CALCULATING METHOD OF HEAVY DIESEL ENGINES EMISSIONS TOXICITY

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Abstract

The method to calculate harmful compounds of exhausts gases from Diesel engines is presented in this topic. It is believed that vehicles with internal combustion engines in European countries release about 89% of CO, 52% of NO_x and 44% of volatile organic compounds of the total amount of pollutants. Therefore, the main Diesel engines pollutants are products of incomplete combustion of fuel and other fuels, i.e. particulates, carbon monoxide CO and hydrocarbons C_mH_n. There are also large quantities of sulphur oxide SO_x compounds, i.e. combustion products of sulphur admixtures. Nitrogen oxides NO_x make the main part of poisonous substances released by Diesel engines (about 60 %). They are formed during the combustion of the nitrogen contained in the air. The poisonous gases amount dependences on engines regimes are presented. Finally, basic conclusions are given.

1. Introduction

It is believed that vehicles with internal combustion engines in European countries release about 89% of CO, 52% of NO_x and 44% of volatile organic compounds of the total amount of pollutants [1, 2]. The main pollutants of Diesel engines are products of incomplete combustion of fuel and other fuels, i.e. particulates, carbon monoxide CO and hydrocarbons C_mH_n. There are also some quantities of sulphur oxide SO_x compounds, i.e. combustion products of sulphur admixtures1. Nitrogen oxides NO_x make the main part of poisonous substances released by heavy Diesel engines (about 60 %). They are formed during the combustion of the nitrogen contained in the ambient air.

Multiplying concentration K by the time t of pollutant action assesses the toxic effect *W*:

$$W = K \cdot t \,, \tag{1}$$

where, *K* – concentration of poisonous substances g/kWh; *t* – time of pollutant action, h.

The amount of poisonous substances released by internal combustion engines (ICE) characterizes the process of combustion rather than its toxic effect. For example, particulates

[1] Now, the amount of sulphur in Diesel fuel does not exceed 0.035 % in Lithuania.

of the same density are 60 times as harmful as CO, while NO_x is 20 times, C_mH_n – 1.2 time, SO_2 – 12 times as toxic as carbon monoxide [3]. The comparative analysis of toxic effect is based on the equivalent concentration of toxic substances, i.e. all toxic chemical compounds are recalculated into the respective concentration of CO, also referred to as CO index, depending on their toxic effect.

This test cycle covers the operation of Diesel engine power ranging from 5% to 100% and camshaft revolutions from idle running to nominal values. Recently, the limits of relative emission (kg/t of fuel) of separate pollutants by ICE and maximum smoke content (optical density or light absorption coefficient) have been established in Lithuania [4].

This paper presents the essential data on the technical condition and maintenance of the freight (1470 kW and 2x1470 kW) and passenger (2200 kW and 2940 kW)[2] locomotives and Diesel multi-units (with the power of 736 kW)3, belonging to the joint-stock company (JSC) "Lietuvos geležinkeliai" ("Lithuanian Railways") as well as methods of calculating the pollutants in heavy Diesel engine emissions.

2. Object and main goals of research

The investigation object is a composition of exhaust gases from internal combustion engines of freight and passenger locomotives and Diesel multi-units operating in various conditions.

The main goal is to develop methodology of calculating the amount of toxic substances in ICE exhaust for locomotives and Diesel multi-units.

3. Methods of calculating of the toxic substances amount in Diesel locomotive emissions

3.1. Determining the operating conditions and toxic emissions from Diesel locomotives

Methods of calculating the amount of toxic substances released by the engines of locomotives and Diesel multi-units (further referred to as locomotives) have been developed. This methodology relies on the amount of Diesel fuel burnt in the engines depending on their operational condition, i.e. determining fuel consumption for any mode of locomotive operation [4, 5, 6]. Based on the data obtained for traction rolling stocks at the speed measurement tracks, a distribution of the locomotive engine operating modes on the routes has been determined in per cent. A table (see Table 1) of the operating engine modes of the locomotives belonging to JSC "Lietuvos geležinkeliai" has been derived, expressing them in percentage of idle running for $0.25 \cdot N_{max}$, $0.5 \cdot N_{max}$ and $0.75 \cdot N_{max}$ operating conditions (N_{max} denoting maximum Diesel engine power).

