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ECOLOGICAL ASPECTS OF USING BIOLOGICAL DIESEL OIL IN RAILWAY TRANSPORT

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Abstract. The number of various transport facilities used in Europe is rapidly growing. They release a big amount of pollutants into the atmosphere. Therefore, environment protection from these pollutants ejected by internal combustion engines is a key problem facing us today and which will be acute in the future. Biofuel is the only effective and widely used alternative fuel which can reduce pollution of the environment. The main aim of the present paper is to perform a comparative analysis of burnt gases of engines using rapeseed oil methyl ester and petroleum diesel oil and to determine ecological effectiveness of biofuel used in diesel locomotive engines in railway transport.

Keywords: biodiesel, RME, rapeseed methyl ester, exhaust gas, emission, diesel engine, engine testing.

1. Introduction

The number of various transport facilities used in Europe is rapidly growing. They release into the atmosphere about a third of carbon dioxide (CO_2), causing changes in the earth climate, as well as carbon monoxide (CO) which is harmful to humans, and the compounds of nitrogen oxides (NO_x), hydrocarbons (C_xH_y), particulate matter (PM), sulphur, etc. Therefore, environment protection from these pollutants ejected by internal combustion engines is a key problem facing us today and which will be acute in the future.

According to a new concept of European policy in power sector, the use of biofuel is paid special attention in the communiqué and the plan of activities developed. Under the conditions of growing oil prices and the need for stable, reliable and environmentally-friendly sources of power, the use of biofuel has become a priority of European policy in the fields of power generation, transport and environment protection (The use of biofuel … 2007).

At present, biofuel is the only effective and widely used alternative fuel which can reduce the dependence of transport sector on oil.

The exhaust gases released by diesel engines using rapeseed oil fatty acids methyl ester (RME) were analysed. The results varied considerably, depending on the engine type and service life as well as the methods of analysis (Krahl *et al.* 1996). In Lithuania, similar tests were made with diesel engine D-240, driven by RME power (Labeckas and Slavinskas 1998).

So far, the use of biofuel in powerful engines of rail vehicles has not been studied. The conditions of engines, operating in various modes, differ considerably from those of automobiles.

The main aim of the present paper is to perform a comparative analysis of burnt gases of engines using rapeseed oil methyl ester and petroleum diesel oil and to determine ecological effectiveness of biofuel used in diesel locomotive engines in railway transport.

2. The analysis of biological diesel oil

Biological diesel oil is a substitute of petroleum oil, made of vegetable oil (e.g. rapeseed, sunflower, etc.) or animal fat.

In Table 1, physical and chemical properties of RME versus the respective characteristics of diesel oil (Makarevičienė, 2001; Office supplies, 2007) are presented.

Biodiesel has a characteristic cetane number (up to 58) and the content of oxygen (about 11 %). Therefore, when burning, it releases much smaller amounts of poisonous gases. Besides, it does not contain sulphur and fragrant hydrocarbons. It has been calculated that a litre of biodiesel releases into the air by 3.253 kg less CO_2 than the respective amount of diesel oil.

Biodiesel oil (with admixtures), intended for winter conditions, can be even used at the temperature of -22°C

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Table 1. Properties of RME and diesel oil

Property	RME	Diesel oil
Density, kg/m^3	886[1]	820…870[2]
Kinematic viscosity (at 40°C), mm^2/s	4.3	1.8…2.8
Ignition temperature, K	384	347
Cetane number	48	> 40
Sulphur amount, mg/kg	2.0	4.0
Iodine number, g J_2/100	115	–
Calorific value, MJ/l	32.6	35.7
Filtration temperature, °C	–12	–8…–13

[1] at 15°C
[2] at 20°C

because it does not contain paraffin, bridging the pores of fine filters.

Biodiesel has a positive effect on solid particles containing about 70–80 % of organic components, which are easily burnt in oxygen-type catalytic exhaust gas neutralizers. In this way, the amount of PM released into the atmosphere is reduced by half, and we are protected from the unpleasant smell of burnt gases.

Biological diesel oil can be used for various types of diesel engines adapted to diesel oil consumption. Moreover, it can be easily mixed with diesel oil without segregating. Therefore, biodiesel can be used as pure oil or in the mixture with petroleum oil in any proportion.

