U.S. Department of Transportation
Federal Railroad Administration

FRA Locomotive Emissions Comparison Tool (LECT): Emissions Data Documentation

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LOCOMOTIVE EMISSIONS COMPARISON TOOL: EMISSIONS DATA

This document supplements the *Locomotive Emissions Comparison Tool (LECT) User Guide*. It discusses primary data sources and how the emission datasets for the tool were derived. Emission estimates from the LECT are not intended to meet specific requirements for State Implementation Plans (SIPs) or transportation conformity analyses.

EMISSION RATES DATA SUMMARY

Emission rates and emission reductions for the LECT were acquired from the following sources:

1. The Environmental Protection Agency's (EPA) *Emission Factors for Locomotives*[1]
2. EPA's *Ports Emissions Inventory Guidance* document[2]
3. EPA's Emissions & Generation Resource Integrated Database (eGRID)[3]
4. EPA's GHG Emissions Factors Hub[4]
5. The California Air Resources Board's (CARB) *Technology Feasibility Assessment for the Proposed In-Use Locomotive Regulation*[5]

EMISSIONS METHODOLOGY

The following sections provide a detailed description of emission rate equations and default input parameters used in the LECT. Please see Tables A1 and A2 in the Appendix for relevant emissions factors and greenhouse gas (GHG) emission rates associated with upstream electricity generation (electric locomotives only). The equations below summarize how the tool calculates emission reductions. The change in emissions is the difference between the emissions from the baseline and replacement engines. Emission reductions are output in short tons per year for air pollutants and metric tons per year for GHGs.

$$\Delta Emissions = Baseline\ Emissions - Replacement\ Emissions \quad (1)$$

[1] U.S. Environmental Protection Agency, *Emission Factors for Locomotives*, EPA-420-F-09-025 (April 2009). Available at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100500B.TXT.
[2] U.S. Environmental Protection Agency, Office of Transportation Air Quality, *Ports Emissions Inventory Guidance: Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emissions*, EPA-420-B-22-011 (April 2022). Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1014J1S.pdf.
[3] U.S. Environmental Protection Agency, Emissions & Generation Resource Integrated Database (eGRID) (web page) (November 8, 2023). Available at: https://www.epa.gov/egrid.
Data Explorer (2021): https://www.epa.gov/egrid/data-explorer.
Summary Data (2021): https://www.epa.gov/egrid/summary-data.
[4] U.S. Environmental Protection Agency, GHG Emission Factors Hub (web page) (April 3, 2023). Available at: https://www.epa.gov/climateleadership/ghg-emission-factors-hub.
[5] California Air Resources Board, *Appendix F: Technology Feasibility Assessment for the Proposed In-Use Locomotive Regulation*. Available at https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/appf.pdf. Accessed December 2023.

A positive change in emissions is equivalent to an emissions reduction (benefit), while a negative change in emissions can be interpreted as an emissions increase (disbenefit). The tool assumes original equipment is powered by diesel fuel, with baseline equipment emissions calculated as:

$$E_{baseline} = EPA_{emission\ factor}\left(\frac{g}{bhp-hr}\right) * CF\left(\frac{bhp-hr}{gal}\right) * Fuel(gal) * UC \quad (2)$$

where $E_{baseline}$ is baseline emissions, *CF* is the EPA-supplied conversion factor for different locomotive applications (see below), *Fuel* is the annual fuel consumption in gallons of diesel for a single representative locomotive, and *UC* is a factor to convert between grams and short tons (air pollutants) and metric tons (GHGs).[6]

Diesel Locomotive Emission Factors

The EPA's locomotive emission factors are given in units of grams of pollutant per brake horsepower-hour (g/bhp-hr). Brake horsepower is a measure of an engine's horsepower before the loss in power caused by the gearbox and drive train. It is measured at the crankshaft, just outside the engine, and is a function of engine torque and rotational speed. The two locomotive applications included in this tool are line-hauling (Class II/III, including passenger trains) and switching. The following conversion factors[7] are applied to calculate the mass of pollutant emitted based on the volume of diesel fuel consumed:

