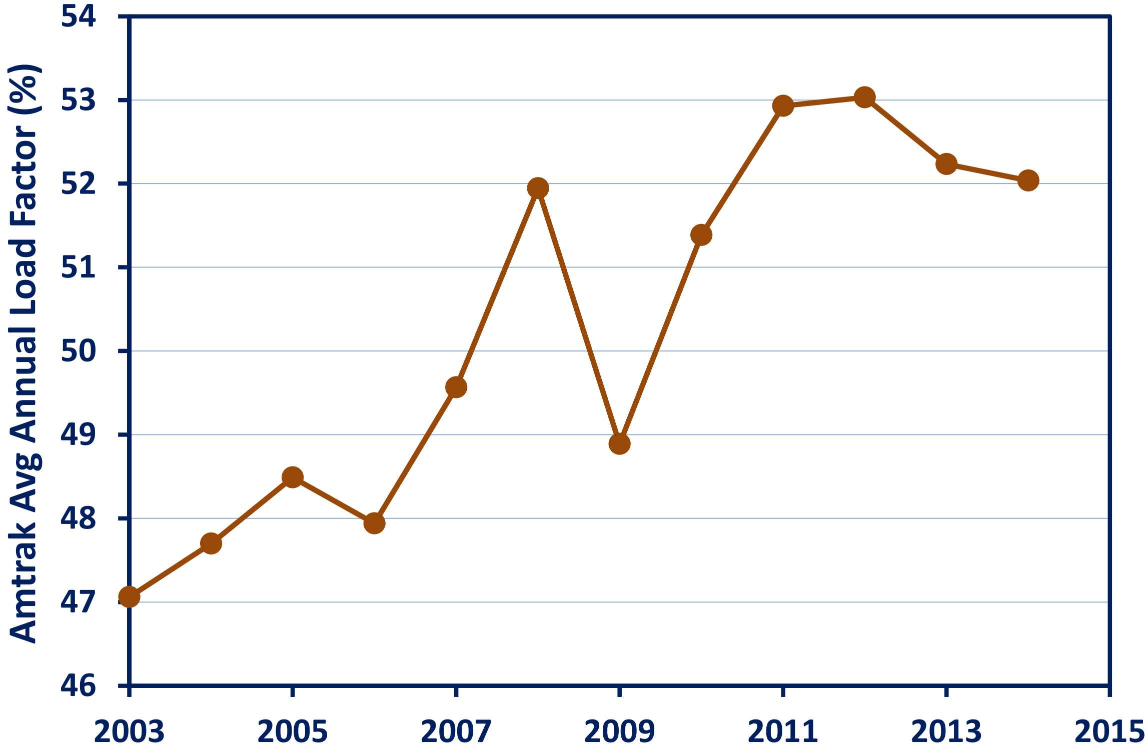

Figure 3. Trend in Average Annual Load Factor for Amtrak

3. Criteria Pollutant Emissions

In this chapter, locomotive exhaust emissions data collected for different EPA Tier standards and in-use locomotive emissions tests are presented, as are data on brake specific fuel consumption (BSFC) from the testing of six locomotives, for both line-haul and switching operations. To estimate future emissions trends of locomotives, locomotives in service by the year of production were assigned EPA Tiers 0, 1, 2, and 3 so that historical shares of each tier for each year can be estimated. The historical trend was then extended to 2040, under the assumption that all future locomotives will comply with Tier 4 emissions standards.

3.1 Locomotive Emissions Standards

The EPA sets exhaust emissions standards for criteria pollutants: hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_X), and particulate matter (PM) for railroad locomotives. These standards are set by the year of locomotive manufacture and are identified as Tier 0 (1973–1992), Tier 1 (1993–2004), Tier 2 (2005–2011), Tier 3 (2012–2014), and Tier 4 (2015 and later). The standards are set in terms of grams of pollutant allowed per brake-horsepower-hour (g/bhp-hr) of operation. The test procedures include certification testing, production line testing, and in-use testing using the Federal Test Procedure (FTP) when the locomotive has reached between 50 and 70 percent of its useful life. Separate standards are set for line-haul and switch locomotives (U.S Environmental Protection Agency, 2015) (Government Publishing Office, 2012). Table 2 summarizes these standards.

Table 2. EPA Locomotive Exhaust Emissions Standards (g/bhp-hr)

			Standards (g/bhp-hr)			
Duty Cycle	**Tier**	**Year of Original Manufacture**	**HC**	**CO**	**NO_X**	**PM**
Line-haul	0	1973–1992	1.00	5.0	9.5	0.22
	1	1993–2004	0.55	2.2	7.4	0.22
	2	2005–2011	0.30	1.5	5.5	0.10
	3	2012–2014	0.30	1.5	5.5	0.10
	4	2015 & Later	0.14	1.5	1.3	0.03
Switch	0	1973–2001	2.10	8.0	11.8	0.26
	1	2002–2004	1.20	2.5	11.0	0.26
	2	2005–2010	0.60	2.4	8.1	0.13
	3	2011–2014	0.60	2.4	5.0	0.10
	4	2015 & Later	0.14	2.4	1.3	0.03

Source: EPA http://www3.epa.gov/otaq/standards/nonroad/locomotives.htm.

These standards can be converted to emissions per million Btu by BSFC rates for locomotives. The Southwest Research Institute (SwRI) conducted tests of locomotives for the California Air Resources Board (CARB) and estimated BSFC for six locomotives using CARB diesel, highway diesel, high-sulfur diesel, and low-sulfur diesel (Fritz, S. G., 2000). We used the average BSFC values for line-haul locomotives and switcher locomotives to convert EPA standards from grams per bhp-hr to grams per million Btu by using the following formula:

$$\frac{grams}{MMBtu} = \frac{grams}{bhp\text{-}hr} * \frac{gallon}{128488} * \frac{bhp\text{-}hr}{BSFC} * \frac{7.068}{gallon} * 1000000 \quad (1)$$

Here, 128,488 represents the LHV value of diesel in Btu per gallon and 7.068 represents the mass of 1 gallon of diesel in pounds. The BSFC values are in pounds of diesel.

The equation can be simplified as follows.

$$\frac{grams}{MMBtu} = grams * \frac{7.068}{BSFC} * \frac{1000000}{128488} \quad (2)$$

The average BSFC value for line-haul locomotive tests for highway diesel was 0.354 lb/bhp-hr, and for switcher locomotive tests, it was 0.405 lb/bhp-hr. The resulting conversion factor for line-haul locomotives was 154.2, and for switcher locomotives it was 134.8. Table 3 summarizes the computed emissions standards in terms of grams per million Btu.

Table 3. Computed Locomotive Exhaust Emissions Standards (g/million Btu)

			Converted Standards (g/million Btu)			
Duty Cycle	**Tier**	**Year of Original Manufacture**	**HC**	**CO**	**NO_X**	**PM**
Line-haul	0	1973–1992	154	771	1,465	34
	1	1993–2004	85	339	1,141	34
	2	2005–2011	46	231	848	15
	3	2012–2014	46	231	848	15
	4	2015 & Later	22	231	200	5
Switch	0	1973–2001	283	1078	1,590	35
	1	2002–2004	162	337	1,483	35
	2	2005–2010	81	323	1,092	18
	3	2011–2014	81	323	674	13
	4	2015 & Later	19	323	175	4

We estimated implications of these emissions standards for actual locomotive stock in 2013. The AAR publishes locomotive stock by the year of manufacture, as shown in Table 4 (Association of American Railroads, 2014).

Table 4. Class I Railroads, 2013 Locomotive Stock by Year of Manufacture

Year Built	Number of Locomotives	Share of Total	EPA Tier
2013	649	2.6%	3
2012	693	2.8%	3
2011	495	2.0%	2
2010	253	1.0%	2
2005–2009	4,039	16.1%	2
2000–2004	4,258	17.0%	1
1995–1999	4,382	17.5%	1
1990–1994	2,363	9.4%	0 & 1
Pre 1990	7,901	31.6%	0
Total	25,033	100.0%	

By using data from older editions of the AAR's *Railroad Facts*, we estimated the share of locomotives manufactured in 1993 and 1994 and separated Tier 1 locomotives from locomotives built during the period of 1990 to 1994 (Association of American Railroads, 1994) (Association of American Railroads, 1995). After developing sums of locomotives by EPA emissions tier standards, we computed tier share-weighted emissions rates of HC, CO, NO_X, and PM, as shown in Table 5. These values represent the upper limits of emissions expected to be emitted by Class I railroad locomotives.