3. Ecological aspects of using biodiesel oil in engines

Tests carried out by Austrian and Swedish companies "AVL LIST" and "MTC" (Zelenka *et al.* 1990; Kerstin 1999) show that the amount of PM in exhaust gases is proportional to sulphur amount in oil. When sulphur content is increased by 0.1 % of mass, the emission of PM grows by 0.027 g/(kW·h). The use of the alternative fuel allows for considerable reduction of PM emission (Xiao, Ladommatos and Zhao 2000). The experiments made by Swedish scientists (Kerstin 1999) show that, using ethanol in diesel engines, the emission of gases or PM of methyl ether (DME) makes only about one-seventh of the amount ejected by engines, using diesel oil of the highest Ec1 standard or RME (Fig. 1). The results of these experiments also suggest that, when a mixture of 15 % ethanol and 85 % diesel oil is used, PM emission is decreased by 30–50 %, while the amount of CO is decreased insignificantly, HC content is increased and the amount of NO$_x$ remains unchanged, compared with the use of pure diesel oil.

The extensive research was carried out by a famous US Environmental Protection Agency to summarize the results obtained by about 80 investigators (A comprehensive analysis … 2002). For this purpose, the data of testing heavy trucks and light-weight automobiles with diesel engines were collected and analysed. These vehicles were designed for using pure diesel oil, but, when tested, they used biodiesel oil and various diesel oil mixtures.

Both vegetable and organic biodiesel oil were used, therefore, their calorific value ranged from 32.25 to 33.230 MJ/l, while the average calorific value of diesel oil was 36.094 MJ/l.

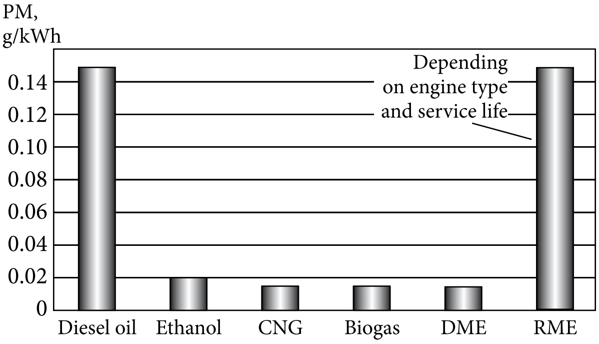

Fig. 1. PM emission of diesel engines, using various kinds of fuel, in ECE R49 cycle

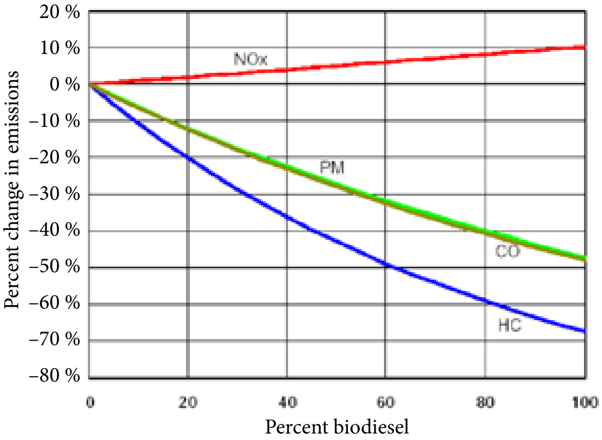

Fig. 2. The relationship between the emission of various pollutants and the amount of biodiesel oil in fuel mixture

The analysis of the available data revealed that, in the case of using biofuel, fuel consumption increased only by 4.6 %. Theoretically, it had to increase higher because calorific values of vegetable and organic diesel oil are by 7.9 % and 10.6 % lower than the value for petroleum diesel oil.

The emission of pollutants in burning various kinds of fuel is given in Fig. 2.

It is clear that the use of biodiesel oil increases NO$_x$ emission and decreases the release of PM, CO and C_xH_y, into the atmosphere. As stated in the research, the addition of 10 % biodiesel oil increases NO$_x$ emission by 1 %.

4. Testing equipment and methods

The use of biodiesel oil in the V-shape 538 kW nominal power engine placed on a special test bed, consisting of AC generator, liquid rheostat and control panel, was studied.

By adjusting the depth of immersion of liquid rheostat electrodes in the electrolyte, the engine load and revolutions are changed (the former by changing the electric current generated and the latter by adjusting the fuel pump).