Small (Class II/III) Line-Haul: 18.2 bhp-hr/gal
Switch locomotives: 15.2 bhp-hr/gal

The replacement engine emissions are based on the type of replacement locomotive, as described under **Replacement Engine Types**. For replacement diesel engines, emission reductions are expected due to newer engines meeting more stringent EPA standards (e.g., replacing a Tier 1 engine with Tier 4). For all calculations, $PM_{2.5}$ emissions are estimated as 97 percent of PM_{10} emissions.[8]

THC-to-VOC Conversion

EPA's hydrocarbon emission factors for locomotive engines are reported in terms of total hydrocarbons (THC). THC is converted to volatile organic compounds (VOC) for consistency with air quality standards, using the following factor for diesel engines.[9]

$$\frac{VOC}{THC} = 1.053 \quad (3)$$

[6] 1 short ton = 907,185 g and 1 metric ton = 1,000,000 g.
[7] These conversion factors were calculated by EPA based on the duty cycles of the different locomotive applications (see footnote 2).
[8] U.S. Environmental Protection Agency, Office of Transportation Air Quality, *Draft Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emission Inventories*. EPA-420-D-20-001 (February 2020). Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100YFY8.pdf.
[9] U.S. Environmental Protection Agency, *Conversion Factors for Hydrocarbon Components,* EPA420-R-05-015 (December 2005). Available at: https://19january2017snapshot.epa.gov/www3/otaq/models/nonrdmdl/nonrdmdl2005/420r05015.pdf.

Replacement Engine Types

The LECT allows users to select from five different engine replacement options: diesel, diesel GenSet (switch locomotives only), all-electric or equivalent, diesel-battery hybrid, and other technology. For lower-emissions locomotives that exceed the Tier 4 standards, users are required to provide manufacturer-supplied certification data. Sources of emission rates by engine type are summarized in Table 1.

Table 1. Emissions Source by Engine Type

Engine Type	Locomotive Application	Emissions Rate Source
Diesel	Line-Haul and Switch	EPA[10, 11] Manufacturer-supplied if engine exceeds Tier 4 standards
Diesel GenSet	Switch only	California Air Resources Board[12]
All-Electric or Equivalent	Line-Haul and Switch	EPA[13]
Diesel-Battery Hybrid	Line-Haul and Switch	Manufacturer-supplied
Other Technology	Line-Haul and Switch	Manufacturer-supplied

The sections that follow describe the engine and fuel types available for modeling with the tool.

Diesel

Emissions savings from a "Diesel" to "Diesel" engine replacement are primarily due to the replacement engine being held to a higher emissions tier (see Table A1). Newer engines may also use fuel more efficiently, resulting in additional emission reductions. Please see the Fuel Use section of the *User Guide* for information on how to estimate fuel efficiency improvements.

As more advanced engine technologies are developed, some diesel locomotives may exceed the current Tier 4 standards. For locomotives that exceed Tier 4 standards for any of the air pollutants (i.e., emission rates lower than the standards), the tool allows for users to input emissions certification data from manufacturers in units of g/bhp-hr.

[10] U.S. Environmental Protection Agency, *Emission Factors for Locomotives*, EPA-420-F-09-025 (April 2009). Available at: https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100500B.TXT.

[11] U.S. Environmental Protection Agency, Office of Transportation Air Quality, *Ports Emissions Inventory Guidance: Methodologies for Estimating Port-Related and Goods Movement Mobile Source Emissions,* EPA-420-B-22-011 (April 2022). Available at: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1014J1S.pdf.

[12] California Air Resources Board, Locomotive Emission Verifications, Technology Demonstrations, and Incentives (web page). Available at: https://ww2.arb.ca.gov/our-work/programs/reducing-rail-emissions-california/locomotive-emission-verifications-technology. Accessed December 2023.

