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Biodiesel Features in the Railway Transport

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1. Introduction

To calculate enterprise expenses on fuel, the above tax should be taken into account. Consumption and the amount of RME, compared to pure diesel oil consumption when 20 % of RME is added, fuel consumption grows by about 4 % (Lingaitis and Pukalskas, 2008), compared to pure diesel oil consumption while the use of 30 % of RME in the mixture with diesel oil increases fuel consumption by about 2.5 %. A further increase in the percentage of RME in the mixture leads to a further increase in fuel consumption. When smaller RME amounts are used, the expenses are increased insignificantly.

A mathematical model allowing fuel costs to be determined for a locomotive engine using a certain amount of biological diesel oil was developed referring to the methods of economic effect calculation described in the present paper. The relationship between the proportion of hydrocarbons (CxHy) in the exhaust emissions and the engine load is expressed by regression equations for all types of mixtures. CxHy emission is growing for all the mixtures except those containing 20 and 30 % of RME (Lingaitis and Pukalskas, 2008). The maximum is reached at 50 % P_{max}, with further decrease of emission. The smallest effect of the engine load on CxHy emission can be observed, when pure diesel oil is used. For the mixture of 10 % RME and diesel oil, CxHy emission is the lowest, being comparable with that of pure diesel oil. 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.

According to the law of the Republic of Lithuania on environment pollution taxes (Lingaitis and Pukalskas, 2007), all physical and juridical persons engaged in commercial activities and using mobile equipment causing environment pollution should pay the environmental tax depending on the type of transport facilities used. The annual fixed tax of 7.53 EUR per one ton of burnt fuel should be used for rail transport in the period from 2005 to 2009.

2. Influence of biodiesel to energetic and ecological indicators of a diesel engine

Research carried out by the Austrian company "AVL LIST" and the Swedish company "MTC" (Makarevičienė et al., 2001) show that the amount of SP (solid particles) in oxides is proportional to the amount of sulphur in the fuel. Having increased amount of sulphur by 0.1 % of the mass, the SP emission increases by 0.027 g/(kW·h). The SP emission may be reduced significantly by using alternative fuel (Xiao et al., 2000). Research carried out by Swedish scientists show that, when using ethanol, gas or dimethyl ether (DME) in a diesel engine, the SP emission is reduced 7 times than when the engine operates using the Ec1 diesel or RME (rapeseed methyl ester) complying with the strictest standard. Besides, the results of these research state that, when using a mixture of 15 % of ethanol and 85 % of diesel, the SP emission is reduced by 30…50 %, the CO emission is reduced slightly, the amount of HC increases, whereas the amount of NOx is the same as when operating using pure diesel. The results of the research are shown in fig. 1 (Lingaitis and Pukalskas, 2008).

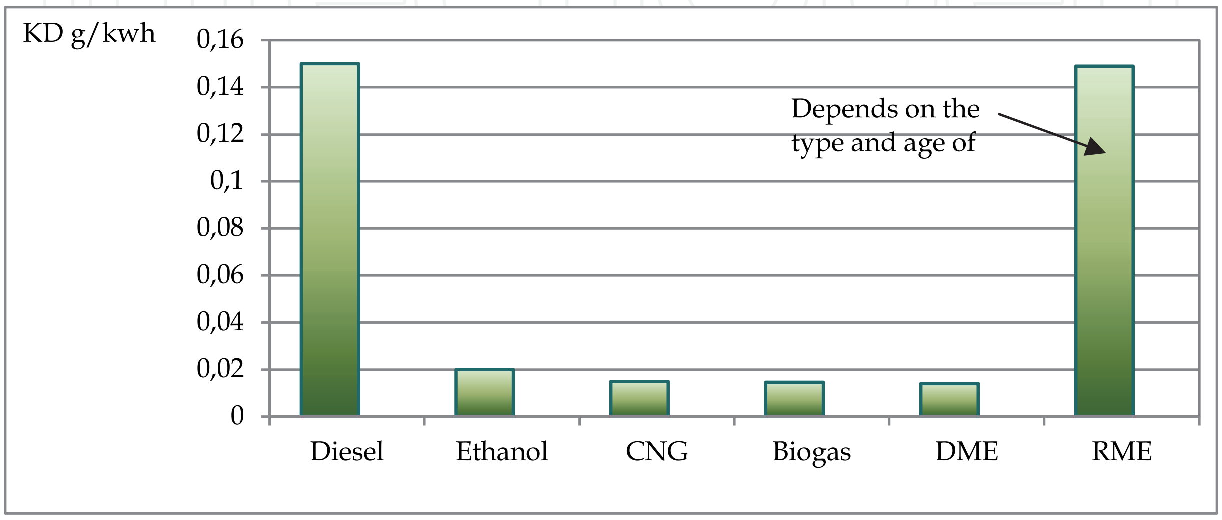


Fig. 1. The SP emission of diesel engines when using various fuel and operating at the ECE R49 cycle: CNG – compressed natural gas; DME – dimethyl ether; RME – rapeseed oil fatty acid methyl ester

It is also known (Wang et al., 1997; Zelenka et al., 1990) that approximately 90 % of oxides of nitrogen oxides contain NO. The reaction takes place at a very high temperature exceeding 1800°C where there is enough oxygen. Thus the origin of NO is thermal. When the combustion process is perfect, the temperature of the cycle is higher (the COP of the cycle is also higher) and the oxides contain more NO. It was determined that the chemical composition of the fuel does not influence the amount of NO in oxides.