Table 5. Computed Emissions Standards (g/million Btu) and Their Effect on 2013 Locomotive Stock

Year Built	Number of Locomotives	Share of Total	EPA Tier	Average 2014 Test Line-Haul Emissions (g/million Btu)				Average 2014 Test Switcher Emissions (g/million Btu)			
				HC	CO	NO_X	PM	HC	CO	NO_X	PM
2012 & 2013	1,342	5.4%	3	46	231	848	15	81	323	674	13
2005–2011	4,787	19.1%	2	46	231	848	15	81	323	1,092	18
1993–2011	9,776	39.1%	1	85	339	1,141	34	162	337	1,483	35
1992 & Before	9,128	36.5%	0	154	771	1,465	34	283	1078	1,590	35
Total	25,033	100.0%									
Locomotive Share-Weighted Values				**101**	**470**	**1,187**	**29**	**186**	**604**	**1,404**	**31**

The actual emissions rates may exceed this value because the locomotive emissions regulations allow for averaging, banking, and trading (ABT) for NO_x, and PM based on the locomotive model year (1999 or later), service class (line-haul or switch), Tier, and the NO_x and PM levels to which the engine family is certified. Under ABT, a railroad may use credits to comply with NO_X and PM emissions standards. Emission credits are defined as the amount of emission reduction below or exceedance above the emissions standards by a locomotive engine family. Emission reductions below the standard are considered as positive credits, while emission exceedances above the standard are considered as negative credits. Locomotive manufactures can average these credits over a family of engines to meet the requirements, bank them to be used against future year model engine emission certification or trade them when engines are sold that do not meet the emissions standards. The ABT program allows specification of family emissions limits (FELs) for each pollutant that must not be higher than the limits specified in the regulations (Government Publishing Office, 2012). FEL defines an emission level that is declared by the locomotive manufacturer to serve in lieu of an emission standard for locomotive emission certification and for the averaging, banking, and trading program.

3.2 AAR In-Use Locomotive Emissions Tests

The AAR conducts tests of some sample locomotives from each EPA-defined Tier and publishes test results (Smith, B., 2015). These results represent actual in-use emissions rates. The results from the AAR's 2014 tests are summarized in Table 6, Table 7, and Table 8. Table 6 shows EPA standards, some FEL values, and actual test values for Tier 0 locomotives. Table 7 shows standards, some FEL values, and test results for Tier 1 locomotives. Table 8 shows such values for Tier 2 locomotives. Although some Tier 3 locomotives were owned by Class I railroads in 2013, they were not tested. Tier 3 locomotives probably represented a small fraction of the total locomotive population or they had not accumulated sufficient hours of operation.

Table 6. Summary Table for 2014 AAR FTP Locomotive Emissions Tests: Tier 0 Locomotives

Emission Standard	RR Unit	Engine Type	Line-Haul (g/hp-hr)				Switcher Cycle (g/hp-hr)			
Tier 0 - FEL			**HC**	**CO**	**NO_x**	**PM**	**HC**	**CO**	**NO_x**	**PM**
FEL Limits			**1.00**	**5.0**	**10.1**	**0.60**	**2.10**	**8.0**	**12.9**	**0.72**
GE	NS 9744	7FDL16	0.29	0.9	9.4	0.12	0.40	1.2	11.7	0.16
FEL Limits			**1.00**	**5.0**	**9.0**	**0.60**	**2.10**	**8.0**	**11.9**	**0.72**
GE	BNSF 738	7FDL16	0.29	1.3	7.5	0.08	0.45	1.7	9.7	0.14
GE	BNSF 1058	7FDL16	0.30	1.0	8.1	0.06	0.49	1.2	10.7	0.12
GE	UP 6285	7FDL16	0.29	1.6	7.2	0.11	0.46	1.7	9.5	0.16
FEL Limits			**1.00**	**5.0**	**9.5**	**0.60**	**2.10**	**8.0**	**10.9**	**0.72**
EMD	CN 5729	16-710	0.22	0.5	7.1	0.37	0.34	0.6	8.4	0.27
FEL Limits			**1.00**	**5.0**	**9.5**	**0.60**	**2.10**	**8.0**	**11.0**	**0.72**
EMD	BNSF 9847	16-710	1.39[a]	2.3	6.1	0.54	2.15[a]	1.6	6.5	0.62
Tier 0 - STD			**HC**	**CO**	**NO_x**	**PM**	**HC**	**CO**	**NO_x**	**PM**
EPA Limits			**1.00**	**5.0**	**9.5**	**0.60**	**2.10**	**8.0**	**14.0**	**0.72**
EMD	CSX T4684	16-710	0.31	3.5	8.9	0.28	0.39	3.0	9.1	0.35
EMD	CSX T4690	16-710	0.30	0.9	9.2	0.34	0.44	1.0	9.4	0.19
EMD	CSX T8128	16-645	0.48	1.9	7.9	0.21	0.75	1.4	11.4	0.18
EMD	CSX T8145	16-645	0.35	1.6	7.2	0.17	0.57	1.4	10.1	0.16
EMD	KCS 3970	16-710	0.29	0.5	8.0	0.33	0.43	0.7	8.2	0.35
[a]Locomotive exceeds HC levels for both line-haul and switcher cycle configurations. EMD = engine manufacture diagnostic system; GE = General Electric										
AVERAGE	**ALL**	**ALL**	**0.41**	**1.5**	**7.9**	**0.2**	**0.62**	**1.4**	**9.5**	**0.2**
Highest, Excluding Non-compliant			0.48	3.50	9.40	0.54	0.75	3.00	11.70	0.62

Source: Smith (2015)

Note that the AAR used FEL under the EPA's ABT program here. Although higher limits are set for NO_X, all locomotives comply with the standard of 9.5 g/bhp-hr for line-haul and

11.8 g/bhp-hr for switcher. The specified FEL values for PM, 0.6 for line-haul locomotives and 0.72 for switcher locomotives, exceed the standards of 0.22 and 0.26 g/bhp-hr.

Table 7. Summary Table for 2014 AAR FTP Locomotive Emissions Tests: Tier 1 Locomotives

Emission Standard	RR Unit	Type	Line-Haul (g/hp-hr)				Switcher Cycle (g/hp-hr)			
Tier 1 - FEL			**HC**	**CO**	**NO_x**	**PM**	**HC**	**CO**	**NO_x**	**PM**
FEL Limits			**0.55**	**2.2**	**9.5**	**0.45**	**1.2**	**2.5**	**12.8**	**0.54**
GE	NS 9830	7FDL16	0.30	1.0	9.0	0.12	0.44	1.1	11.5	0.20
FEL Limits			0.55	2.2	7.4	0.45	1.20	2.5	9.0	0.54
EMD	NS 2611	16-710	0.36	0.3	6.3	0.32	0.38	0.6	6.6	0.40
EMD	UP 5140	16-710	0.34	1.2	5.6	0.40	0.49	0.7	6.3	0.44
EMD	UP 5187	16-710	0.30	0.8	5.6	0.30	0.40	0.5	5.9	0.19
Tier 1 – STD			**HC**	**CO**	**NO_x**	**PM**	**HC**	**CO**	**NO_x**	**PM**
EPA Limits			**0.55**	**2.2**	**7.4**	**0.45**	**1.20**	**2.5**	**11.0**	**0.54**
GE	UP 6077	7FDL16	0.32	1.1	6.4	0.08	0.56	1.2	8.7	0.15
AVERAGE	ALL	ALL	0.32	0.88	6.58	0.24	0.45	0.82	7.80	0.28
Highest			0.36	1.20	9.00	0.40	0.56	1.20	11.50	0.44

Source: Smith (2015)

Note that the AAR has used FEL, since some locomotives exceed the NO_X standard of 7.4 g/bhp-hr for line-haul locomotives and 11 g/bhp-hr for switcher locomotives. Similarly, PM standards of 0.22 for line-haul locomotives and 0.26 for switcher locomotives are exceeded, and higher FEL values are used.

Table 8. Summary Table for 2014 AAR FTP Locomotive Emissions Tests: Tier 2 Locomotives

Emission Standard	RR Unit	Type	Line-Haul (g/hp-hr)				Switcher Cycle (g/hp-hr)			
Tier 2 - STD			**HC**	**CO**	**NO_x**	**PM**	**HC**	**CO**	**NO_x**	**PM**
EPA Limits			**0.30**	**1.5**	**5.5**	**0.20**	**0.60**	**2.4**	**8.1**	**0.24**
GE	BNSF 6157	GEVO 12LDB7	0.17	0.2	4.7	0.04	0.19	0.3	5.4	0.07
GE	BNSF 7238	GEVO 12LDB22	0.14	0.2	5.2	0.08	0.19	0.4	5.5	0.15
EMD	BNSF 9373	16-710-G3C-T2	0.15	0.3	5.1	0.07	0.22	0.4	6.8	0.08
GE	CN 2270	GEVO 12LDB8	0.15	0.3	4.9	0.11	0.18	0.5	5.3	0.19
GE	CP 8828	GEVO 12LDB8	0.13	0.3	4.7	0.07	0.15	0.4	5.3	0.16
GE	UP 5495	GEVO 12LDB5	0.15	0.3	4.5	0.04	0.18	0.4	5.2	0.08
GE	UP 5529	GEVO 12LDB5	0.19	0.3	4.7	0.06	0.24	0.5	5.3	0.11
EMD	UP 8415	16-710-G3C-T2	0.14	0.5	4.6	0.07	0.23	0.6	5.9	0.08
AVERAGE	**ALL**	**ALL**	**0.15**	**0.30**	**4.80**	**0.07**	**0.20**	**0.44**	**5.59**	**0.12**
Highest			0.19	0.50	5.20	0.11	0.24	0.60	6.80	0.19

Source: Smith (2015)

Here too, PM standards of 0.1 for line-haul locomotives and 0.13 for switcher locomotives are exceeded, and higher FEL values are specified.