[13] U.S. Environmental Protection Agency, Diesel Emissions Quantifier (DEQ) version 9.1. (May 2, 2022). Available at: https://cfpub.epa.gov/quantifier/.

Diesel GenSet

The "Diesel GenSet" option is currently only available for switch locomotives.[14] While it is technically feasible for a diesel GenSet to be used for other applications, they are not commonly used in line-haul locomotives. Diesel GenSets use a multi-engine configuration (typically 2-3 engines) that operate in series with each engine powering up as the load increases. These engines are designed for switch locomotives operating in railyards where locomotives can spend the majority of time idling. During idle, two of the engines in a three-engine GenSet can be turned off with only one engine idling. Compared with a single diesel engine with the same load capacity as the three-engine GenSet, emissions will be lower (mainly due to reductions in fuel use). As the load increases on the GenSet (e.g., the switcher begins moving rail cars around the yard), additional engines power up to meet the work demand. GenSets are typically built with non-road diesel engines/generators and are certified at EPA's Tier 4 emissions standard for switch locomotive applications.[15] When selected as the replacement equipment type, the module calculates emissions based on the EPA Tier 4 standard for switch locomotives.

While fuel savings will vary by switcher use, it is estimated that railyards can observe 20 to 50 percent fuel savings by replacing a diesel switcher with a GenSet.[16] It should be noted that these fuel savings are assumed only due to the operation of the multi-engine configuration and not based on assumptions with individual engine characteristics, such as age. The LECT does not account for these fuel savings automatically and the user must account for them in their replacement fuel use input value.

All-Electric or Equivalent

"All-Electric, Battery or Equivalent" replacement equipment is assumed to have zero operational emissions. This category can be applied to a variety of zero-emission solutions, including, but not limited to batteries, hydrogen fuel cells,[17] and connection to the grid via overhead lines.

Diesel-Battery Hybrid

Several railroads and locomotive manufacturers are pursuing hybrid technology as a more cost-effective and lower-emissions option to traditional diesel engines. For example, Union Pacific and locomotive manufacturer ZTR have partnered on new hybrid-electric locomotives, including "drop-in" technologies that can be used to modify existing systems.[18,19]

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[14] If new applications and emissions data become available for GenSet locomotives, the tool will be updated accordingly.

[15] California Air Resources Board, Locomotive Emission Verifications, Technology Demonstrations, and Incentives (web page). Available at: https://ww2.arb.ca.gov/our-work/programs/reducing-rail-emissions-california/locomotive-emission-verifications-technology. Accessed December 2023.

[16] Manufacturer claims and demonstrations, including: https://archive.epa.gov/midwestcleandiesel/web/pdf/il2008.pdf, and https://ww3.arb.ca.gov/railyard/docs/nrele_finalreport_201507.pdf.

[17] K. Hess et al. (Fuelcell Propulsion Institute), "Demonstration of a Hydrogen Fuel-Cell Locomotive" (2010). Available at: https://pdfs.semanticscholar.org/bc5b/8df3251a993d608295aad4ae795678c046cf.pdf.

[18] Union Pacific, "Union Pacific and ZTR Partner on New Hybrid-Electric Locomotives" (October 6, 2022). Available at: https://www.up.com/media/releases/hybrid-electric-locomotives-nr-221006.htm.

[19] Union Pacific, "Union Pacific Railroad to Assemble World's Largest Carrier-Owned Battery-Electric Locomotive Fleet" (January 28, 2022). Available at: https://www.up.com/media/releases/battery-electric-locomotive-nr-220128.htm.