A thorough research generalizing works carried out by approximately 80 researchers was carried out in the USA. This research was carried out by the Environmental Protection Agency, an agency famous in all states that carries out environment protection research. Data from various works analyzing different diesel vehicles from heavy goods trucks to cars was collected and analyzed for this generalizing research. All these vehicles were designed for using the ordinary diesel but they used pure biodiesel or various mixtures containing diesel during the experiments.

Both vegetable- and animal-based biodiesel was used in the research; therefore, calorific value thereof fluctuated from 32.25 to 33.230 MJ/l, whereas average calorific value of diesel amounted to 36.094 MJ/l (Lingaitis and Pukalskas, 2008). Having analyzed the data available, it turned out that increase of fuel consumption was only 4.6 % when using diesel. It was theoretically reasoned that this difference should be higher, as calorific value of vegetable-based biodiesel is 7.9 % and animal-based biodiesel is 10.6 % lower than that of mineral diesel. Comparative data about emission of pollutants is presented in fig. 2.

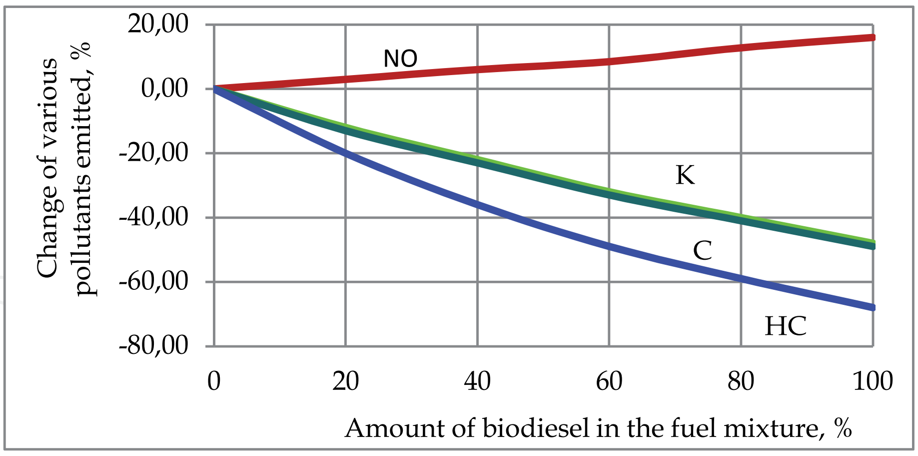


Fig. 2. Dependence of the change of various pollutants on the amount of biodiesel in the fuel mixture

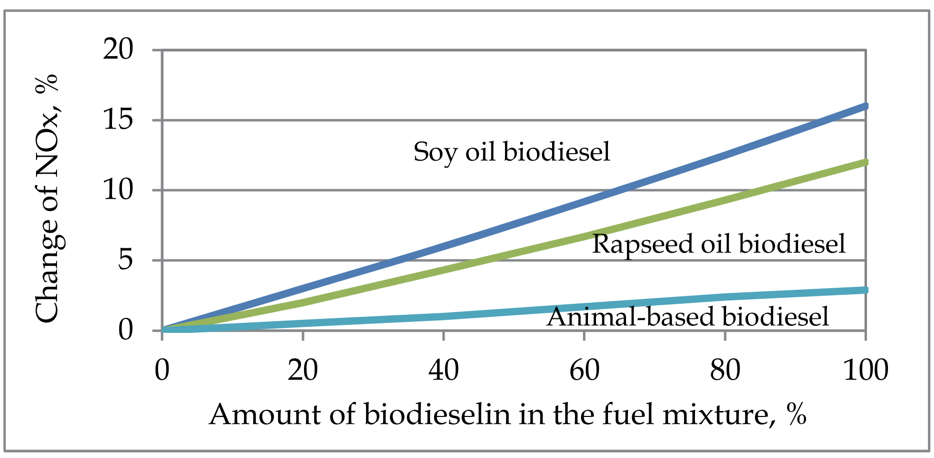


Fig. 3. Dependence of the amount of nitrogen oxides NOx on the type of biodiesel and the amount thereof in the fuel mixture

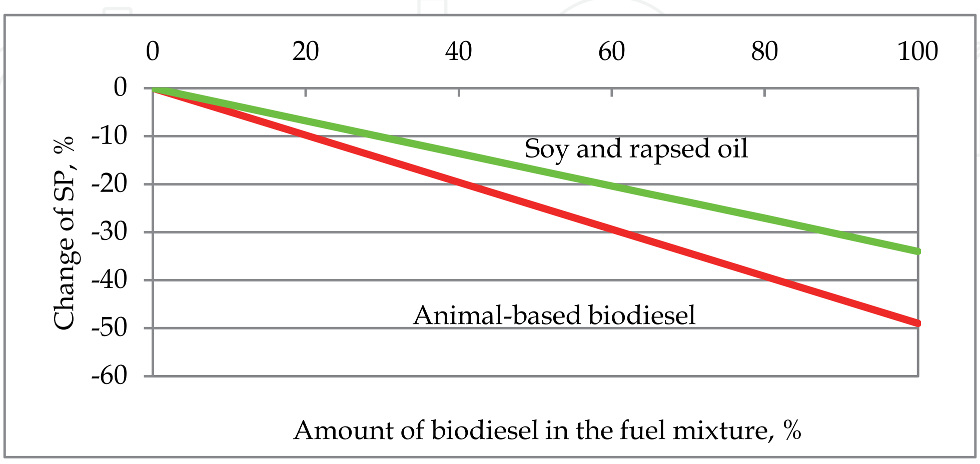


Fig. 4. Dependence of solid particles on the type of biodiesel and the amount thereof in the fuel mixture