We converted the in-use emissions from grams per bhp-hr to grams per million Btu by using factors based on average BSFC for highway diesel and Equation (2) (Fritz, S. G., 2000). As mentioned earlier, the factor value is 154.2 for line-haul and 134.8 for switching. Table 9, Table 10, and Table 11 summarize in-use emissions per million Btu.

Table 9. 2014 AAR FTP Emissions Test Results Converted to g/million Btu: Tier 0 Locomotives

Locomotive Manufacturer	RR & Unit Number	Engine Type	Line-Haul Cycle Emissions (g/million Btu)				Switcher Cycle Emissions (g/million Btu)			
			HC	CO	NO_X	PM	HC	CO	NO_X	PM
Tier 0 EPA Limits			**154**	**771**	**1,465**	**93**	**283**	**1,078**	**1,887**	**97**
GE	NS 9744	7FDL16	45	139	1,449	19	54	162	1,577	22
GE	BNSF 738	7FDL16	45	200	1,156	12	61	229	1,307	19
GE	BNSF 1058	7FDL16	46	154	1,249	9	66	162	1,442	16
GE	UP 6285	7FDL16	45	247	1,110	17	62	229	1,280	22
EMD	CN 5729	16-710	34	77	1,095	57	46	81	1,132	36
EMD	BNSF 9847	16-710	214	355	941	83	290	216	876	84
EMD	CSX T4684	16-710	48	540	1,372	43	53	404	1,226	47
EMD	CSX T4690	16-710	46	139	1,419	52	59	135	1,267	26
EMD	CSX T8128	16-645	74	293	1,218	32	101	189	1,536	24
EMD	CSX T8145	16-645	54	247	1,110	26	77	189	1,361	22
EMD	KCS 3970	16-710	45	77	1,234	51	58	94	1,105	47
AVERAGE	**ALL**	**ALL**	**63**	**224**	**1,214**	**37**	**84**	**190**	**1,283**	**33**
Highest excluding non-compliant			74	540	1,449	57	101	404	1,577	47

Table 10. 2014 AAR FTP Emissions Test Results Converted to g/million Btu: Tier 1 Locomotives

Locomotive Manufacturer	RR & Unit Number	Engine Type	Line-Haul Cycle Emissions (g/million Btu)				Switcher Cycle Emissions (g/million Btu)			
			HC	CO	NO_x	PM	HC	CO	NO_x	PM
Tier 1 EPA Limits			**85**	**339**	**1,141**	**69**	**162**	**337**	**1,483**	**73**
GE	NS 9830	7FDL16	46	154	1,388	19	59	148	1,550	27
EMD	NS 2611	16-710	56	46	971	49	51	81	890	54
EMD	UP 5140	16-710	52	185	863	62	66	94	849	59
EMD	UP 5187	16-710	46	123	863	46	54	67	795	26
GE	UP 6077	7FDL16	49	170	987	12	75	162	1,173	20
AVERAGE	**ALL**	**ALL**	**50**	**136**	**1,015**	**38**	**61**	**111**	**1,051**	**37**
Highest			56	185	1,388	62	75	162	1,550	59

Table 11. 2014 AAR FTP Emissions Test Results Converted to g/million Btu: Tier 2 Locomotives

Locomotive Manufacturer	RR & Unit Number	Engine Type	Line-Haul Cycle Emissions (g/million Btu)				Switcher Cycle Emissions (g/million Btu)			
			HC	CO	NO_x	PM	HC	CO	NO_x	PM
Tier 2 EPA Limits			**46**	**231**	**848**	**31**	**81**	**323**	**1,092**	**32**
GE	BNSF 6157	GEVO 12LDB7	26	31	725	6	26	40	728	9
GE	BNSF 7238	GEVO 12LDB22	22	31	802	12	26	54	741	20
EMD	BNSF 9373	16-710- G3C-T2	23	46	786	11	30	54	916	11
GE	CN 2270	GEVO 12LDB8	23	46	756	17	24	67	714	26
GE	CP 8828	GEVO 12LDB8	20	46	725	11	20	54	714	22
GE	UP 5495	GEVO 12LDB5	23	46	694	6	24	54	701	11
GE	UP 5529	GEVO 12LDB5	29	46	725	9	32	67	714	15
EMD	UP 8415	16-710- G3C-T2	22	77	709	11	31	81	795	11
AVERAGE	**ALL**	**ALL**	**24**	**46**	**740**	**10**	**27**	**59**	**753**	**15**
Highest			29	77	802	17	32	81	916	26

The in-use FTP test results show that all locomotives, except one Tier 0 locomotive, have exhaust emissions lower than EPA standards for HC, CO, and NO_X. Figure 4 shows in-use emissions as a percentage of EPA emissions standards and FEL values for the line-haul locomotive cycle for Tier 0, Tier 1, and Tier 2 locomotives. Figure 5 shows similar results for the switcher locomotive cycle for Tier 0, Tier 1, and Tier 2 locomotives. Note that FEL values were used only for PM emissions. In-use emissions of HC, CO, and NO_X are compared to EPA's emissions standards.

For Tier 0 locomotives, HC emissions average 41 percent of the standard for line-haul and 30 percent of the standard for switcher. Tier 0 CO emissions average 29 percent of the standard for line-haul and 18 percent of the standard for switcher cycle. Tier 0 NO_X emissions average 83 percent of the standard for line-haul and 68 percent of the standard for switcher cycle. Tier 0 PM emissions average 40 percent of the FEL for line-haul and 34 percent of the FEL for switcher cycle. The average emissions values for Tier 0 are calculated including emissions by one non-compliant locomotive.

For Tier 1 locomotives, HC emissions average 59 percent of the standard for line-haul and 38 percent of the standard for switcher. CO emissions average 40 percent of the standard for line-haul and 33 percent of the standard for switcher. NO_X emissions average 89 percent of the standard for line-haul and 71 percent of the standard for switcher, and PM emissions average 54 percent of the FEL for line-haul and 51 percent of the FEL for switcher.

For Tier 2 locomotives, HC emissions average 51 percent of the standard for line-haul and 33 percent of the standard for switcher. CO emissions average 20 percent of the standard for line-haul and 18 percent of the standard for switcher. NO_X emissions average 87 percent of the standard for line-haul and 69 percent of the standard for switcher, and PM emissions average 34 percent of the FEL for line-haul and 48 percent of the FEL for switcher.

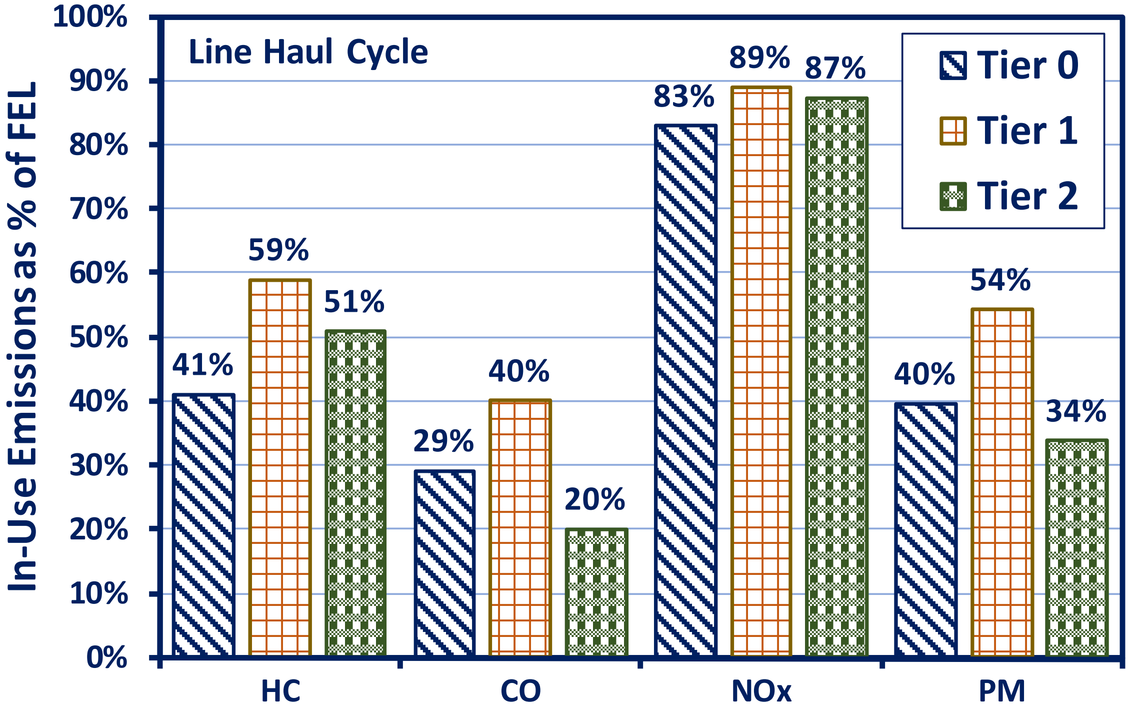

Figure 4. In-Use Emissions as a Percentage of EPA Emissions Standards/ FEL Values for Line-Haul Locomotives

