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Contents

Report on railway emission factors

Erik Fridell, Jana Moldanová

IVL, Swedish Environmental Research Institute, Box 5302, 40014 Gothenburg, Sweden

Introduction

Trains are normally propelled by diesel engines or electrical engines. The latter give no emissions from the engine and are therefore not considered in this report. Of course the electricity generation will give emissions of various substances depending on the type of power plant (see e.g. EcoTrans-IT 2010). The focus of this report is on emissions of particulate matter (PM) expressed as mass, as well as some characteristics of the particle emissions such as black carbon, elemental carbon and PAH. However, emission factors for a number of other compounds will be described briefly. In the following text the emission factors reported in a few papers with compiled data will be used to present suggested emission factors.

Emissions from engines are usually calculated by means of quantifying the fuel consumption from the power production first and then multiplying the consumption by emission factors for different compounds. Emission factors (EF) used are then related either to the generated power EF_p ($g_{(species)}$/kWh) or to the fuel consumed EF_f ($g_{(species)}/kg_{(fuel)}$), where the first one divided by the specific fuel consumption (SFC, unit $g_{(fuel)}$/kWh) is equal to the second one.

Emissions from a locomotive engine will depend on the type of fuel used as well as on characteristics of the engine. The most important fuel parameters are the sulphur content (FSC) and the aromatics content but the variations are usually small since diesel fuel is used. There are some fuels that are much more uncommon such as biodiesel and coal.

Locomotives are sometimes divided into the categories line-haul locomotives, shunting locomotives and railcars. Line-haul locomotives are for long distance rail traction with engines of typically 400 – 4000 kW, while shunting locomotives have engines of typically 200 – 2000 kW. Railcars are usually used for short distance rail traction and have engines of typically 150 – 1000 kW.

The specific fuel consumption (SFC), expressed as mass of fuel per unit of work by the engine (g/kWh), depend on the engine size and type. The values are typically in the range 206 to 246 g/kWh and some data are presented in Table 1. Often it is more useful to describe the electricity or diesel fuel consumption of a train as a function of the its size as expressed in gross-tonnage. Table 2 gives such data for a number of diesel trains taken from EcoTransIt (2010).

Table 1. Specific fuel consumption for locomotive engines. The types are those used in the respective reference.

Locomotive type	*Reference*	*SFC (g/kWh)*
Diesel	EPA 1997	205
Railcar	Halder 2005	218
Mainline Loc.	Halder 2005	224
Shunting	Halder 2005	228

In the following we use a SFC of 223 (average for Halder, 2005) to recalculate emission factor between mass per mass of fuel (g/kg-fuel) and mass per mechanical work (g/kWh).

Table 2. Fuel consumption for diesel trains

Category	*Gross Tonnage (GT)*	*Fuel (heat) consumption*	*Fuel (diesel) consumption*
	tonnes	Wh/GTkm	g/GTkm
Light train	500	66.8	5.50
Average train	1000	44.8	3.69
Large train	1500	34.8	2.87
Extra large train	2000	29.1	2.40
Heavy train	>2000	27.0	2.22

Emissions of some species like SO_2, CO_2 and metals are directly proportional to the SFC and fuel composition, regardless the type of engine or its operation regime (abatement techniques not accounted). Others, like NO_X, VOC, CO and PM are dependent on combustion regime and thus on type of engine, its power setting and on physical properties of the fuel.

International legislation on emissions from locomotive engines

The European legislation to regulate emissions from railroad locomotives is included in legislation for nonroad (off-road) mobile equipment. The railroad locomotives were included in stage III (Directive 2004/26/EC). European Union standards for railroad locomotives (R, RH and RL) and railcars (RC) stages IIIA and IIIB are given in Table 3.