It is obvious that biodiesel increases the NOx emission and reduces the emissions of solid particles, CO and CxHy. The research states that an addition of 10 % of biodiesel increases the NOx emission by 1 %. However, it is noteworthy that biodiesel of different origin affects the composition of the pollutants emitted differently (fig. 3, 4 and 5 (Lingaitis and Pukalskas, 2008)).

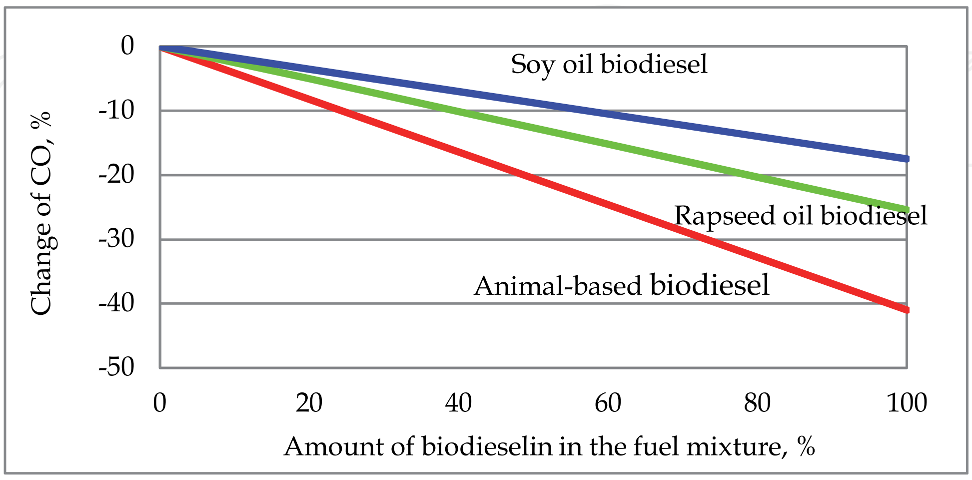


Fig. 5. Dependence of the amount of carbon monoxide CO on the type of biodiesel and the amount thereof in the fuel mixture

It can be seen from the examples presented that soy oil biodiesel increases the amount of NOx pollutants the most (fig. 3) and reduces the amounts of solid particles (fig. 4) and CO (fig. 5) the least, whereas animal-based biodiesel is the best one in ecological respect, although having the lowest calorific value, as it increases the amount of NOx the least (fig. 4) and reduces the amounts of solid particles (fig. 5) and CO (fig. 5) the most.

2. Experimental biodiesel tests

The experimental tests were carried out in the production premises designed for testing engines of UAB (Private Limited Liability Company) “Vilniaus lokomotyvų remonto depas”. The tests were carried out in a closed room. The ambient air temperature fluctuated from 5 to 10°C.

The engine of a Hungarian-made diesel train D1 was used for the tests. The characteristics thereof are presented in table 1.

During the course of the experiments, the engine being tested was secured in the engine testing stand. The stand consists of an AC generator, a liquid rheostat and a control panel. The generator is connected to the engine by a cardan shaft. The engine produces electrical current by rotating the generator; the current is supplied to the liquid rheostat. Here electrical current is transformed into heat that disperses in the environment. The engine load is changed by regulating the depth of submersion of the electrodes of the liquid rheostat in electrolyte.

The cooling system of the engine does not contain a cooling radiator. A water tank of approximately 2 m^3 volume is used for cooling. When water in it reaches maximum permissible temperature, a tap is opened and the tank is cooled by water from water-supply.

No	Indicator	Value
1.	Make	12VFE17/24
2.	Type	four strokes, pre-chamber, V-shaped
3.	Number of cylinders	12
4.	Cylinder diameter, mm	170
5.	Piston stroke, mm	240
6.	Engine revolutions, min^{-1}: minimum maximum	 550 1250
7.	Compression degree	13.6
8.	Average effective pressure, MPa	0.551
9.	Nominal power, kW	538
10.	Operating volume of the engine, l	65.3
11.	Average piston speed, m/s	10
12.	Comparative fuel consumption at nominal power, g/(kW h): fuel engine oil	225+8 % 4
13.	Maximum permissible temperature, °C: water engine oil (recommended)	 95 95 (80)
14.	Type of turbo compressor	centrifugal, single-step
15.	Rotor revolutions of turbo compressor, min^{-1}	21 000
16.	Inflation pressure, MPa	0.09±0.015
17.	Fuel injection angle, °	21±1.5
18.	Engine dimensions, mm: length × width × height	 3210 × 1300 × 1700
19.	Engine mass without oil and water, kg	4600

Table 1. Technical characteristics of the engine of the diesel train D1

An additional pump was used for supplying fuel from the fuel tank to the high-pressure fuel pump of the engine.