Two types of fuels – the first produced by "Mažeikių nafta" and satisfying the requirements of the standard

LST EN 590, and the second – methyl ester of fatty acids (RME), satisfying the requirements of the standard LST EN 14214:2003, which is produced by "Rapsoila", were used in testing. About 10, 20, 30 and 40 % of RME were added to diesel oil to form a mixture.

Three different methods and devices were used to determine the amounts of various components of exhaust gases:

- a gravimetric method was used for determining the amount of PM;
- an electrochemical method and the device Testo 350-M/XL were used to determine the amount of nitrogen oxides (NO_x), carbon monoxide (CO) and carbon dioxide (CO_2);
- a chromatographic method and the chromatograph SRI 8610 were used to establish the amount of hydrocarbons (C_xH_y).

The concentration of PM in the oxides released by the engine was determined by using a gravimetric method. For this purpose, perchlorovinyl fiber filters AFA-VP-20, permeable to air, which retain PM of the oxides sucked by a respirator pump are used.

The speed of the gas flow in the air duct was also measured by using pneumatic tubes, allowing the dynamic gas pressure to be measured by micromanometer. The dynamic pressure PD is equal to the difference between the total pressure PB and static pressure PS. The dynamic pressure is proportional to the square gas speed, therefore, air speed in the air duct can be determined indirectly by fixing the dynamic pressure variations.

5. Testing results

The data obtained in the tests were processed by using the least square method.

The emission of nitrogen oxides (NO_x), i.e. its dependence on RME amount in diesel oil and engine load, was described by regression equations (1–5) for:

1) engines using pure diesel oil:

$$y_D = 65060 \cdot P^{-1.13}, \tag{1}$$

2) engines using a mixture of 10 % RME and diesel oil:

$$y_{10\,\%\,\mathrm{RME}} = 59941 \cdot P^{-1.124}, \tag{2}$$

3) engines using a mixture of 20 % RME and diesel oil:

$$y_{20\,\%\,\mathrm{RME}} = 16502 \cdot P^{-0.827}, \tag{3}$$

4) engines using a mixture of 30 % RME and diesel oil:

$$y_{30\,\%\,\mathrm{RME}} = 12008 \cdot P^{-0.757}, \tag{4}$$

5) engines using a mixture of 40 % RME and diesel oil:

$$y_{40\,\%\,\mathrm{RME}} = 12151 \cdot P^{-0.768}, \tag{5}$$

where: P is engine load, %.

A graphical view of these equations is presented in Fig. 3.

As shown in the graphs, the increase of RME proportion in diesel oil leads to the decrease of the amount of NO_x in the exhaust gases (though an opposite effect is described in literature). Moreover, the content of this oxide also depends on the engine power developed – the higher the engine power, the smaller the amount of NO_x.

Given that the formation of NO_x oxides is directly proportional to combustion temperature (the higher the temperature, the larger NO_x amount), a decrease of pollution can be easily explained. Hence, when the load increases and the excess-air coefficient decreases, a mixture is more fatty, therefore, the combustion temperature decreases, making the conditions for NO_x formation less favourable.

It is very important to determine carbon dioxide (CO_2) emission because this gas causes the so-called greenhouse effect. The relationships between its amounts and RME content in diesel oil and the engine load, are described by the regression equations (6–10) for:

1) engines using pure diesel oil:

$$y_D = 0.045 \cdot P + 5.438, \tag{6}$$

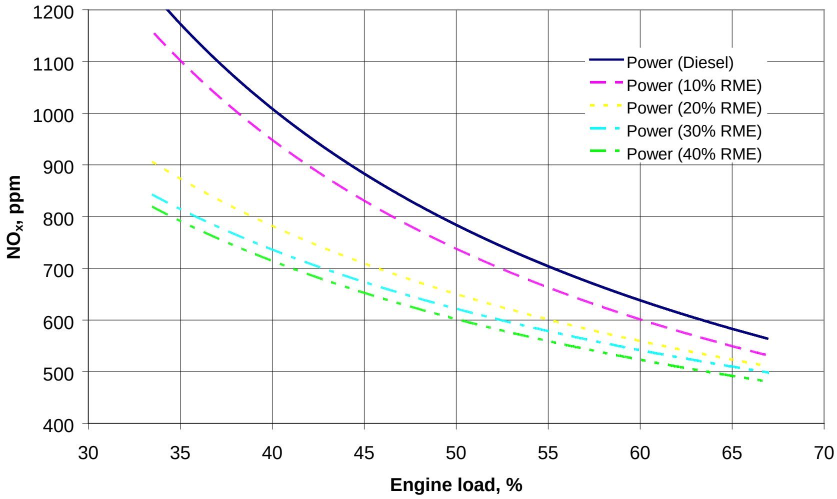

Fig. 3. The relationship between nitrogen emission and engine power (% P_{max}) for engine using various fuel mixtures