The suggested methods may be used to determine toxic emissions from locomotives with Diesel engines as primary power plants. The mass of the pollutants, such as carbon monoxide CO, hydrocarbons C_mH_n, nitrogen oxides NO_x and particulates, may be determined for the respective amount of Diesel fuel burnt in the engine cylinders.

Methods of calculating the amount of pollutants take into account the available statistical data and the amount of Diesel fuel consumed by a locomotive. The sufficient accuracy of the method is achieved by subdividing the locomotives into groups depending on their age and engine condition as well as grouping them according to four modes of engine operation with different toxic emissions.

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[2] 1470 kW refers to the power of freight locomotives of M62 series, (2x1470) kW to 2M62 locomotives.
[3] 2200 kW refers to the power of passenger locomotives TEP60, 2940 kW to TEP70 locomotives.
[4] 736 kW refers to the power of DR1A series Diesel multi-units

3.2. Determining the emission based on the content of particular pollutants

The amount of pollutants in the emissions from Diesel locomotive engines is determined from formula (2), while the total amount of the particular locomotive pollutant is expressed in tons:

$$W_k = K_1 \cdot K_2 \cdot \sum_{i=1}^{n} W_{k,i}, \tag{2}$$

where, the total amount of k-th pollutant (CO, CH, NO_x, SO_2, particulates) for all i-th series locomotives, ton; *n* – number of locomotives series considered; *K1* – coefficient of rolling stock service life; *K2* – coefficient of power plant design features.

$$W_{k,i} = \sum_{j=1}^{4} W_{k,i,j}, \tag{3}$$

where, the j-th loading mode: idle running, $0.25 \cdot N_{max}$, $0.5 \cdot N_{max}$ and $0.75 \cdot N_{max}$.

The amount of k-th pollutant $W_{k.i.j}$ when the amount of Diesel fuel Q_j is burnt under the *j*-th loading mode, tons, is expressed as follows:

$$W_{k,i,j} = l_{k,i,j} \cdot Q, \tag{4}$$

where, $l_{k,i,j}$ a relative portion of k-th pollutant for the locomotive of the *i*-th series operating in the j-th loading mode, kg/ton; $Q_{i,j}$ amount of Diesel fuel consumed by *i*-th series locomotive operating in *j*-th loading mode, ton.

$$Q_{i,j} = 10^{-3} \cdot G_{i,j} \cdot t_{i,j}, \tag{5}$$

where, $G_{i,j}$ fuel consumption by *i*-th series locomotives operating in *j*-th mode per hour, kg/h; $t_{i,j}$ time of i-th series locomotive operation in *j*-th mode, h.

The values of $G_{i,j}$ and $l_{i,j,k}$ are given in tables 1, 2.

The total amount of Diesel fuel Q_i consumed by *i*-th series locomotive is equal to:

$$Q_i = Q_0 + Q_{0.25} + Q_{0.5} + Q_{0.75}. \tag{6}$$

The total amount of Diesel fuel consumed by the locomotives of different series is determined based on actual residues.

The remaining fuel is used for idle running and warming the engines in cold weather:

$$Q_i = Q_0 - Q_{0.25} - Q_{0.5} - Q_{0.75} = Q - Q_{apkr}, \tag{7}$$

where, Q_{apkr} fuel consumption of an operating engine, ton.

Table 1. Fuel consumption by Diesel locomotives under different loading modes, kg/h

Locomotive or Diesel multi-units series	Engine trademark	Engine power, kW	Locomotive operation mode			
			0 (idle)*	$0.25 \cdot N_{max}$	$0.5 \cdot N_{max}$	$0.75 \cdot N_{max}$
M62	14D40	1470	25.2	84.0	168.0	252.0
2M62	14D40	2940	50.4	168.0	336.0	504.0
TEP60	11D45	2200	30.0	127.5	255.0	382.5
TEP70	2A-5D49	2940	16.2	155.0	310.0	465.0
DR1A	M756B	736	16.8	90.0	180.0	270.0

Table 2. Distribution of engine operating time (in percentage) for Diesel locomotives of JSC "Lietuvos geležinkeliai", depending on their loading modes