The control panel of the stand regulates the engine load (by changing the value of the current produced by the generator) and revolutions (by regulating the fuel pump).

Fuel of two types was used for the tests: diesel produced by UAB "Mažeikių nafta" conforming with the requirements of the standard LST EN 590 and biodiesel produced by UAB "Rapsoila", i.e. fatty acid methyl ester (RME), conforming with the requirements of the standard LST EN 14214:2003.

Three different methods and units were used for analyzing various components contained in exhausted gas:

1. the weight method was used for determining the amount of solid particles;
2. the electrochemical method and the unit "Testo 350-M/XL" was used for determining the amounts of nitrogen oxides (NOx), carbon monoxide (CO) and carbon dioxide (CO_2);

3. the amount of carbohydrates (CxHy) was determined by the chromatographic method and the chromatograph SRI 8610.

The concentration of solid particles in the oxides of the engine was determined by the weight method. Perchlorvinyl AFA-VP-20 type filters permeable to air, on which solid particles contained in the oxides attracted by the aspirator deposit, were used for that purpose. The difference of the weight of the filters before and after sampling divided by the volume of the air pumped shows the concentration of solid particles. The filters are weighted by the analytical scale VLR-200. The filters are kept in the exicator for 3...4 hours before weighting in order to remove moisture from them. Error of the method: ±25 %.

The characteristics of the parameters measured by the unit "Testo 350-M/XL" are presented in table 2.

No	Parameter measured	Measurement limits	Measurement accuracy
1.	Oxygen (O_2), %	0...25	< 0,8 %
2.	Carbon monoxide (CO), ppm	0...10,000	<5 ppm at 0...99 ppm <5 % mv at 100...2,000 ppm <10 % mv at 2,100...10,000 ppm
3.	Nitrogen oxides, ppm: NO	0...3,000	<5 ppm at 0...99 ppm <5 % mv at 100...2,000 ppm <10 % mv at 2,100...3,000 ppm
	NO_2	0...500	<5 ppm at 0...99 ppm <5 % mv at 100...500 ppm
	NO_x	0...3,000	<5 ppm at 0...99 ppm <5 % mv at 100...2,000 ppm <10 % mv at 2,100...3,000 ppm
4.	Sulphur dioxide (SO_2), ppm	0...5,000	<5 ppm at 0...99 ppm <5 % mv at 100...2,000 ppm <10 % mv at 2,100...5,000 ppm
5.	Lambda λ	0.5...2.0	0.1
6.	Carbon dioxide (CO_2), %	0...50 %	<0.3 % at 0...25 % <0.5 % at 25..50 %
7.	Gas temperature, °C	0...1,000	<0.1°C at 100°C <1°C at 100...1,000°C

Table 2. Technical characteristics of the unit "Testo 350-M/XL" measuring pollutants

Measurements of the speed of gas flow were also carried out. Pneumatic pipes allowing measuring dynamic pressure of gas by a micromanometer are used for determining the speed of gas flow in the air duct. Dynamic pressure PD is equal to the difference of total pressure PB and pressure of the building PS. As dynamic pressure is proportionate to the speed of gas square, the speed of gas flow in the air duct is measured indirectly by recording fluctuations of dynamic pressure.

A short description of the course of experimental tests is presented. The following was measured during the tests:

1. amount of fuel used by the engine (by the weight method);

2. time of tests;
3. revolutions of the engine;
4. value of electrical current and voltage produced by the load generator;
5. components of exhausted gas: NOx, CO, CO_2, CxHy and SP;
6. pressure generated by the turbo compressor in the air intake collector;
7. temperature of the air sucked;
8. temperature of engine oil and coolant.

The tests were carried out using the engine heated up to the operating temperature. Temperature of water cooling the engine fluctuated between 70...80°C during the tests. It was not possible to keep a more stable temperature mode of the engine because of the old, non-automated oil and engine cooling units of the stand.

The plan of the tests containing the course of the experiment is presented in table 3. In the beginning, the tests were carried out using pure diesel at 4 different engine modes. Fuel consumption was measured, exhausted gas was analyzed and the temperature state of the engine was observed during them. After that, 10 % of RME was added to diesel and tests were carried out at the same engine operation modes as when testing pure diesel. In this way, tests were repeated with the engine operating with an increasing load and, after that, by increasing the amount of RME in the fuel mixture by 10 %. The results obtained were recorded in the table.

No.	Fuel	Engine mode		
		revolutions, min^{-1}	generator current, A	generator voltage, V
1.	diesel	540	0	0
2.	diesel	1,050	600	300
3.	diesel	1,250	700	350
4.	diesel	1,325	800	400
5.	diesel + 10 % of RME	540	0	0
6.	diesel + 10 % of RME	1,050	600	300
7.	diesel + 10 % of RME	1,250	700	350
8.	diesel + 10 % of RME	1,325	800	400
9.	diesel + 20 % of RME	540	0	0
10.	diesel + 20 % of RME	1,050	600	300
11.	diesel + 20 % of RME	1,250	700	350
12.	diesel + 20 % of RME	1,325	800	400
13.	diesel + 30 % of RME	540	0	0
14.	diesel + 30 % of RME	1,050	600	300
15.	diesel + 30 % of RME	1,250	700	350
16.	diesel + 30 % of RME	1,325	800	400
17.	diesel + 40 % of RME	540	0	0
18.	diesel + 40 % of RME	1,050	600	300
19.	diesel + 40 % of RME	1,250	700	350
20.	diesel + 40 % of RME	1,325	800	400