2) engines using a mixture of 10 % RME and diesel oil:

$$y_{10\ \%\ \mathrm{RME}} = 2.086 \cdot P^{0.342}, \tag{7}$$

3) engines using a mixture of 20 % RME and diesel oil:

$$y_{20\ \%\ \mathrm{RME}} = 0.002 \cdot P^2 - 0.075 \cdot P + 7.707, \tag{8}$$

4) engines using a mixture of 30 % RME and diesel oil:

$$y_{30\ \%\ \mathrm{RME}} = 1.17 \cdot P^{0.482}, \tag{9}$$

5) engines using a mixture of 40 % RME and diesel oil:

$$y_{40\ \%\ \mathrm{RME}} = 0.001 \cdot P^2 - 0.004 \cdot P + 6.205. \tag{10}$$

The above equations are graphically shown in Fig. 4.

The proportion of CO_2 in the exhaust gases is always smaller, compared to the emission of CO_2, when pure diesel oil is used, and the engine load is not higher than 0.5 P_{max} for various RME amounts (up to 30 %) in diesel oil, with the only exception being the case when RME content in diesel oil reaches 40 %. The increase of the engine load leads to increasing emission of CO_2 by all fuel mixtures and pure diesel oil in similar proportions. Only when the amount of RME in the mixtures reaches 20 and 30 %, CO_2 content increases with the increasing engine load slightly more rapidly than in other cases. However, the increase is insignificant, and, taking into account the errors, CO_2 emission can be considered similar for all the mixtures used.

On the one hand, smaller amounts of CO_2 released into the atmosphere seem to reduce greenhouse effect, however, on the other hand, higher CO_2 emission shows better combustion of the mixture and respectively lower fuel consumption.

It is stated in the literature that the use of biofuel does not increase the concentration of carbon dioxide in the atmosphere because plants used for obtaining biofuel absorb the same amount of CO_2 that is released by burning this type of fuel.

Considering carbon monoxide (CO) emission, expressed by regression equations (11–15) for:

1) the engines using pure diesel oil:

$$y_D = 5 \cdot 10^{-5} \cdot P^2 - 0.004 \cdot P + 0.108, \tag{11}$$

2) engines using a mixture of 10 % RME and diesel oil:

$$y_{10\ \%\ \mathrm{RME}} = 10^{-5} \cdot P^2 + 0.0004 \cdot P + 0.005, \tag{12}$$

3) engines using a mixture of 20 % RME and diesel oil:

$$y_{20\ \%\ \mathrm{RME}} = 5 \cdot 10^{-5} \cdot P^2 - 0.004 \cdot P + 0.097, \tag{13}$$

4) engines using a mixture of 30 % RME and diesel oil:

$$y_{30\ \%\ \mathrm{RME}} = 6 \cdot 10^{-5} \cdot P^2 + 0.005 \cdot P + 0.13, \tag{14}$$

5) engines using a mixture of 40 % RME and diesel oil:

$$y_{40\ \%\ \mathrm{RME}} = 2 \cdot 10^{-5} \cdot P^2 - 0.001 \cdot P + 0.047, \tag{15}$$

and their graphical interpretation (Fig. 5), we can see that the proportion of CO in the exhaust gases increases for all fuel mixtures examined, when the engine load is increasing, with $P \geq 0.5\, P_{max}$. The increase is relatively slower when RME proportion in diesel oil makes 30–40 %.

However, in all cases (except for the mixture consisting of 10 % RME and diesel oil), the addition of biodiesel decreases CO emission.