Locomotive or Diesel multi-units series	Engine operation mode, %			
	0 (idle)	$0.25 \cdot N_{max}$	$0.5 \cdot N_{max}$	$0.75 \cdot N_{max}$
M62, 2M62	67.5	6.5	17.0	9.0
TEP60, TEP70	35.0	7.0	50.0	8.0
DR1A	36.0	10.0	42.0	12.0

The amount of sulphur dioxide SO_2 in engine emission is directly proportional to the amount of sulphur in Diesel fuel (not exceeding 0.035% of mass). Given the content of sulphur in Diesel fuel, the amount of the released sulphur dioxide may be determined:

$$W_{SO_2} = 0.35 \cdot S \cdot Q \cdot K_2 \ , \qquad (8)$$

where, S sulphur content in the exhaust, kg/ton; Q consumed Diesel fuel, ton; $K2$ coefficient evaluating specific engine design characteristics (see Table 6).

When relative amounts of pollutants (see Table 3) and time distribution of various operation modes of the respective series locomotives are determined, the average relative amounts of pollutants l_{vid} are calculated for a particular locomotive series, kg/ton:

$$l_{vid} = \sum_{1}^{4} \frac{\Delta t_j \cdot l_j \cdot G_j}{\Delta t_j \cdot G_j} = \frac{\Delta t_0 \cdot l_0 \cdot G_0 + \Delta t_{0.25} \cdot l_{0.25} \cdot G_{0.25} + \Delta t_{0.5} \cdot l_{0.5} \cdot G_{0.5} + \Delta t_{0.75} \cdot l_{0.75} \cdot G_{0.75}}{\Delta t_0 \cdot G_0 + \Delta t_{0.25} \cdot G_{0.25} + \Delta t_{0.5} \cdot G_{0.5} + \Delta t_{0.75} \cdot G_{0.75}} \ , \qquad (9)$$

where, Δt_0, $\Delta t_{0.25}$,$\Delta t_{0.5}$,$\Delta t_{0.75}$ time of locomotive engine operation in particular modes, % (see Table 2); l_0, $l_{0.25}$, $l_{0.5}$, $l_{0.75}$ relative amount of k-th pollutant for an engine operating in a particular mode, kg/ton; G_0, $G_{0.25}$, $G_{0.5}$, $G_{0.75}$ fuel consumption in an hour, kg/h; j four operation modes of an engine – 0; $0.25 \cdot N_{max}$; $0.5 \cdot N_{max}$ and $0.75 \cdot N_{max}$.

The data obtained in calculations are given in Table 4.

Table 3. Relative emissions from Diesel locomotive engines, operating in different modes, kg/t

Rolling-stocks type and series	Engine trademark	Pollutant	Operation mode			
			0 (idle)	0.25·Nmax	0.5·Nmax	0.75·Nmax
freight locomotive M62, 2M62	14D40	CO	5	19	22	43
		C_mH_n	1	3	3	5
		NO_x	43	118	125	158
		particulates	0.4	1	1	1
passenger locomotive TEP60	11D45	CO	2	14	20	30
		C_mH_n	1	4	6	10
		NO_x	15	34	47	81
		particulates	2	5	5	5
passenger locomotive TEP70	2A-5D49	CO	2	9	10	18
		C_mH_n	1	3	4	6
		NO_x	14	27	36	72
		particulates	2	4	4	4
Diesel multi-units DR1A	M756B	CO	3	5	5	6
		C_mH_n	0.5	1	2	2
		NO_x	15	34	47	81
		particulates	1.5	2	3	3

Table 4. Average relative emissions by Diesel engines of locomotives exploited by JSC "Lietuvos geležinkeliai"

Locomotive series	Locomotive type	Engine trademark	Amount of pollutants, kg/h			
			CO	C_mH_n	NO_x	particulates
M62; 2M62	freight	14D40	24.3	3.2	115.7	0.9
TEP60	passenger	11D45	20.4	6.3	50.3	4.8
TEP70	passenger	2A-5D49	11.2	4.2	41.4	3.9
DR1A	passenger	M756B	5.2	1.8	52.7	2.8

The formula for calculating the total amount of one kind of pollutants, ton:

$$W_{i,k} = 10^{-3} \cdot Q_i \cdot l_{vid.,i,k}\,, \tag{10}$$

where, Q_i total amount of fuel consumed by i-th series locomotives, ton; $l_{vid,i,k}$ k-th pollutant average relative portion in i-th series locomotives, kg/ton.