Table 3. EU emission regulations for locomotive diesel engines (A – Stage IIIA standard, B – Stage IIIB standard)

Category	Net Power	Date	CO	HC	HC+NO_X	NO_X	PM
	kW		g/kWh	g/kWh	g/kWh	g/kWh	g/kWh
RC A	130 < P	2006.01	3.5		4.0		0.2
RL A	130 < P < 560	2007.01	3.5		4.0		0.2
RH A	P > 560	2009.01	3.5	0.5*		6.0*	0.2
RC B	130 < P	2012.01	3.5	0.19		2.0	0.025
R B	130 < P	2012.01	3.5		4.0		0.025

*HC = 0.4 g/kWh and NO_X = 7.4 g/kWh for engines of P > 2000 kW and D > 5 litres/cylinder

In USA the first emission regulation for railroad locomotives was adopted in 1997 and introduced Tier 0, Tier 1 and Tier 2 standards. In 2008 regulation introduced new Tier 3 and Tier 4 emission standards and tightened the older Tier 0-2 standards. The emissions standards of the 2008 regulation are given in Tables 4 and 5 below. The applicability of these standards depends on the date a locomotive is first manufactured as indicated in the Tables.

Table 4. US Line-Haul Locomotive Emission Standards, g/kWh

Tier	*Manufact. year*	*Date*	*HC*	*CO*	*NOx*	*PM*
Tier 0[a]	1973-1992[c]	2010[d]	0.75	3.7	6.0	0.16
Tier 1[a]	1993[c]-2004	2010[d]	0.41	1.6	5.5	0.16
Tier 2[a]	2005-2011	2010[d]	0.22	1.1	4.1	0.07[e]
Tier 3[b]	2012-2014	2012	0.22	1.1	4.1	0.07
Tier 4	2015 or later	2015	0.10 [f]	1.1	1.0 [f]	0.02

a - Tier 0-2 line-haul locomotives must also meet switch standards of the same tier.
b - Tier 3 line-haul locomotives must also meet Tier 2 switch standards.
c - 1993-2001 locomotive that were not equipped with an intake air coolant system are subject to Tier 0 rather than Tier 1 standards.
d - As early as 2008 if approved engine upgrade kits become available.
e - 0.15 g/kWh until January 1, 2013 (with some exceptions).
f - Manufacturers may elect to meet a combined NOx+HC standard of 1.05 g/kWh.

Table 5. US Switch Locomotive Emission Standards, g/kWh

Tier	*Manufact. year*	*Date*	*HC*	*CO*	*NOx*	*PM*
Tier 0	1973-2001	2010[b]	1.57	6.0	8.8	0.19
Tier 1[a]	2002-2004	2010[b]	0.89	1.9	8.2	0.19
Tier 2[a]	2005-2010	2010[b]	0.45	1.8	6.0	0.10
Tier 3	2011-2014	2011	0.45	1.8	3.7	0.07
Tier 4	2015 or later	2015	0.10	1.8	1.0	0.02

a - Tier 1-2 switch locomotives must also meet line-haul standards of the same tier.

b - As early as 2008 if approved engine upgrade kits become available.

c - 0.18 g/kWh until January 1, 2013 (with some exceptions).

d - Manufacturers may elect to meet a combined NOx+HC standard of 1.0 g/kWh.

Emission factors for SO_2 and CO_2

The emission of SO_2 is proportional to the fuel consumption and the sulphur content in the fuel. This is because virtually all the sulphur in the fuel will be oxidised into SO_2 in the engine. The emission factor expressed as mass of SO_2 emitted per mass of fuel consumed is therefore

$$EF_{SO2}\text{ (mg/kg fuel)} = f_S\text{(ppm-wt)} * 2, \qquad \text{(E 1)}$$

where f_S is the mass fraction of S in the fuel (in weight ppm) and factor 2 (1.997) comes from recalculation of the molar weight from S to SO_2 and from ppm to mg/kg. For Europe the maximum allowed sulphur content in diesel fuel for locomotives is 10 ppm-wt. To express the emission in mass per engine work the specific fuel consumption must be used. In a more detailed analysis one should consider that some sulphur is oxidised further into SO_3 and may form sulphate particles.