The relationship between the proportion of hydrocarbons (C_xH_y) in the exhaust emissions and the engine load is expressed by regression equations (16–20) for all types of mixtures:

1) engines using pure diesel oil:

$$y_D = 0.001 \cdot P^2 - 0.068 \cdot P + 3.53, \tag{16}$$

2) engines using a mixture of 10 % RME and diesel oil:

$$y_{10\ \%\ \mathrm{RME}} = 0.007 \cdot P^2 - 0.637 \cdot P + 15.537, \tag{17}$$

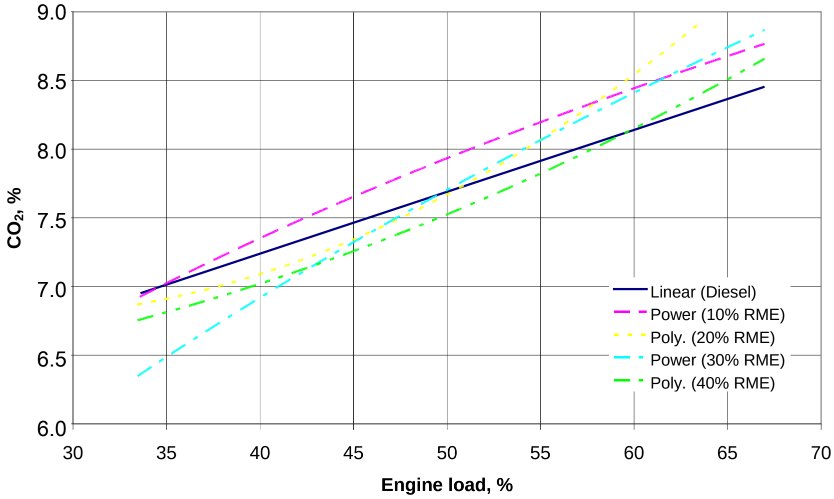

Fig. 4. The relationship between CO_2 emission and engine power (% P_{max}) for engines using various fuel mixtures

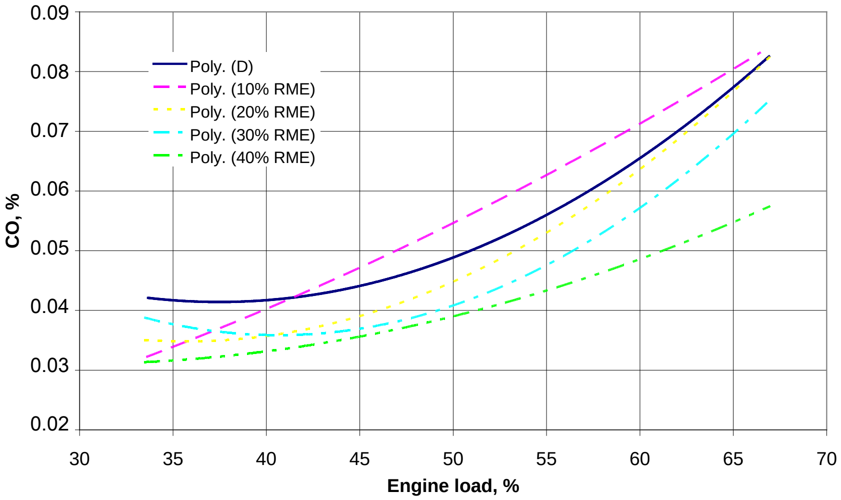

Fig. 5. The relationship between CO emission and engine load (% P_{max}) for various fuel mixtures

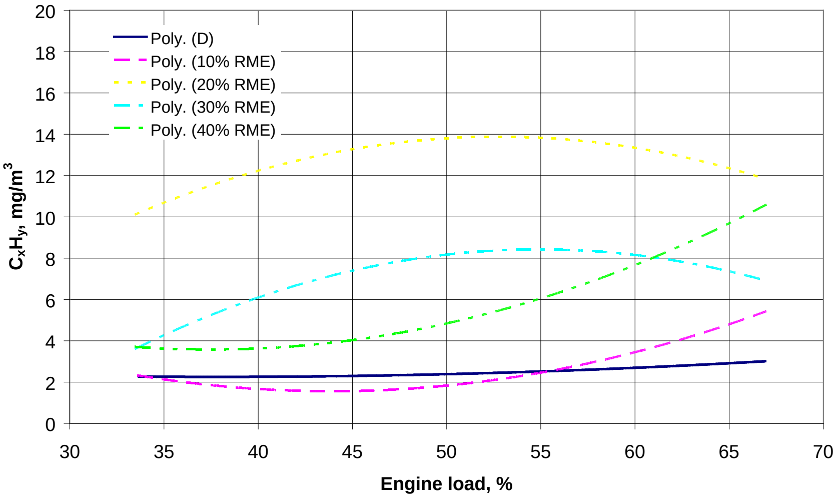

Fig. 6. The relationship between C_xH_y emission and the engine power (% P_{max}) for various fuel mixtures