3.3. The values of correction coefficients *K1* and *K2*

Coefficient *K1* indicates the locomotive service life. The locomotive engine, especially the main parts of its piston, are subject to heavy wear in operational conditions. This causes the formation of gaps between the piston parts which, in turn, leads to the decrease of the engine pressure and drop of combustion temperature of the mix in the cylinders. Cylinder parts are covered with carbon deposits and other substances. Under these conditions, the products of incomplete combustion of CO and C_mH_n are formed, though the amount of nitrogen oxides NO_x in the exhaust is slightly decreased (up to 5%).

An average service life R of the particular series locomotives is calculated from the formula:

$$R = \frac{\sum [t \cdot P(t)]}{P}, \tag{11}$$

where, P total number of particular series locomotives, units; t locomotive service life, years; $P(t)$ number of locomotives of t years of service, units.

When the average service life of the locomotives of a particular series is calculated, the value of coefficient *K1* may be taken from Table 5.

The coefficient *K2* describes the peculiar design characteristics of the locomotive power plant, directly affecting the emission of pollutants (see Table 6). If the locomotive engine has several special design characteristics, then coefficient *K2* is the production of particular coefficient *K2(p)* values:

$$K_2 = \prod_{p=1}^{n} K_{2(p)}, \tag{12}$$

where, *Π* - production; *n* - number of coefficients; *p* - number of special engine design characteristics.

Based on the data from Table 6, the ultimate *K2* value may be calculated by formula (12).

Table 5. Values of coefficient K1 for estimating service life of traction rolling stocks

Poisonous pollutant	Average service life of rolling stock park, years				
	less than 5	(5-9)	(10-19)	(15-20)	more than 20
CO	1.0	1.2	1.3	1.5	1.5
CmHn	1.0	1.2	1.3	1.5	1.6
NOx	1.0	1.0	0.95	0.95	0.95
SO2	1.0	1.0	1.0	1.0	1.0
particulates	1.0	1.1	1.15	1.2	1.3

Table 6. Values of coefficient K2 for assessing the influence of Diesel locomotive engine characteristics characteristics on the amount of pollutants

Diesel engine design characteristics	Pollutants				
	CO	C_mH_n	NO_x	SO_2	particulates
Manifold vacuum ventilation system is damaged or not provided	1.02	1.02	1.02	1.0	1.0
Exhaust gas recirculation system is provided	1.05	1.05	0.50	1.0	0.9
Fuel soot trap is provided	1.0	1.0	1.0	0.8	0.1
No specific design characteristics	1.0	1.0	1.0	1.0	1.0

4. Variation of toxic effect of gases released by locomotive engines under various operation conditions

The relationship between the amount of pollutants in the emissions from 2940 kW freight and passenger locomotives and operation condition (for engines with no special design characteristics) may be also found in Fig.1,2.