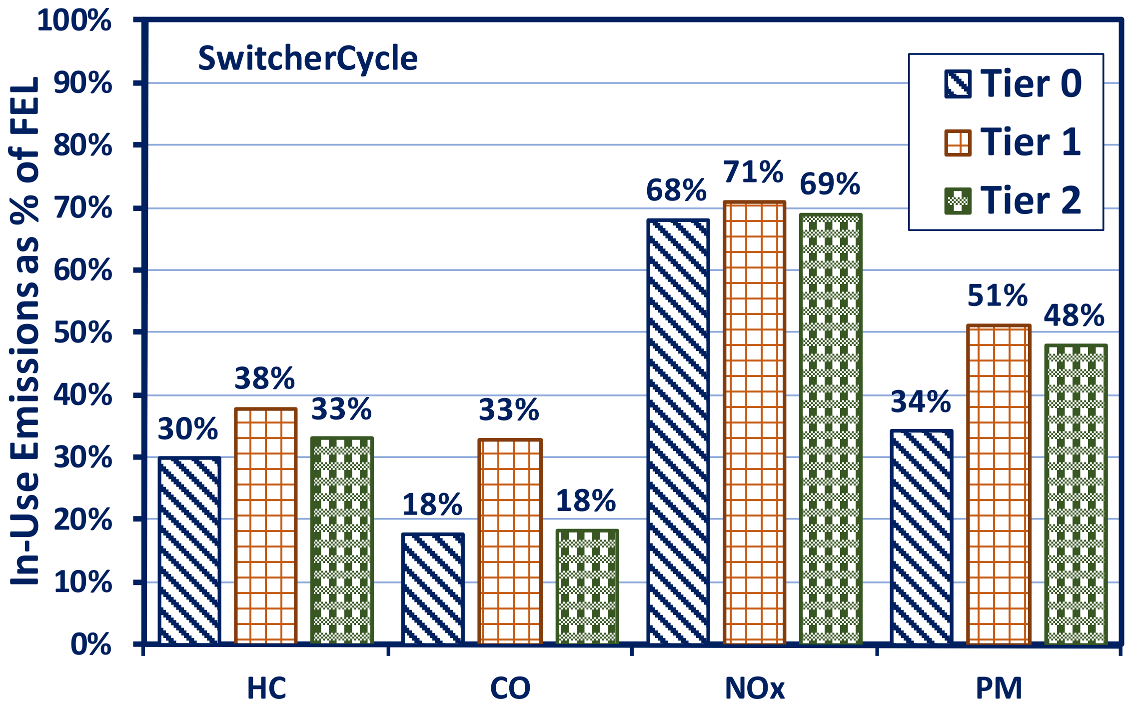

Figure 5. In-Use Emissions as a Percentage of EPA Emissions Standards/ FEL Values for Switcher Locomotives

We computed 2013 locomotive stock share-weighted emissions by using the shares by EPA tier, as shown in Table 5, and compared the values in Table 5 to in-use emissions. Figure 6 shows the results of this comparison.

The share-weighted values for HC, CO, and NO_X are lower than the share-weighted standards for both line-haul and switcher cycle tests. However, PM emissions for the line-haul cycle are slightly higher (31 vs. 29 g), and PM emissions for the switcher cycle are slightly lower (30 vs. 31).

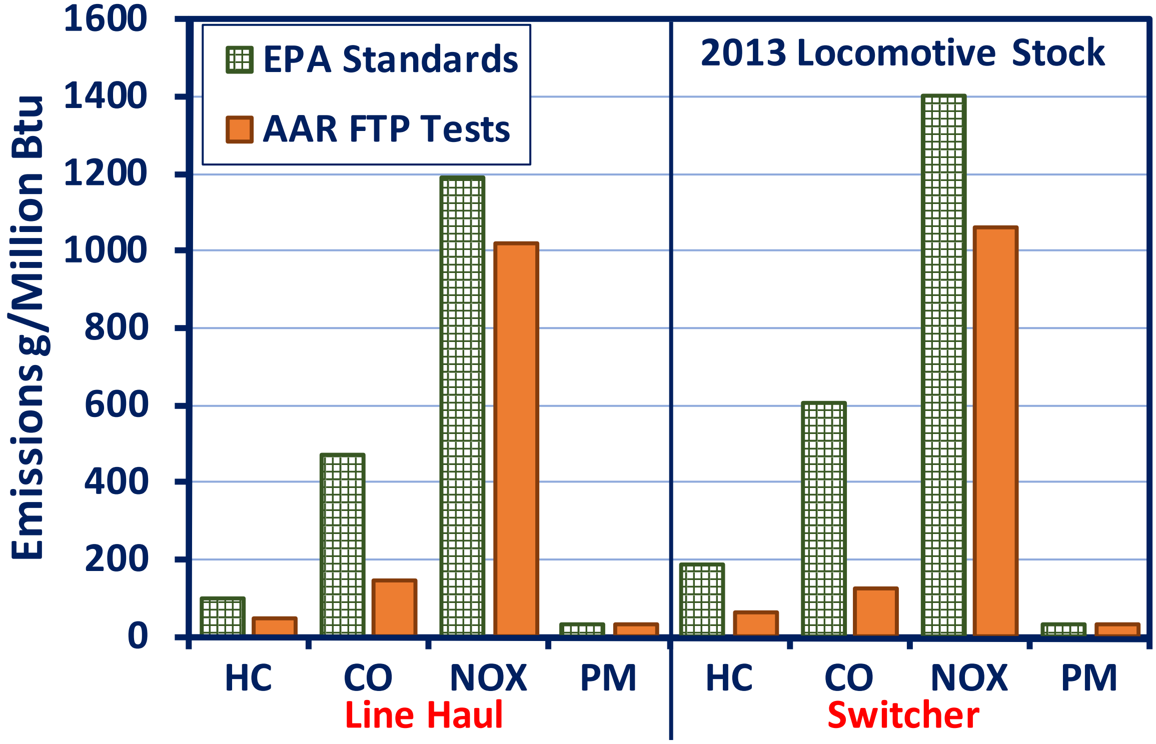

Figure 6. Comparison of 2013 Locomotives Share-Weighted Emissions to EPA Standards

3.3 Future Locomotive Emissions

In order to provide some estimates of locomotive emissions in the future, we examined the past composition of railroad locomotives in service. Past issues of the AAR publication *Railroad Facts* were used for this purpose (Association of American Railroads, 1982-2014). The number of locomotives in service declined from 27,269 in 1981 to 18,004 in 1992. The trend reversed after 1992, and the number of locomotives in service increased slowly to 24,143 in 2007. After some fluctuations, the number of locomotives in service reached 25,033 in 2013.

We also analyzed locomotives in service by the year of production and assigned EPA Tiers 0, 1, 2, and 3 to them. We estimated historical shares for each year, as shown in Figure 7. It can be seen that the share of Tier 0 locomotives declined from 70.4 percent in 2000 to 36.5 percent in 2013. The share of Tier 1 locomotives increased from 29.7 percent in 2000 to 46.1 percent in 2004. As all new locomotives after 2004 were of Tier 2, and the Tier 1 share declined to 39 percent in 2013. The share of Tier 2 locomotives increased from 3.5 percent in 2005 to 20.1 percent in 2011, and then declined to 19.1 percent by 2013, as all new locomotives were of Tier 3 beginning in 2012. Tier 3 locomotive share was 5.4 percent by 2013.