3) engines using a mixture of 20 % RME and diesel oil:

$$y_{20\,\%\,\mathrm{RME}} = -0.01 \cdot P^2 + 1.071 \cdot P - 14.357, \quad (18)$$

4) engines using a mixture of 30 % RME and diesel oil:

$$y_{30\,\%\,\mathrm{RME}} = -0.011 \cdot P^2 + 1.15 \cdot P - 23.153, \quad (19)$$

5) engines using a mixture of 40 % RME and diesel oil:

$$y_{40\,\%\,\mathrm{RME}} = 0.008 \cdot P^2 - 0.605 \cdot P + 14.92. \quad (20)$$

While in Fig. 6, graphical interpretation of the relationships is given.

As shown by the chart, C_xH_y emission is growing for all the mixtures except those containing 20 and 30 % of RME. The maximum is reached at 50 % P_{max}, with further decrease of emission. The smallest effect of the engine load on C_xH_y emission can be observed, when pure diesel oil is used. For the mixture of 10 % RME and diesel oil, C_xH_y emission is the lowest, being comparable with that of pure diesel oil.

In considering PM' emission, it could be observed that dust content is the lowest at the engine load of 0.5 P_{max}, while, when the mixture of 10 and 20 % is used, it is even lower than the respective value obtained for pure diesel oil. However, further research, using various power engines, is needed to check this result.

The emission of harmful gases was also analysed for non-loaded engines because such cases are often met in practice when diesel locomotives are used. The emission of NO_x and CO_2 is lower except for the use of 20 % RME in the mixture, compared with the emission when pure diesel oil is used. In this case, the emission increases by about 15 %. The emission of CO is, in general, lower than that for using pure diesel oil, while the emission of hydrocarbons is higher (except for the case when 10 % RME and diesel oil mixture is used).

The environment pollution depends not only on the amount of contaminants released into the atmosphere, but on their aggressivity as well. Aggresivity indices of contaminants presented in Table 2 show that PM have the highest aggressivity index.

Table 2. Aggresivity indices of the contaminants

Pollutant	Aggresivity index *A*
CO	1.0
NO_x	41.1
C_xH_y	3.16
PM	300

Table 3. The total amount of contaminants with aggressivity considered

Type of fuel	PM emission considered	PM emission not considered
diesel oil	124.197	89.004
10 % RME	120.075	83.768
20 % RME	108.485	78.690
30 % RME	130.333	76.025
40 % RME	132.438	73.381

However, in all cases of using biodiesel, dust content is smaller than that produced by burning pure diesel oil. Besides, 70–80 % of PM of biodiesel are organic substances which are easily burnt in the oxide catalyst neutralizer of exhaust gases. However, PM released by diesel oil contain up to 80 % unburnt carbon residue, which cannot be eliminated by common-type oxide catalyst neutralizers.

Generalizing the calculated data, the total aggressivity index of the contaminants was determined, which is presented in Table 3.

It can be concluded, based on the data presented in Table 1, that the use of biodiesel oil with the addition of 30–40 % RME is most rational from ecological perspective because PM released in the process of its burning disintegrate more rapidly than the particles ejected in diesel oil combustion.

6. Conclusions

By determining the composition of exhaust gases, as well as relative values of the contaminants and their aggressivity, the total amount of the contaminants was found, showing that:

1. When the total amount of contaminants is considered without PM emission, the use of biodiesel with 30-40 % RME added is most rational from the ecological perspective.
2. The first statement also applies to engines, running idle (without load). This is important because, usually, passenger locomotives' engines are not shut down at the stations and are warmed up in cold seasons.
3. By using the regression equations (1–20) offered, it is possible to calculate the amounts of pollutants (NO_x, CO, C_xH_y) in the exhaust gases, depending on the engine load.

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