Hybrid locomotives use a diesel engine and battery power and include different operational and charging modes. Modes can include a diesel generator, battery pack, and hybrid drive.[20] An on-board computer controls which mode or combination of modes receives priority. For example, when the locomotive is used in high power, the diesel generator and battery pack may be used together; at low power, the battery pack may have priority and the diesel generator is turned off. Three methods may be used for charging: diesel generator set to charge the battery pack, regenerative braking that uses recovered energy to charge the battery, and ground charging equipment (e.g., wayside connection to commercial grid). Industry reports indicate that use of hybrid locomotives can result in fuel savings between 30 and 50 percent.[21]

The LECT models diesel-battery hybrid locomotives as diesel engines that conform to EPA's Tier 3 or Tier 4 standards or exceed the Tier 4 standards (requires manufacturer-supplied emission rates). The current tool version does not model upstream electricity emissions from hybrid locomotives due to a lack of data on time spent in different drive and charging modes.

Greenhouse Gas Emissions

GHG Emission Rates—Operational

The tool calculates GHG emissions from locomotive engines based on fuel consumption (gallons) and emission factors (grams per gallon). CO_2 emission benefits in the LECT are reported as both atmospheric CO_2 and CO_2 equivalents (CO_2e).

CO_2 emissions are based on the carbon content of the fuel, while CO_2e is calculated based on the global warming potentials (GWPs) of CO_2, CH_4, and N_2O.[22] The carbon content of diesel locomotive engines is 3,200 grams per gallon and the CH_4 and N_2O mass emitted by diesel locomotives is estimated to be 0.8 grams and 0.26 grams per gallon, respectively.[23]

GHG Emission Rates—Upstream

For electric locomotives, the LECT estimates upstream emissions from electricity generation based on what eGRID region the project is located in[24]:

[20] Railway Technology, "Hybrid locomotives will effectively replace traditional diesel locomotives in the future." Available at: https://www.railway-technology.com/sponsored/hybrid-locomotives-replace-diesel-locomotives/. Accessed December 2023.
[21] Ibid.
[22] U.S. Environmental Protection Agency. "Understanding Global Warming Potentials" (April 18, 2023). https://www.epa.gov/ghgemissions/understanding-global-warming-potentials.
[23] T. W. P. Smith et al., *Third IMO Greenhouse Gas Study 2014: Executive Summary and Final Report* (London: International Maritime Organization, April 2015). Available at: https://www.imo.org/en/ourwork/environment/pages/greenhouse-gas-studies-2014.aspx; U.S. Environmental Protection Agency, *Emission Factors for Greenhouse Gas Inventories* (2023). Available at: https://www.epa.gov/system/files/documents/2023-03/ghg_emission_factors_hub.pdf.
[24] U.S. Environmental Protection Agency, eGrid Data Explorer 2021 (web page) (September 26, 2023). Available at: https://www.epa.gov/egrid/data-explorer.

$$Upstream\ emissions = eGRID_{emission\ rate}\left(\frac{lb}{MWh}\right) \times 1/Eff\ \left(\frac{MWh}{gallon}\right) \times fuel\ consumption\ (gallons)$$

where *Eff* is the fuel efficiency for a switcher locomotive (73.7 gal/MWh) or line-haul/passenger locomotive (64.5 gal/MWh).[25]

Upstream emissions from diesel equipment are estimated based on emission factors from GREET[26] that include contributions from diesel fuel production, transportation, and storage (well-to-use):

Table 1. Emissions factors for diesel well-to-use activities (derived from GREET 2022)

Greenhouse Gas	Well-to-Use Emission Factor (grams per gallon)
CO_2	1662.1
CH_4	14.0581
N_2O	0.0285264
CO_2 Equivalents (GWP-100)	2096.7

Energy Consumption

The tool also calculates upstream and operational energy use for diesel and electric locomotives using outputs from GREET 2022. Upstream energy consumption is based on well-to-use energy factors:

Well-to-use energy for diesel: 44.71 kWh/gallon
Well-to-use energy for electricity production: 1.07 kWh/kWh used

Operational energy use for diesel locomotives is calculated as:

$$Upstream\ emissions = fuel\ consumption\ (gallons) \times \frac{1}{Eff}\left(\frac{MWh}{gallon}\right) \times energy\ use\left(\frac{kWh}{kWh\ used}\right) \times 1000\frac{kWh}{MWh}$$

[25] California Air Resources Board. *Appendix F: Technology Feasibility Assessment for the Proposed In-Use Locomotive Regulation*. Available at: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/locomotive22/appf.pdf (see Table 8). Accessed December 2023.
[26] Argonne National Laboratory. The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET) Tool (2022). Available at: https://greet.anl.gov/net.