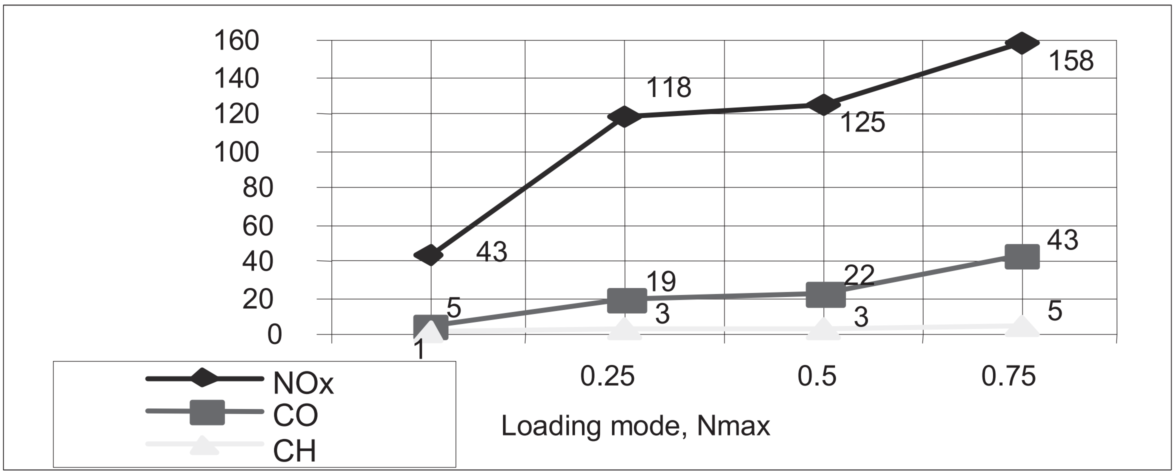

Fig .1. The relationship between the relative amount of pollutants in the 2940 kW power freight locomotive emissions and the engine-loading mode

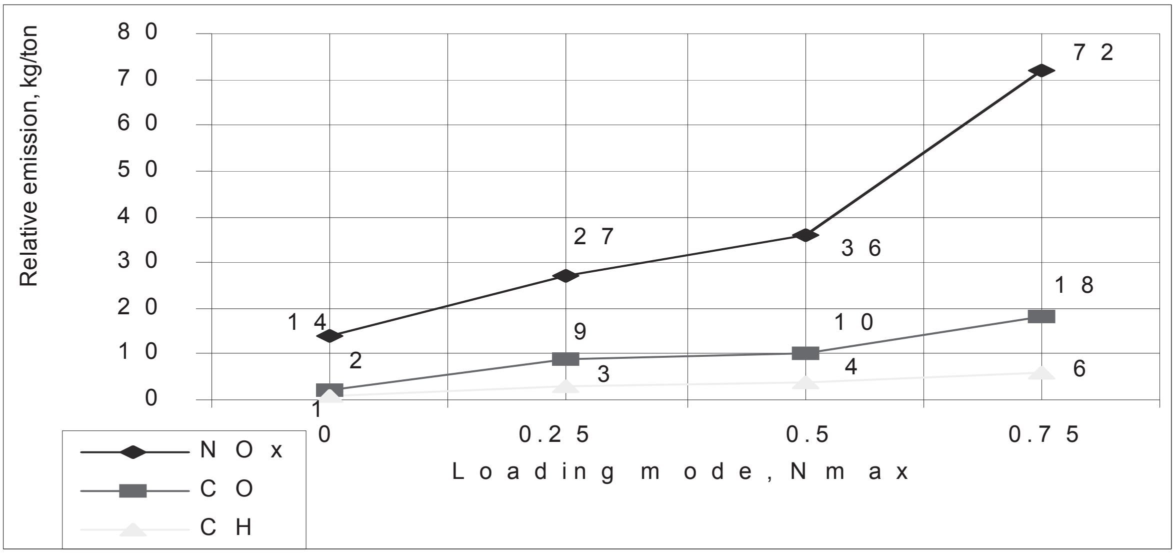

Fig .2. The relationship between the relative amount of pollutants in the 2940 kW power passenger locomotive emissions and the engine-loading mode

As shown in Fig.1 and Fig.2 the amount of poisonous pollutants in the exhausts gases immediately concerned with engine-loading mode.

5. Conclusions

1. In calculating the total Diesel locomotive engine emission, the service life of the rolling stock and special engine design characteristic are taken into consideration by using the correction coefficients K1 and K2 (see Tables 5, 6).
2. In order to accurately calculate the emissions from the Diesel locomotive engines, the latter are subdivided into four groups according to operational conditions. Relative fuel

consumption and pollution are calculated for each condition based on the amounts of particular pollutants (see Table 1-3).

3. Considering the problem of air pollution (and the amount of NOx in the emissions, in particular), it may be recommended that the engine loading does not exceed 0.5·Nmax (see Fig.1,2.), implying that the engines should operate as short as possible under maximum loading. In railway transport selecting the respective number of the locomotive sections as well as taking into account the condition of railway and the weight of rolling stock can meet this condition.
4. Nitrogen oxides NOx are the most dangerous pollutants (see Tables 1,2), because their relative quantity is 15-20 times the amount of carbon monoxide, with toxic effect being 35 times more that of CO.

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