Table 3. Plan of experimental tests

An electronic scale with a tank with the fuel being tested placed on it was used for measuring fuel consumption. Each test lasted for about 10 min. The amount of fuel used was weighted and measurements of pollutants were carried out during this time. Each test was repeated three times in order to ensure accuracy.
The results of the tests were processed on the basis of the least squares method and are presented in fig. 6–16.
When analyzing the charts presented, we can see that comparative fuel consumption (g/(kW·h)) increases slightly when the engine operates at low load mode up to 0.30...0.35 maximum power (P_{max}) and having mixed rapeseed oil fatty acid methyl ester (RME) compared to consumption of pure diesel. It may be maintained that this increase is directly proportionate to the amount of RME in diesel. However, consumption of the mixtures approaches consumption of pure diesel when increasing the engine load and, having reached 0,6 P_{max}, this consumption becomes similar to consumption when using pure diesel.

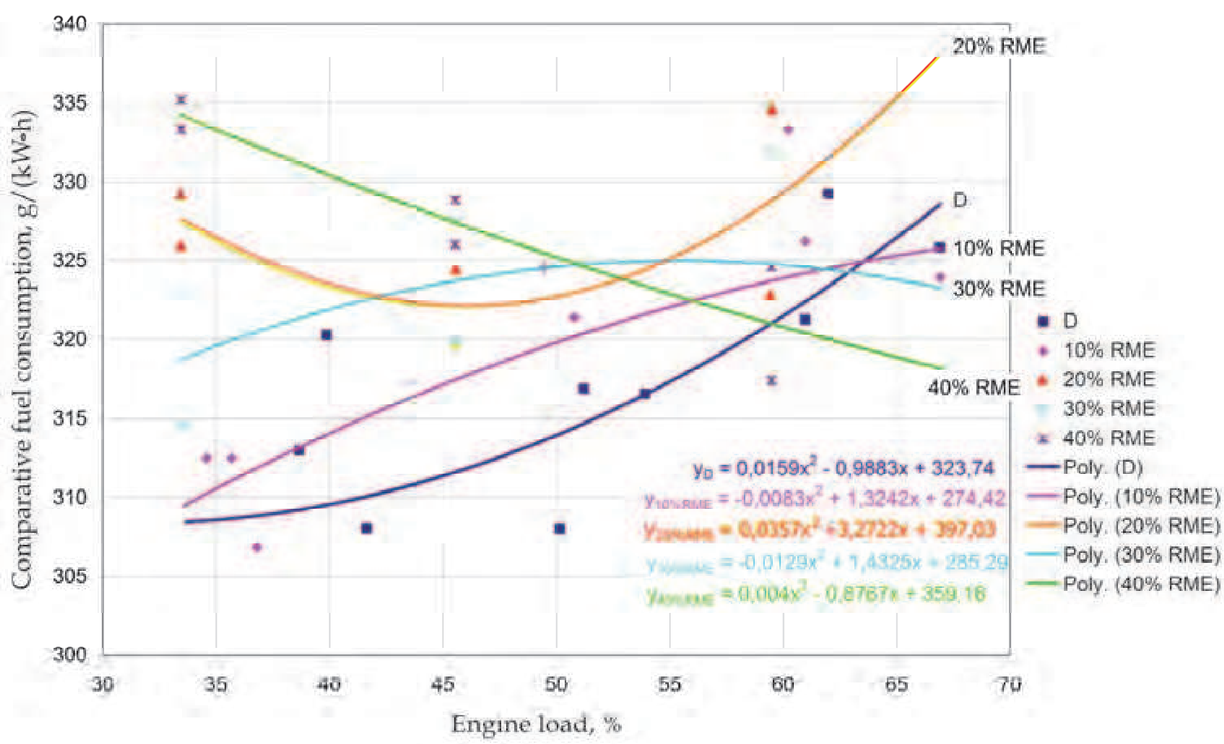


Fig. 6. Dependence of comparative fuel consumption on the engine power (% P_{max}) when using various fuel mixtures

We believe that oxygen contained in RME does not significantly influence improvement of effectiveness of the combustion process and fuel consumption increases slightly due to lower calorific value of RME (approximately 8…9 % compared to diesel) when the engine operates at low loads with a high air surplus coefficient. However, as mentioned before, having increased the engine load more than 0.5 P_{max} and reduced the air surplus coefficient in the engine cylinders, this additional oxygen improves the combustion process of the mixture and reduces fuel consumption.
This can be obviously seen in the chart of percentage comparison of comparative fuel consumption of various fuel mixtures and pure diesel presented in fig. 7. When the engine power amounts to $P \leq 0.5\ P_{max}$, comparative fuel consumption increases in proportion to the

increase of the amount of RME in the mixture; however, when the engine power reaches 0.65 P_{max}, comparative fuel consumption of the mixtures starts decreasing (excluding the mixture of 10 % of RME and diesel). Here we can see a reverse result: the higher the amount of RME in the mixture, the lower the comparative fuel consumption.