Appendix: Emissions Tables & Load Factors

Table A1. Locomotive Emission Factors[27]

			Emission Factors (g/bhp-hr)			
Fuel Type	**Year of Manufacture**	**Tier**	**NO_X**	**PM**	**HC[28]**	**CO**
Diesel (Line-haul)	Pre-1973	Uncontrolled	13.00	0.32	0.48	1.28
	1973-1992	Tier 0	8.60	0.32	0.48	1.28
	1973-1992	Tier 0+	7.20	0.20	0.30	1.28
	1993-2004	Tier 1	6.70	0.32	0.47	1.28
	1993-2004	Tier 1+	6.70	0.20	0.29	1.28
	2005-2011	Tier 2	4.95	0.18	0.26	1.28
	2005-2011	Tier 2+	4.95	0.08	0.13	1.28
	2012-2014	Tier 3	4.95	0.08	0.13	1.28
	2015+	Tier 4	1.00	0.015	0.04	1.28
Diesel (Switch)	Pre-1973	Uncontrolled	17.40	0.44	1.01	1.83
	1973-2001	Tier 0	12.60	0.44	1.01	1.83
	1973-2001	Tier 0+	10.60	0.23	0.57	1.83
	2002-2004	Tier 1	9.90	0.43	1.01	1.83
	2002-2004	Tier 1+	9.90	0.23	0.57	1.83
	2005-2010	Tier 2	7.30	0.19	0.51	1.83
	2005-2010	Tier 2+	7.30	0.11	0.26	1.83
	2011-2014	Tier 3	4.50	0.08	0.26	1.83
	2015+	Tier 4	1.00	0.015	0.08	1.83
GenSet*	2015+	Tier 4	1.00	0.015	0.08	1.83
Electric◊ (or equivalent)	All	N/A	0.0	0.0	0.0	0.0

Tiers with "+" are applicable only to locomotives that were originally manufactured in the corresponding Year of Manufacture range and remanufactured in 2008 or later; EPA holds these remanufactured locomotives to a higher emissions standard.

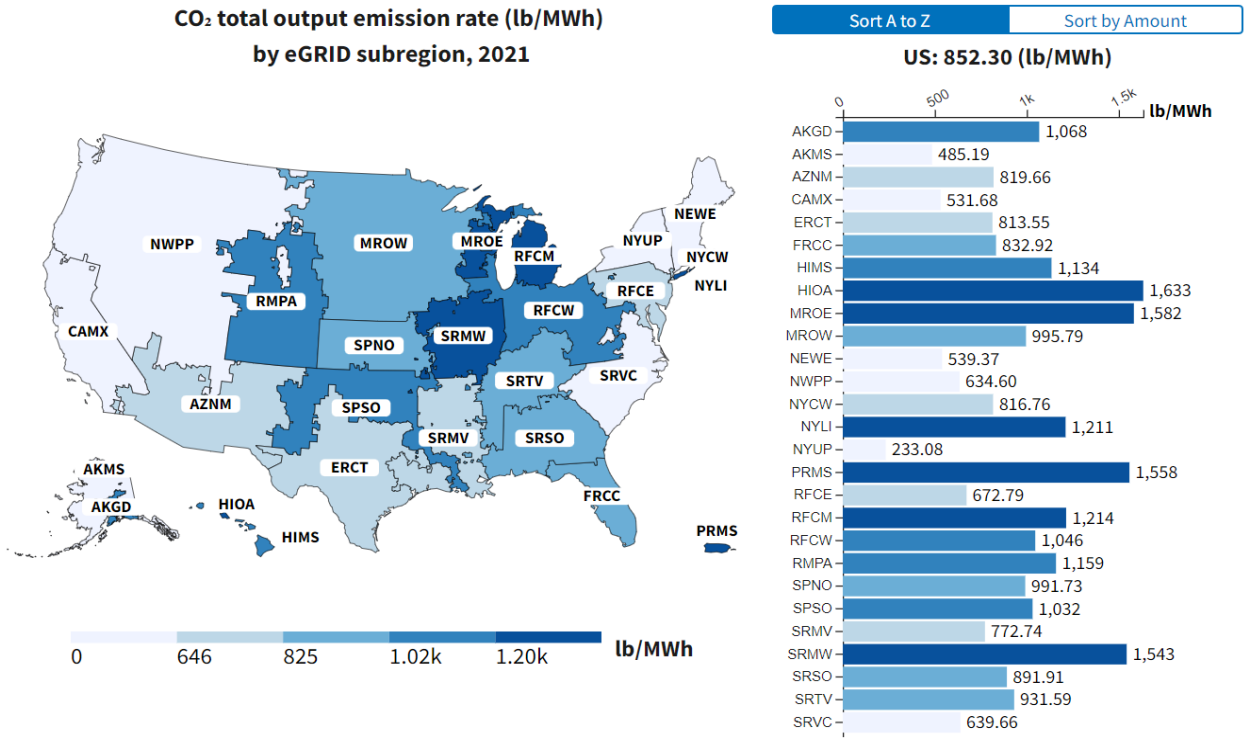
* Emission rates are estimated at the Tier 4 switch locomotive emission rates.