In a corresponding way the emissions of CO_2 will be dependent on the carbon content in the fuel and the fuel consumption. This then neglects the small fraction of the carbon that will be emitted as carbon monoxide, organic compounds and soot. The sum of these will typically be two to three orders of magnitude lower than the CO_2-emissions. Table 6 shows the emission factors for SO_2 and CO_2 expressed in mass of emission per engine work and mass of emission per mass of fuel consumed.

Table 6 Emission factors for CO_2 and SO_2 Data recalculated using SFC = 223 g/kWh are shown in italic.

Engine type	*Fuel type*	*FSC (ppm)*	*EF_{CO_2} (g/kWh)*	*EF_{CO_2} (g/kg_{fuel})*	*EF_{SO_2} (mg/kWh)*	*EF_{SO_2} (mg/kg_{fuel})*
Diesel	Diesel	10	*709*	3 179	*4.5*	20

Emission factors for VOC and CO

The emissions of hydrocarbons and carbon monoxide represent incomplete combustion of the fuel. These emissions from diesel engines are typically small due to the lean burning conditions and stable engine loads, but sharp increases may occur during rapid load changes of engines (acceleration/deceleration phases) because of incomplete combustion. Some reported emissions factors are presented in Table 7.

Table 7. Emission factors for CO (EF_{CO}) and HC (EF_{HC}). Data recalculated using SFC = 223 g/kWh are shown in italic.

Engine type	*Fuel type*	*Reference*	*EF_{CO} (g/kWh)*	*EF_{CO} (g/kg_{fuel})*	*EF_{HC} (g/kWh)*	*EF_{HC} (g/kg_{fuel})*
Diesel	Diesel	Ecotransit 2010			*1.0*	4.63
Diesel	Diesel	Trends 2002	*2.41*	10.8	*0.65*	2.9
Precontrol Line-haul	Diesel	Ladco 2005	*1.86*	8.36	*0.70*	3.14
Switching	Diesel	Sawant 2007	3.53	*15.8*	0.79	*3.5*
Line-Haul	Diesel	Osborne 2011	0.31	*1.4*	0.19	*0.85*

Emission factors for NO_X

The absolute main part of the nitrogen oxides emitted from diesel engines is formed from nitrogen in the air at the high temperatures prevailing in the combustion zones in the cylinders. The emissions of nitrogen oxides is as mentioned earlier regulated for engines manufactured after the year. Typical emission factors can be found in Table 8.

Table 8. Emission factors for NO_X. Data recalculated using SFC = 223 g/kWh are shown in italic.

Engine type	*Fuel type*	*Reference*	*EF_{NOx} (g/kWh)*	*EF_{NOx} (g/kg_{fuel})*
Diesel	Diesel	Ecotransit	*10.8*	48.3
Diesel	Diesel	Trends 2002	*12.9*	57.7
Precontrol Line-haul	Diesel	Ladco 2005	*18.9*	84.9
Railcar		Halder 2005	8.7	*39*
Line-haul		Halder 2005	14.1	*63.2*
Shuntig		Halder 2005	12.4	*53.9*
Switching	Diesel	Sawant 2007	14.3	*64.1*
Line-Haul Tier 2	Diesel	Osborne 2011	6.47	*29.0*

Emissions factors for PM mass

Particles emitted by diesel engines consist of a volatile and non-volatile fraction. Volatiles are sulphates with associated water, nitrates and organic compounds. Non-volatiles consist of elemental carbon (soot) and of ash. Because of the high content of condensable matter in the exhaust the methodology of sampling impacts the PM mass found. Sampling directly in the hot exhaust captures to a large extend only the non-volatile part of PM while sampling in the diluted and cooled exhaust captures also some of the volatiles. The amount, however, depends on the dilution and temperature program of the sampling. Table 9 gives emission factors for PM from various sources. These should represent the emissions of $PM_{2.5}$.

Table 9. Emission factors for PM. Data recalculated using SFC = 223 g/kWh are shown in italic.