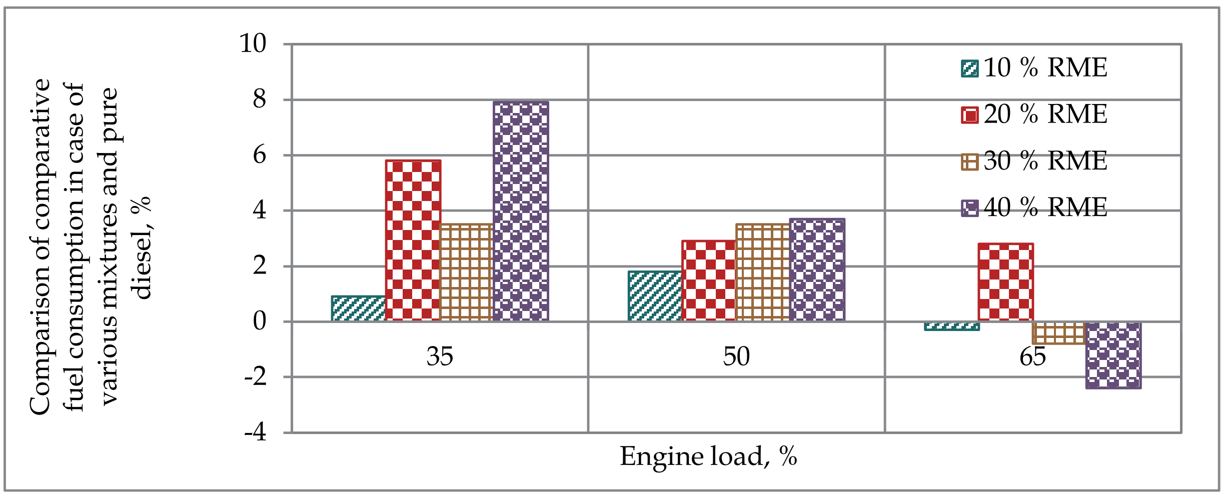


Fig. 7. Percentage comparison of comparative fuel consumption in case of various fuel mixtures and pure diesel

When analyzing emission of solid particles (exhaust smoke) presented in fig. 8, we can also see the same situation as in case of fuel consumption. When the engine power reaches 0.5 P_{max}, exhaust smoke is the lowest and when using the mixture containing 10 % and 20 % of RME and diesel, it is even lower than that of pure diesel.

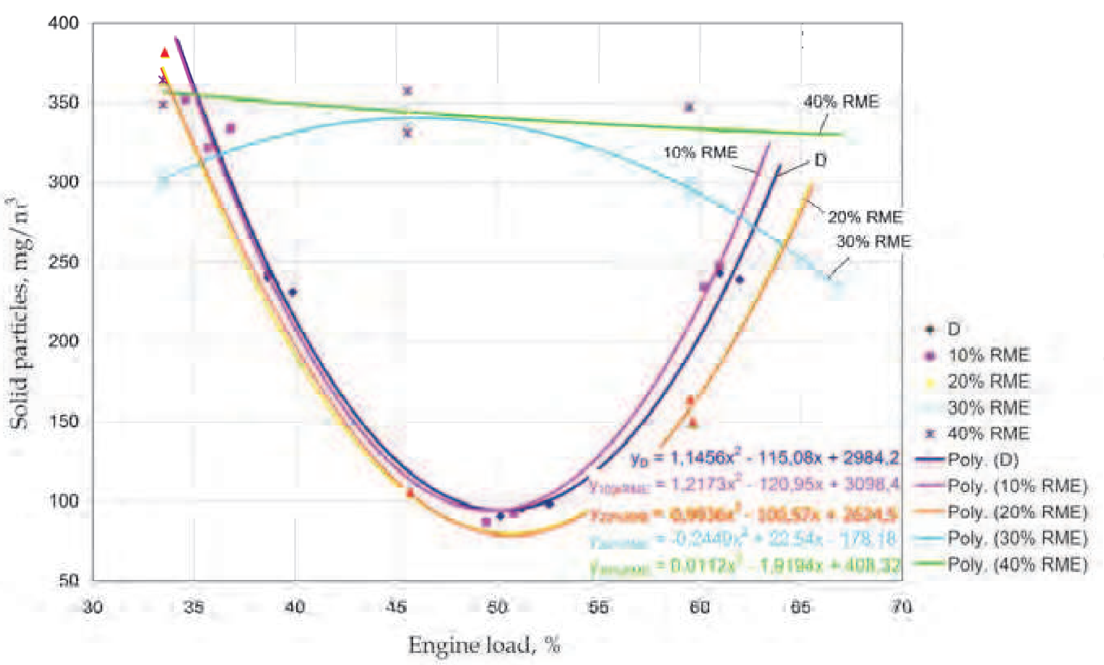


Fig. 8. Dependence of emission of solid particles on the engine power (% P_{max}) when using various fuel mixtures

However, when the amount of RME in diesel amounts to 30 % or 40 %, regularity of exhaust smoke changes radically. Trying to find out the reasons of this change was unsuccessful. The curves of emission of solid particles of the mixtures containing 30 % and 40 % of RME and diesel show that exhaust smoke is reduced when the engine load increases; however, exhaust smoke is higher when using the mixture containing 40 % of RME and diesel than when using the mixture containing 30 % of RME and diesel.