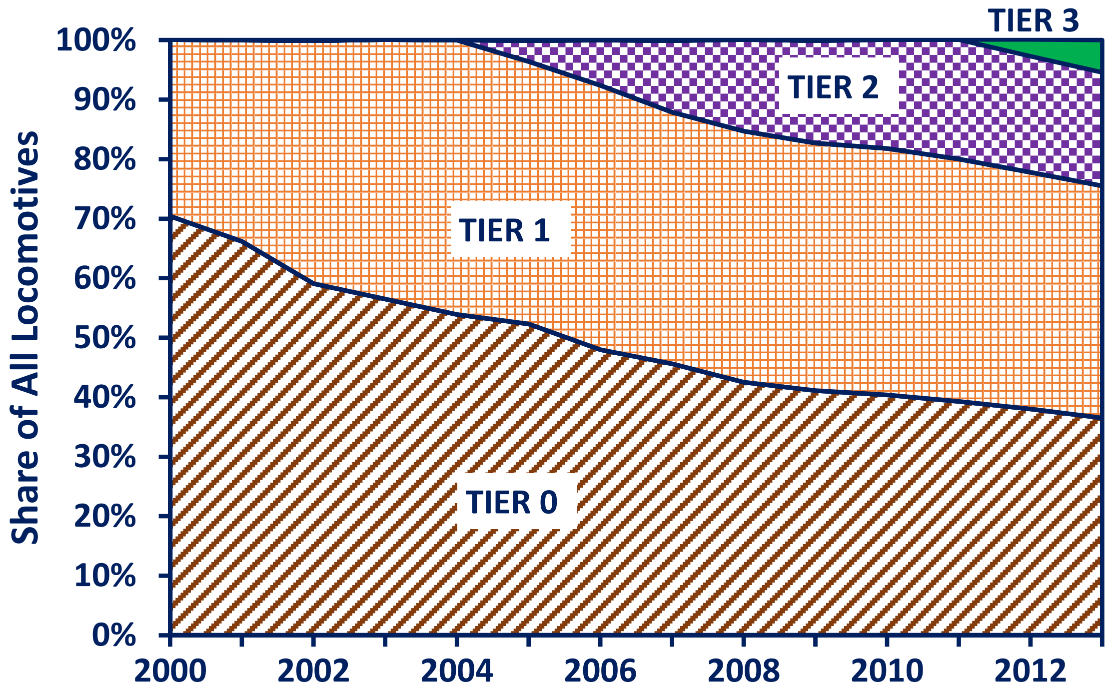

Figure 7. Share of Locomotives in Service by EPA Tiers

Based on the historical trend, we extended the shares of locomotives by EPA tier to 2040. We assumed that all future locomotives will comply with Tier 4 emissions standards. Figure 8 shows historical shares to 2013 and our extension to 2040. Our extension shows that all Tier 0 and Tier 1 locomotives will be retired by 2040, and that shares of Tier 2 and Tier 3 locomotives will be nearly halved.

We used these shares of locomotive tiers and EPA emissions standards to estimate resulting tier share-weighted criteria pollutant emissions per million Btu. Table 12 shows the resulting estimates for 2015, 2020, 2025, 2030, 2035, and 2040. As can be seen from the table, as older locomotives are retired and replaced by Tier 4 locomotives, criteria pollutant emissions rates would drop substantially. The estimated HC emissions rate in 2040 would be 27 percent of the emissions rate in 2015, the CO emissions rate would be 51 percent, the NO_X emissions rate 26 percent, and the PM emissions rate 23 percent for the line-haul locomotives. Similar drops also would be experienced by the switcher locomotives, with 2040 HC emissions rate at 17 percent of 2015, CO at 56 percent, NO_X at 22 percent, and PM at 21 percent.

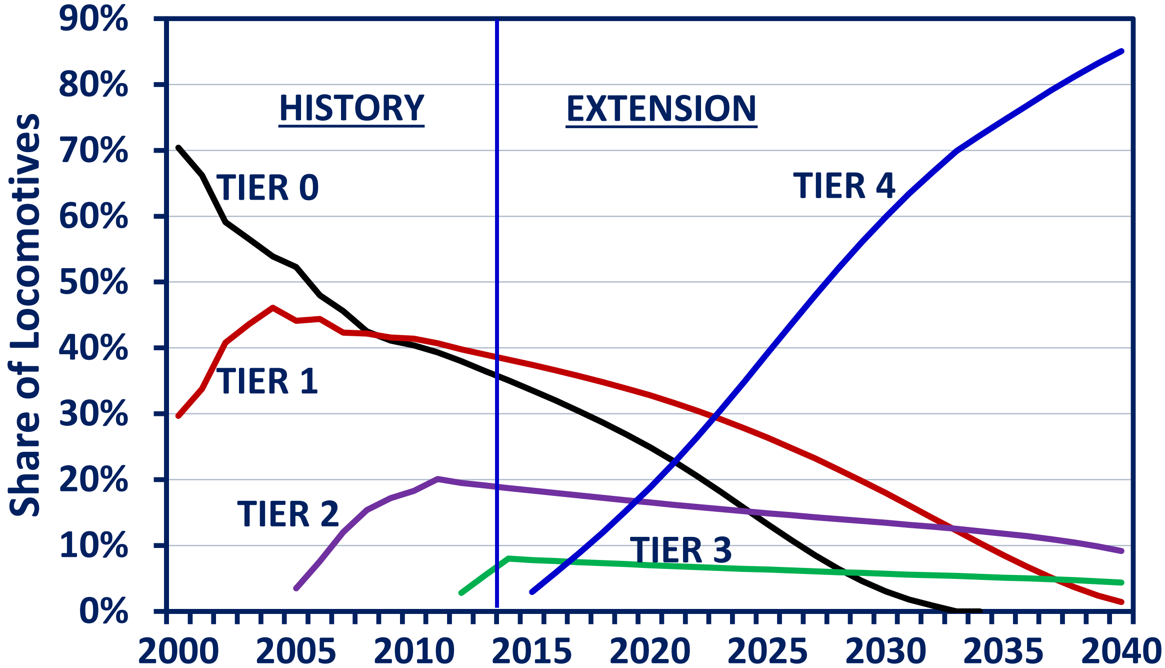

Figure 8. Extension of Locomotive Shares by EPA Tiers Through 2040

Table 12. Estimated Locomotive Tier Share-Weighted Emissions Rates Under EPA Standards (g/million Btu)

	Tier Share-Weighted Emissions Rates under EPA Standards for Line-haul Locomotives (g/million Btu)				Tier Share-Weighted Emissions Rates under EPA Standards for Switcher Locomotives (g/million Btu)			
Year	**HC**	**CO**	**NO_X**	**PM**	**HC**	**CO**	**NO_X**	**PM**
2015	96	453	1146	28	177	582	1346	29
2020	81	401	976	24	146	516	1143	25
2025	61	331	753	19	105	427	875	19
2030	42	267	531	13	64	349	604	13
2035	31	240	390	9	42	325	420	9
2040	26	233	301	6	29	324	299	6

Earlier it was pointed out that actual in-use emissions rates for all but one (PM) criteria pollutant were lower in the AAR's 2014 locomotive tests than the EPA's emissions standards. We used average emissions rates from AAR test results for Tier 0, Tier 1, and Tier 2 locomotives and assumed that Tier 3 locomotive emissions rates would be the same as Tier 2 emissions. Since Tier 4 emissions standards are much lower, we assumed that all Tier 4 locomotives will just meet the EPA standards, excepting for the CO standards. As the ratio of AAR test emissions to EPA standards for CO for both Tier 2 and Tier 3 locomotives was 0.2 for line-haul locomotives (and even lower for switcher locomotives), we applied a factor of 0.2 to CO standards. The resulting Tier share-weighted emissions rates for line-haul and switcher locomotives are listed in Table 13.

It appears from Table 13 that in-use emissions rates will be much lower than the EPA emissions standards in the 2015 to 2030 period, but very close to the standards after that. This is because the locomotive fleet would be dominated by Tier 4 locomotives by 2030, and our assumption that all Tier 4 locomotives would just meet the EPA standards.

Table 13. Estimated Locomotive Tier Share-Weighted Emissions Rates Under AAR Tests and Tier 4 EPA Standards (g/million Btu)

	Tier Share Weighted Emissions Under AAR Tests and Tier 4 EPA Standards[a] for Line-haul Locomotives (g/Million Btu)				Tier Share Weighted Emissions Under AAR Tests and Tier 4 EPA Standards[a] for Switcher Locomotives (g/Million Btu)			
Year	**HC**	**CO**	**NO_X**	**PM**	**HC**	**CO**	**NO_X**	**PM**
2015	47	139	986	29	59	122	1026	29
2020	42	120	847	25	51	110	874	25
2025	35	93	663	19	40	92	675	19
2030	28	68	481	13	30	76	477	13
2035	24	54	361	8	24	68	348	9
2040	22	48	285	6	21	65	266	6

[a] A factor of 0.2 is applied to Tier 4 CO standards, same as that observed in AAR emissions tests for Tier 2 and Tier 3 locomotives.