Engine type	*Fuel type*	*Reference*	*EF_{PM} (g/kWh)*	*EF_{PM} (g/kg_{fuel})*
Diesel	Diesel	Ecotransit 2010	*0.29*	1.3
Diesel	Diesel	Trends 2002	*0.74*	3.3
Precontrol Line-haul	Diesel	Ladco 2005	*0.47*	2.1
Railcar		Halder 2005	0.23	*1.0*
Line-haul		Halder 2005	0.27	*1.2*
Shunting		Halder 2005	0.47	*2.1*
Switching	Diesel	Sawant 2007	0.67	*2.9*
Line-Haul Tier 2	Diesel	Osborne 2011	0.122	*0.53*

Emissions factors for PAH and benzo(a)pyrene

Polycyclic aromatic hydrocarbons (PAH) are compounds that consist of fused aromatic rings and do not contain heteroatoms or carry substituents. PAH cover a large group where naphthalene is the simplest species. There are several different groupings of PAH compounds defined for criteria pollutant critical levels. Widely used are EPA’s 16 priority PAH “PAH-16” and EPA’s 7 carcinogenic “PAH-7’. In Europe “Total PAH-6” and “Total PAH-4” are defined for emission reporting to the European Commission (EC, 2000).

Sawant et al. (2007) report emission factors for the substances included in PAH-16 for four different engines and different “notch-positions”, i.e. power output. The average value for the engines and the notch positions is 224 $mg/kgCO_2$ (70.5 mg/kg-fuel) of which 222 $mg/kgCO_2$ (69.8 mg/kg-fuel) is naphtalene and about 108 $\mu g/kgCO_2$ (34 μg/kg-fuel) benzo(a)pyrene.

Emissions factors for EC and OC

Sawant et al. (2007) report emission factors for EC and OC for four different engines and different notch positions. The average emissions factors they report are 0.33 $g/kgCO_2$ (0.99 g/kg-fuel) for EC and 0.24 g/gCO_2 (0.72 g/kg-fuel) for OC.

Emission factors for PN

No emission factors for PN from locomotive diesel engines have been found. In lack of data one may use emission factors measured on other similar diesel engines. From the data for pre-controlled and Euro 1 HDV engines suitable emission factors for PN (solid and total, respectively) have been derived. By relating these values to the PM emissions presented in Table 9 the PN emission factors presented in Table 10 are obtained (Vouitsis and Samaras). It should be noted that the data originates from engines on HD trucks.

Table 10. Emission factors for PN calculated by Voutsis and Samaras from data for HDV.

Engine type	*Fuel type*	*Reference*	*PN solid (#/kg fuel)*	*PN tot (#/kg fuel)*
Diesel	Diesel	Calculated	1.03E+15	2.59E+15
Diesel	Diesel	Calculated	2.62E+15	6.59E+15
Precontrol Line-haul	Diesel	Calculated	1.67E+15	4.19E+15
Railcar		Calculated	7.95E+14	2.00E+15
Line-haul		Calculated	9.54E+14	2.39E+15
Shunting		Calculated	1.67E+15	4.19E+15
Switching	Diesel	Calculated	2.31E+15	5.79E+15
Line-Haul Tier 2	Diesel	Calculated	4.21E+14	1.06E+15

Recommended emission factors

The emission factors that are recommended for diesel locomotive engines are presented in Table 11.

Table 11 Recommended emission factors.

Emission	*Unit*	*Value*	*Ref*
CO_2	g/kg	3179	from typical carbon content and heating value
SO_2	mg/kg	20	from 10 ppm-wt S
CO	g/kg	10.8	Trends 2002
HC	g/kg	2.9	Trends 2002
NO_X	g/kg	48.3	Ecotransit 2010
$PM_{2.5}$	g/kg	1.3	Ecotransit 2010
PNtotal	#/kg	2.6 E+15	Vouitsis and Samaras
PNsolid	#/kg	1.0 E+15	Vouitsis and Samaras
PAH-16	mg/kg	70.5	Sawant 2007
Naphtalene	mg/kg	69.8	Sawant 2007
Benzo(a)pyrene	µg/kg	34	Sawant 2007
EC	g/kg	1.0	Sawant 2007
OC	g/kg	0.72	Sawant 2007

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