Higher exhaust smoke means poorer combustion of the mixture in the engine cylinders, although it should be vice versa due to a higher amount of oxygen in biodiesel. In order to clarify contradiction once and for all, additional tests with a few different engines should be carried out.

It can be seen from the chart presented in fig. 9 that SP emission is lower than when using diesel in almost all cases. Its values exceed SP emission of diesel even 2.5 times at two points, reliability of which is the most doubtful, only.

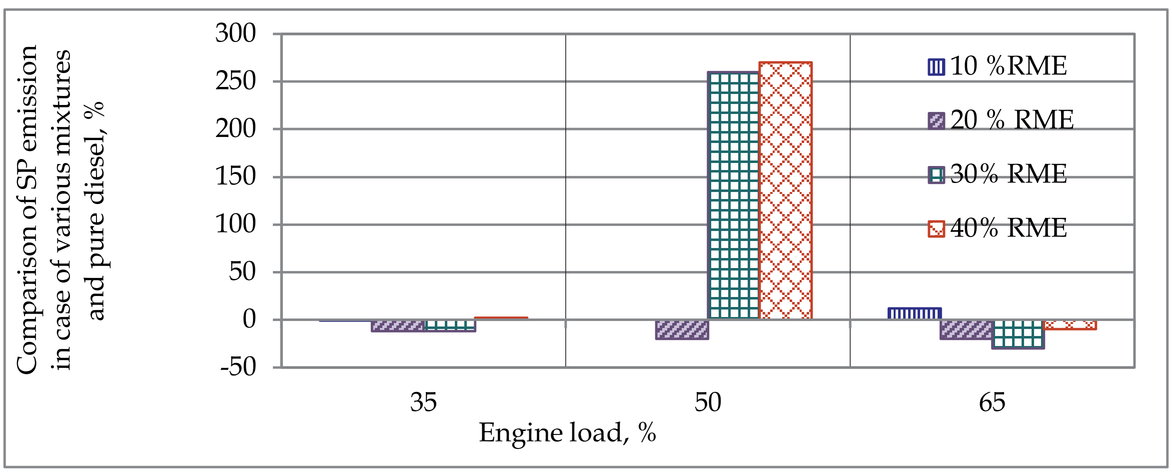


Fig. 9. Percentage comparison of emission of solid particles in case of various mixtures to emission when using pure diesel

Emissions of nitrogen oxides (NOx) are presented in fig. 10. The charts clearly show that the amount of NOx in oxides decreases when the amount of RME in diesel increases (although a reverse effect is known from the literature). Besides, it also depends on the engine power achieved: the higher the engine power, the lower the amount of NOx.

Knowing that intensity of formation of NOx is proportionate to the combustion temperature (the higher the temperature, the higher the amount of NOx), reduction of pollutants when the engine power increases can be easily explained: as the load increases and the air surplus coefficient decreases, the mixture becomes richer; therefore, combustion temperature decreases and conditions for formation of NOx worsen.

The values of carbon dioxide CO_2 are very important. This gas causes the “greenhouse effect”. Dependence of the change of emission thereof on the amount of RME in diesel and on the engine load is shown in fig. 11. Compared to pure diesel when the engine load does not exceed 0,5 P_{max} at various amounts of RME (up to 30 %) in diesel, the amount of CO_2 gas emitted is always lower, excluding the case when the amount of RME in diesel is 40 %. As the engine load increases, emissions of CO_2 gas of all mixtures and pure diesel increase proportionately and regularities thereof are similar. Only CO_2 values of the mixtures containing 20 % and 30 % of RME may be distinguished; they increase slightly more sharply than those of other mixtures or pure diesel as the engine load increases. However, they increase insignificantly and, having assessed errors, it may be maintained that CO_2 values of all mixtures are similar.