4. Conclusion

Argonne assessed the energy efficiency and emissions of current rail transportation, and evaluated the environmental benefits of alternative fuels as potential replacement fuels for diesel locomotive engines by updating their GREET® model. The results of the analysis of railroad energy intensity, locomotive emissions standards, and AAR's in-use emissions tests can be summarized as follows and as presented in Table 14:

- The energy intensity of Class I freight railroads in 2014 ranged from 229 Btu/ton-mile to 310 Btu/ton-mile, with the average for all Class I railroads at 270 Btu/ton-mile. These energy intensity values are based on the LHV of diesel fuel.
- The EIA's AEO 2015 projects that freight rail energy intensity will decline by 3.58 percent every 5 years. When applied to a Class I freight railroad's current energy intensity, it would result in an energy intensity of 225 Btu/ton-mile in 2040.
- Two Class I freight railroads, BNSF and UP, accounted for 70.7 percent of total revenue ton-miles and 69.4 percent of energy use in 2014.
- Intercity passenger rail, Amtrak, served 6,654.53 million passenger-miles in FY14, of which 1,928.8 million passenger-miles were by electric trains and 4,725.73 million passenger-miles were by diesel trains.
- Extrapolation of Amtrak's 2013 energy use gave Amtrak's FY14 energy use as 542,457.4 MWh of electricity and 65.746 million gallons of diesel.
- Amtrak's estimated FY14 energy intensity on electricity is 960 Btu/PM and on diesel, it is 1,788 Btu/PM. The combined passenger-mile weighted energy intensity is 1,548 Btu/PM.
- A 1 percent decline every 5 years in passenger rail energy intensity would result in energy intensity of 1,472 Btu/PM in 2040.
- The EPA's locomotive criteria pollutant emissions standards for HC, CO, NO_X, and PM were presented in terms of g/bhp-hr by each Tier. These standards were converted to g/million Btu by using BSFC values from a past publication. The locomotive stock share for each Tier was computed, and the expected emissions limit for each criteria pollutant applicable to the 2013 locomotive stock was estimated.
- AAR in-use FTP test results for HC, CO, NO_X, and PM were presented in g/bhp-hr for Tiers 0, 1, and 2. These values were converted to g/million Btu and applied to the 2013 locomotive stock. The analysis of the AAR test results showed that FEL values were used for PM emissions for all Tiers and for NO_X emissions for one Tier.
- When AAR in-use test results were compared to the specified FEL values, in-use emissions rates for all Tiers were lower than the limits.
- When AAR test results were applied to the 2013 locomotive stock and an EPA Tier share-weighted average was computed for each criteria pollutant, only line-haul cycle PM emissions were higher than the standards.

- Historical shares of locomotives in service by EPA emissions Tier were analyzed, and data were extended to 2040 by using historical retirement rates. The resulting composition of the locomotive fleet was used to estimate future emissions.
- If each locomotive met its applicable Tier standard in the future, criteria pollutant emissions rates from locomotives would be reduced by 75 to 77 percent in 2040 compared to 2015.

Table 14. Values Generated as a Result of this Analysis

		Value as a Result of This Analysis					
Item	**Unit**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**
Energy Intensity							
Freight Rail Energy Intensity	Btu/Ton-mile	270	260	251	242	233	225
Passenger Rail Energy Intensity	Btu/PM	1,548	1,533	1,517	1,502	1,487	1,472
Passenger Rail Load Factor	Percentage	52.0%	52.5%	53.0%	53.5%	54.0%	54.5%
Line-haul Locomotives Emissions Rates							
Line-haul Locomotive HC Emissions Rate Based on EPA Standards	grams/Million Btu	96	81	61	42	31	26
Line-haul Locomotive CO Emissions Rate Based on EPA Standards	grams/Million Btu	453	401	331	267	240	233
Line-haul Locomotive NO_X Emissions Rate Based on EPA Standards	grams/Million Btu	1,146	976	753	531	390	301
Line-haul Locomotive PM Emissions Rate Based on EPA Standards	grams/Million Btu	28	24	19	13	9	6
Line-haul Locomotive HC Emissions Rate Based on AAR In-use Tests and Tier 4 EPA Standards	grams/Million Btu	47	42	35	28	24	22
Line-haul Locomotive CO Emissions Rate Based on AAR In-use Tests and Tier 4 EPA Standards × 0.2	grams/Million Btu	139	120	93	68	54	48
Line-haul Locomotive NO_X Emissions Rate Based on AAR In-use Tests and Tier 4 EPA Standards	grams/Million Btu	986	847	663	481	361	285
Line-haul Locomotive PM Emissions Rate Based on AAR In-use Tests and Tier 4 EPA Standards	grams/Million Btu	29	25	19	13	8	6
Switcher Locomotives Emissions Rates							
Switcher Locomotive HC Emissions Rate Based on EPA Standards	grams/Million Btu	177	146	105	64	42	29
Switcher Locomotive CO Emissions Rate Based on EPA Standards	grams/Million Btu	582	516	427	349	325	324
Switcher Locomotive NO_X Emissions Rate Based on EPA Standards	grams/Million Btu	1,346	1,143	875	604	420	299
Switcher Locomotive PM Emissions Rate Based on EPA Standards	grams/Million Btu	29	25	19	13	9	6
Switcher Locomotive HC Emissions Rate Based on AAR In-use Tests and Tier 4 EPA Standards	grams/Million Btu	59	51	40	30	24	21
Switcher Locomotive CO Emissions Rate Based on AAR In-use Tests and Tier 4 EPA Standards × 0.2	grams/Million Btu	122	110	92	76	68	65
Switcher Locomotive NO_X Emissions Rate Based on AAR In-use Tests and Tier 4 EPA Standards	grams/million Btu	1,026	874	675	477	348	266
Switcher Locomotive PM Emissions Rate Based on AAR In-use Tests and Tier 4 EPA Standards	grams/million Btu	29	25	19	13	9	6

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Appendix A. Alternate Fuels for Locomotives

A.1 Natural Gas

Natural gas is oftentimes deemed to be an effective alternative to diesel because of the benefits of lower fuel costs and cleaner, greener combustion in internal combustion engines. However, a broader and deeper analysis may refute that conventional wisdom when applied to the rail industry. In 2007, the railroads prepared an assessment report entitled *An Evaluation of Natural Gas-fueled Locomotives*, which includes several stakeholders' feedback (i.e., California air districts and California Air Resources Board [CARB]) (Burlington Northern Santa Fe Railway et al., 2007). This section contains a brief background of natural-gas-related attempts made by the rail industry and assumptions made for the Greenhouse gases, Regulated Emissions, and Energy use in Transportation model (GREET®) analysis. Further, the potential of using dimethyl ether (DME) is presented due to its derivation from natural gas using synthetic processes.

Any new technology in the locomotive industry is driven by safety, reliability, fuel economy, exhaust emissions, and power density. Safety and reliability invariably take priority. Although fuel economy is a major revenue affecting factor, reliability is of higher priority as it affects the mode of engine operation. For example, the ability to switch to diesel operation is a logical requirement should there be any issues with natural gas fuel supply/delivery to the engine. This precludes implementation of any efficiency gains offered by advanced combustion strategies such as high pressure direct injection (HPDI), which currently uses very low pilot quantities. However, pushing the boundaries of efficient engine operation still warrants research for future gains, especially with advanced controls using high-speed feedback.

Natural gas has the potential to reduce oxides of nitrogen (NO_x) emissions but suffers on the unburned hydrocarbon (HC) and carbon monoxide (CO) fronts. Therefore, the most stringent applicable U.S. Environmental Protection Agency (EPA) locomotive emission standards should be the basis for evaluating the performance of any locomotive technology. In fact, correspondence with locomotive manufacturers for data gathering yielded similar outcomes. Since 2015, Tier 4 emissions standards are being enforced, and, therefore, for this analysis, these levels were chosen as a baseline.

Energy Conversions Inc., a natural gas retrofit company, demonstrated NO_x emissions reduction using natural gas for Tier 2 standards and reported higher levels for all other emissions (BNSF, UP, AAR, & CAE 2007). However, significant barriers have to be crossed to make it a railroad fuel of choice. The railroads believe that except for some niche applications, such as the liquefied natural gas (LNG) rail yard locomotives in service in Los Angeles for BNSF, natural gas may not offer the often touted benefits, especially given the associated infrastructure costs. In addition, by creating captive fleets (interchanging high horsepower line-haul locomotives) using natural gas locomotives, they argue that the economic competitiveness of the rail industry would be impaired. Also, emissions benefits from fuel shift (alternate fuels) vs. mode shift (rail freight in lieu of truck freight) could be misleading as explained in the BNSF, UP, AAR, & CAE report (2007).

The use of alternate fuels in line-haul and switch locomotives is dictated by the size and horsepower of the engine that powers the locomotive, the amount of tractive effort the locomotive produces, the duty cycle of the locomotive (percent of time at different power levels or throttle notches), the fueling infrastructure requirements, and the range of operations (Burlington Northern Santa Fe Railway et al., 2007). Other considerations and concerns for alternate fuels include:

- Emissions — exhaust after-treatment, its cost, durability, and packaging;
- Cost effectiveness — life-cycle costs, commodity price, fuel processing, delivery, storage, etc.; and
- Power and interoperability concerns.

Natural gas can be used in three distinct ways in a locomotive:

- Spark-ignited (single fuel),
- Low-pressure LNG: dual fuel with diesel pilot, and
- High-pressure LNG: dual fuel with diesel pilot.

Table A.1 summarizes the primary differences between these three approaches to using natural gas as a fuel for locomotives. Low-pressure gas injection is the most practical approach because of its simplicity and previous on-rail demonstrations. Also, the ability to switch to neat diesel should there be any problems with natural gas availability, delivery, or handling is of prime importance. High-pressure direct injection has merit in terms of higher brake thermal efficiency (BTE), but is limited on reliability as explained in BNSF, UP, AAR, & CAE (2007). Single-fuel spark ignition mode negatively impacts power density and BTE. ECI's Dual Fuel Sourcebook further highlights the differences (Energy Conversions, Inc., 2002).