◊ Operational emissions only. See Table A2 for emission rates used to quantify emissions from upstream electricity generation.

[27] U.S. Environmental Protection Agency, *Emission Factors for Locomotives*, EPA-420-F-09-025 (April 2009).Available at https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100500B.TXT.

[28] Hydrocarbon (HC) emission factors were converted to volatile organic compounds (VOC) emission factors using EPA conversion factors.

Figure A1. eGRID Regions[29]



[29] U.S. Environmental Protection Agency, eGrid Data Explorer 2021 (web page) (September 26, 2023). Available at: https://www.epa.gov/egrid/data-explorer.

Table A1. eGRID Subregion Total Output Emission Rates (lb/MWh)[30]

eGRID Subregion	CO_2	CH_4	N_2O	CO_2e
AKGD	1067.7	0.091	0.012	1073.7
AKMS	485.2	0.025	0.004	487.1
AZNM	819.7	0.052	0.007	823.1
CAMX	531.7	0.031	0.004	533.6
ERCT	813.6	0.054	0.008	817.2
FRCC	832.9	0.053	0.007	836.3
HIMS	1134.4	0.135	0.021	1143.9
HIOA	1633.1	0.176	0.027	1645.5
MROE	1582.1	0.148	0.022	1592.3
MROW	995.8	0.107	0.015	1003.1
NEWE	539.4	0.072	0.009	544
NWPP	634.6	0.058	0.008	638.5
NYCW	816.8	0.019	0.002	817.9
NYLI	1210.9	0.126	0.016	1218.9
NYUP	233.1	0.015	0.002	234
PRMS	1558	0.081	0.013	1563.9
RFCE	672.8	0.049	0.007	676
RFCM	1214.1	0.115	0.016	1221.8
RFCW	1046.1	0.095	0.014	1052.5
RMPA	1158.9	0.109	0.016	1166.2
SPNO	991.7	0.108	0.016	999.1
SPSO	1031.6	0.08	0.012	1037
SRMV	772.7	0.04	0.006	775.4
SRMW	1543	0.171	0.025	1554.7
SRSO	891.9	0.067	0.01	896.4
SRTV	931.6	0.087	0.013	937.5
SRVC	639.7	0.052	0.007	642.9
U.S.	852.3	0.071	0.01	857

[30] U.S. Environmental Protection Agency, Summary Data eGRID with 2021 Data (web page) (January 30, 2023). Available at https://www.epa.gov/egrid/summary-data.