Table A.1. Comparison of Methods for Using Natural Gas as a Locomotive Fuel

Method	Conversion to Spark Engine	Low-Pressure Gas Injection	High-Pressure Gas Injection
Injection method	Gas is premixed with air and ignited by spark plug as in gasoline engines.	Gas is injected at low pressure, and diesel pilot fuel is used to ignite gas.	Gas is injected at high pressure, and diesel pilot fuel is used to ignite gas.
Status	In use in four BNSF yard engines in Los Angeles.	Method used in ECI conversion kits, demonstrated in over the road locomotives.	Experimental promise, but not current over the road demonstrations.
Emissions	Large reductions in NO_x and PM, increases total HC and CO; should meet Tier 1 locomotive standards.	Reduces NO_x to Tier 2 levels, with increases in other pollutants; does not meet Tier 2 locomotive standards.	Experimental notch-8 demonstration of NO_x reductions from 14.1 to 7.3 g/bhp-hr, with no loss in power or efficiency. Another study reduced NO_x from 12 g/bhp-hr to 3 g/bhp-hr, with an 8% loss in efficiency.
Problems	Significant loss of rated power and efficiency.	8% loss in efficiency from 1991 data computed on EPA duty cycle.	Experimental work limited to laboratory assessment; not capable of being demonstrated in revenue service operation.

Source: BNSF, UP, AAR, & CAE (2007)

Because of its greater power rating and higher load factor, a line-haul locomotive will burn up to 10 times the fuel compared to a switch locomotive (Burlington Northern Santa Fe Railway et al., 2007). For this analysis, the average annual fuel consumption for switchers and line-haul locomotives was assumed to be around 40,000 gallons and 400,000 gallons, respectively. Also, the best currently available natural gas conversion technology yields a moderate engine BTE of 33.3% (Burlington Northern Santa Fe Railway et al., 2007). From a performance standpoint, natural gas is being used successfully in several power generation and mobile applications. Significant progress has been made in natural-gas-fueled stationary power with BTE over 50 percent, while meeting aggressive emissions goals (Advanced Reciprocating Engine System, 2016). However, the BNSF, UP, AAR, and CAE 2007 report states:

> *The existence of natural gas engines in a variety of stationary and on-road applications identified does not, however, mean that LNG technology: (a) can be transferred to a variety of locomotive classes operating in all types of service conditions, (b) can meet NO_x and other criteria pollutant emission reduction requirements and (c) can meet the railroads' operating requirements for high horsepower, reliability, and overall fuel efficiency*.

After several unsuccessful attempts to gather data from locomotive manufacturers and railroad partners, it was decided that published results would be used in lieu of test results. The following assumptions were made while considering data input variables for the GREET® rail module. Previous attempts (data from 1991) with natural gas operation yielded high CO and HC emissions compared to diesel. However, due to the lack of sufficient data and the significant progress made in natural gas engines (stationary) in recent years, it was assumed here that a natural gas locomotive could meet Tier 4 emissions standards for all pollutant emissions, while maintaining a conservative BTE of 33.3 percent.

Although the railroads have legitimate concerns about natural gas in line-haul applications, if the fuel cost differential between diesel and natural gas becomes significant in the future, there may still be a pathway for natural gas. The assumptions made for alternate fuels are given below.

A.1.1 Assumptions

- Line-haul annual fuel usage: 400,000 gallons (Burlington Northern Santa Fe Railway et al., 2007)
- Switcher annual fuel usage: 40,000 gallons (Burlington Northern Santa Fe Railway et al., 2007)
- Natural gas BTE: 33.3 percent (Burlington Northern Santa Fe Railway et al., 2007)
- Fuel use: 20 bhp-hr/gallon (Burlington Northern Santa Fe Railway et al., 2007)
- Natural gas lower heating value: 45 MJ/kg (Heywood, J., 1988)
- Diesel BTE: 36 percent (private communication with a locomotive manufacturer)

A.2 Dimethyl Ether (DME)

Dimethyl ether (DME) has gained widespread attention, especially in Europe, Japan, China, and Korea. Volvo, a major truck manufacturing company, has adopted DME as a surrogate diesel fuel.

DME is an attractive alternative to diesel due to its high cetane number (>55), which translates to higher propensity to auto-ignite at lower temperatures. In addition, having significant oxygen content (34.8 percent) enables less soot formation than diesel. DME can be produced by using an indirect synthetic method through a dehydration reaction following a synthetic reaction of methanol, or by a direct synthetic method from natural gas. The surge in the natural gas supply due to recent advances in fracking techniques, makes DME production a safe, viable, and cost-effective option from natural gas.

DME is the simplest ether (CH_3OCH_3). It is a colorless, non-toxic, slightly narcotic, and highly flammable gas under ambient conditions, but liquefies above 5 bar (Lee, C. S., and Park, S. H., 2013). DME is not considered a greenhouse gas, unlike natural gas, which is 23 times more potent than carbon dioxide (CO_2).

DME, unlike diesel, has very low density and viscosity which results in leakage from fuel storage tanks and fuel supply systems, and surface wear of moving parts in fuel injection systems. The absence of C-C bonds results in much less smoke and particulate matter. The explosion limits range from 3.4 to 18 percent, unlike diesel. DME has only 67 percent energy density (28.43 MJ/kg) of diesel (42.5 MJ/kg), and hence a higher flow rate is required to attain comparable engine power. The vapor pressure curve for DME falls between propane and butane, which makes fuel storage tank and delivery similar to liquefied petroleum gas (LPG). The auto-ignition temperature of DME is less than that of diesel and various other fuels (Kapus, P., and Ofner, H., 1995). It has high latent heat and a low boiling temperature which reduces NO_x emissions, due to its instant evaporation upon injection and subsequent drop in combustion temperature. Ignition delay and spray tip penetration lengths are shorter for DME (Kim et al., 2008) (Kim et al., 2011). All in all, DME has excellent diesel replacement potential.

A.2.1 Emissions of DME Engines

There are many reasons why emissions from DME truck engines vary and some are discussed below.

NO_x Emissions: Opposing views were presented with regard to NO_x emissions from DME-fueled engines. Lower NO_x emissions observed by some were due to lower heating value, higher cetane number, and higher latent heat capacity than diesel (Li et al., 2012) (Ahmed et al., 2006). Other studies reported higher NO_x emissions due to short ignition delay under the same energy input conditions (Kim et al., 2008) (Chen et al., 1997). For the GREET® analysis, lower trends were selected based upon a Japanese study of medium duty DME trucks (Goto et al., 2005).

HC and CO Emissions: HC emissions are a result of partial or unburned fuel under fuel-rich conditions or incomplete fuel–air mixing. It was reported that HC emissions from DME combustion are usually lower than or equal to those from diesel combustion (Basu et al., 1995). Similarly, CO emission is also due to incomplete combustion and occurs under mixture conditions that either are too rich or too lean (Heywood, J., 1988). Several researchers concurred that CO emission from DME combustion is usually less than that from diesel combustion because DME (1) has a low C/H ratio, (2) lacks C–C bonds, and (3) has a high oxygen content (Kim et al., 2008) (Fu et al., 2003) (Gill et al., 1998).

Soot Emission: A high equivalence ratio and a temperature higher than 1,500 K are needed to form soot. Soot precursors decrease with an increase in oxygen content and absence of C-C bonds. Therefore, DME combustion has significantly less soot (Arima et al., 1996).

Brake Thermal Efficiency: The BTE of truck engines can be assumed to be fairly similar to diesel counterparts when adjusted for diesel energy equivalent (Iyer et al., 2014). For this study, this premise was upheld based on a literature review, and therefore a 36 percent BTE was used in the GREET® model.

Since DME can be produced by synthesizing natural gas, and because of its conducive natural state, it has the potential to be considered as an alternative to LNG locomotives. However, no relevant locomotive data were available for GREET® analysis. Therefore, DME truck engine data were used to generate GREET® results. The National Traffic Safety and Environmental Laboratory (NTSEL) in Japan developed a DME-fueled medium-duty truck in 2005. The data reported in Goto et al. (2005) were used as a reference to characterize the percentage drop in emissions from the Tier 4 level (Table A.2). We acknowledge that the values may not be representative of the locomotive duty cycle; however, the trends may be similar. BTE was assumed to be similar to diesel, as explained earlier.

Table A.2. Modified Emissions from EPA Tier 4 Based upon Emissions Reduction due to DME Combustion

Locomotive Type	Tier of Standards	Standards (g/bhp-hr)			
		NO_X	PM	HC	CO
Expected reduction from Tier 4 level due to DME[a]		27%	94%	74%	95%
Line-Haul	Tier 4	0.949	0.0018	0.0364	0.075
Switcher	Tier 4	0.949	0.0018	0.0364	0.12

Source: Goto et al. (2005)

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Appendix B.
Rail Module in the GREET® Model

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET®) model developed at the Argonne National Laboratory has been expanded to include well-to-wheels (WTW) analysis of rail operation with diesel fuel, as well as alternative fuels such as natural gas and dimethyl ether (DME).

Life-cycle analysis (LCA) includes all the stages of a product's life—from the extraction of raw materials through the materials' processing, manufacture, distribution, use, and disposal or recycling. For this analysis, we accounted for all the stages in the life cycle of rail fuels, including feedstock recovery and transportation, fuel production and transportation, and fuel consumption by locomotive. The exploration and recovery activities from the well to fuel production, and the subsequent transportation to the pump, constitute the well-to-pump (WTP) stage. The combustion of fuel during rail operation constitutes the pump-to-wheels (PTW) stage. The combination of these two stages makes up the WTW fuel cycle. Figures B.1, B.2, and B.3 show the WTW greenhouse gas (GHG) and Tier 4 air pollutant emissions for freight movement using conventional diesel fuel, as well as natural gas fuels in comparison to combination long-haul heavy-duty vehicles (HDVs). The figures show significant reductions in GHG emissions with rail compared to HDV. However, the criteria pollutant emissions of NOx and PM10 during the operation phase (PTW) are comparable between rail and HDV.

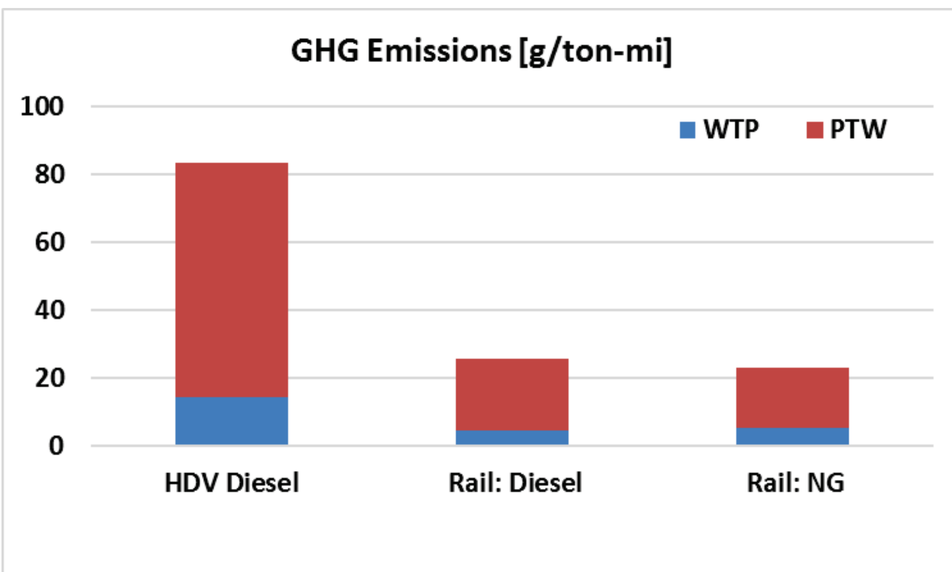

Figure B.1. GHG Emissions for Diesel and Natural Gas Use in Rail Operation Compared to Diesel Use in HDV for Freight Transport

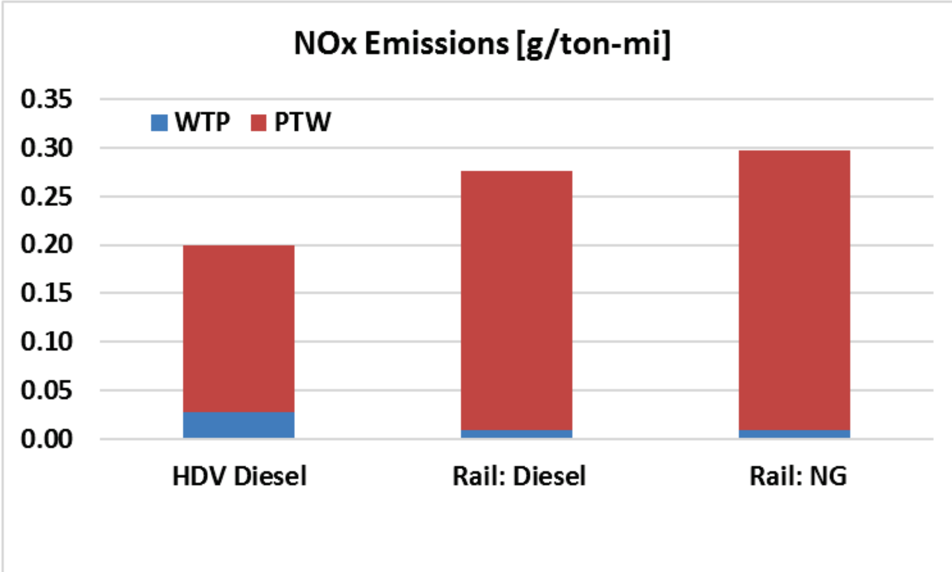

Figure B.2. NOx Emissions for Diesel and Natural Gas Use in Rail Operation Compared to Diesel Use in HDV for Freight Transport

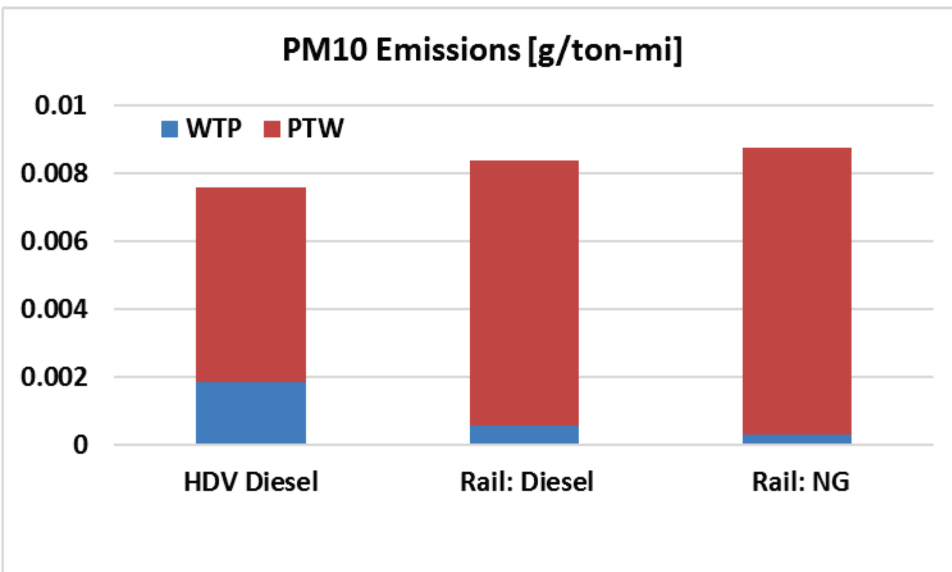

Figure B.3. PM10 Emissions for Diesel and Natural Gas Use in Rail Operation Compared to Diesel Use in HDV for Freight Transport

Abbreviations and Acronyms

AEO	Annual Energy Outlook
Argonne	Argonne National Laboratory
AAR	Association of American Railroads
ABT	Averaging, Banking, and Trading
bar	Unit of Pressure (1 bar = 10 Newtons per square centimeter)
bhp-hr	Brake-Horsepower-Hour(s)
BNSF	BNSF Railway
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
Btu	British Thermal Unit(s)
BTS	Bureau of Transportation Statistics
CAE	California Environmental Associates
CARB	California Air Resources Board
CO	Carbon Monoxide
CSX	CSX Transportation
CY	Calendar Year
DOT	U.S. Department of Transportation
DME	Dimethyl Ether
ECI	Energy Conversions Inc.
EIA	Energy Information Administration
EPA	U.S. Environmental Protection Agency
FEL	Family Emissions Limit
FRA	Federal Railroad Administration
FTP	Federal Test Procedure
FY	Fiscal Year
g	Gram(s)
GHG	Greenhouse Gas
GREET®	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HDT	Heavy-Duty Truck

HDV	Heavy-Duty Vehicle
HPDI	High Pressure Direct Injection
hr	Hour(s)
HC	Hydrocarbon
K	degree(s) Calvin
KCS	Kansas City Southern Railway
kg	Kilogram(s)
kWh	Kilowatt Hour(s)
lb	Pound(s)
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MJ	Megajoule(s)
NEC	Northeast Corridor
NG	Natural Gas
NO_X	Oxides of Nitrogen
NS	Norfolk Southern Corporation
NTS	National Transportation Statistics
PM	Particulate Matter
PM_{10}	Particulate Matter with an Aerodynamic Diameter of 10 Microns or Less
PTW	Pump-To-Wheels
SOO	Soo Line Railroad
STB	Surface Transportation Board
SwRI	Southwest Research Institute
UP	Union Pacific Railroad
WTP	Well-To-Pump
WTW	Well-To-Wheels
YTD	Year-To-Date