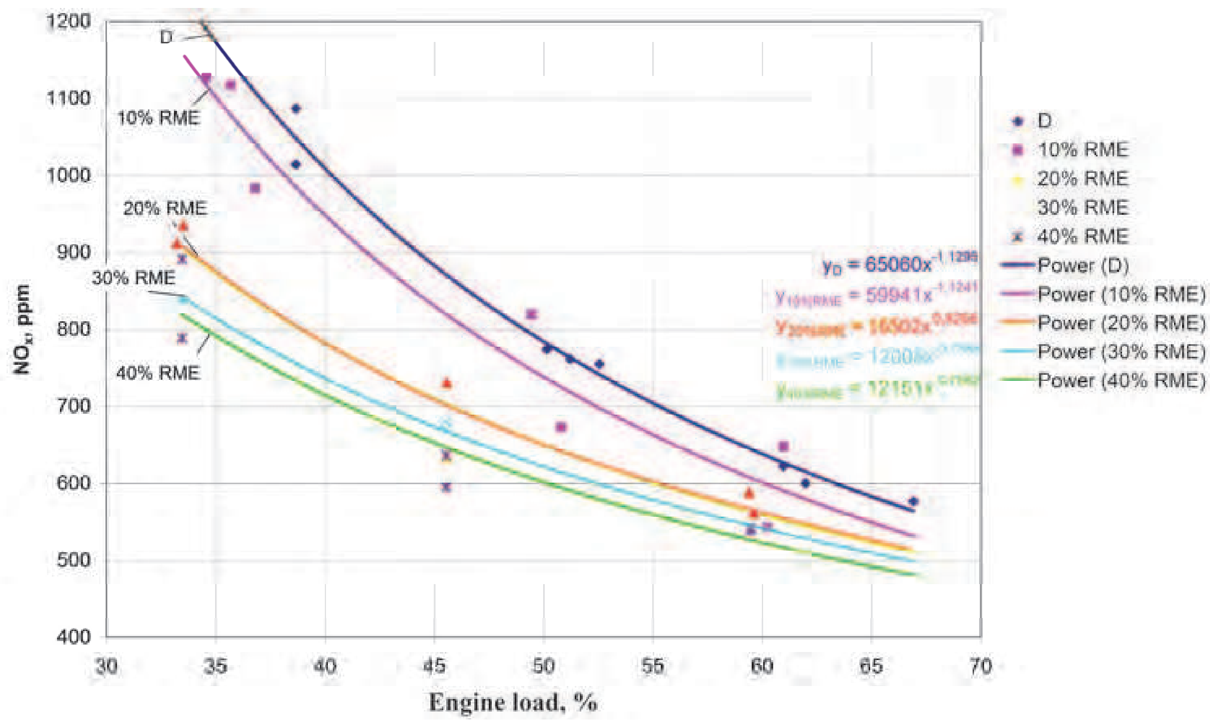


Fig. 10. Dependence of emission of nitrogen oxides on the engine power (% P_{max}) when using various fuel mixtures

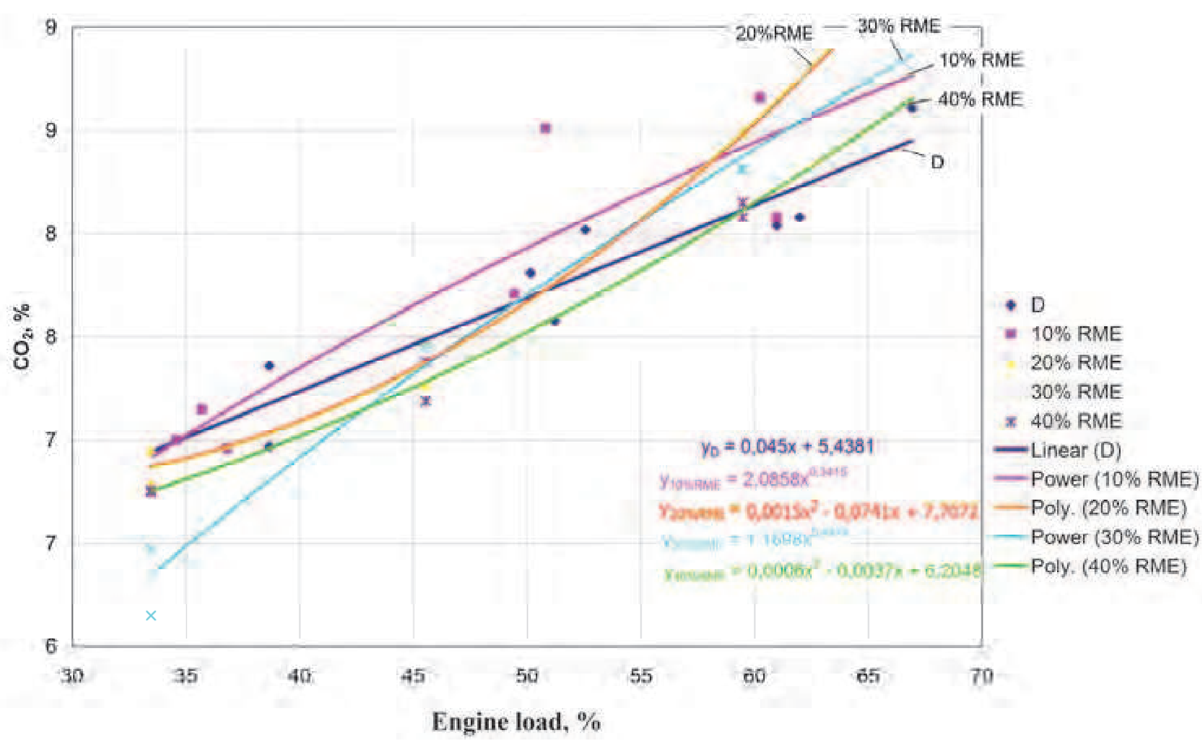


Fig. 11. Dependence of emission of CO_2 on the engine power (% P_{max}) when using various fuel mixtures

On the one hand, lower formation of CO_2 seemingly reduces formation of the "greenhouse effect"; on the other hand, higher emission of CO_2 gas shows better combustion of the combustible mixture and, consequently, lower fuel consumption.
Scientific literature upholds the opinion that burning biofuel does not increase the concentration of CO_2 in the atmospheric air, as growing plants, from which this fuel is produced, absorb the same amount of CO_2 that was emitted during combustion.
When analyzing emissions of charcoal fumes, i.e. carbon monoxide (CO) (fig. 12), it can be seen that, as the engine load increases, when P ≥ 0,5 P_{max}, CO increases at all compositions of all the mixtures tried. It increases slightly slowly when the amount of RME in diesel is 30...40 %.

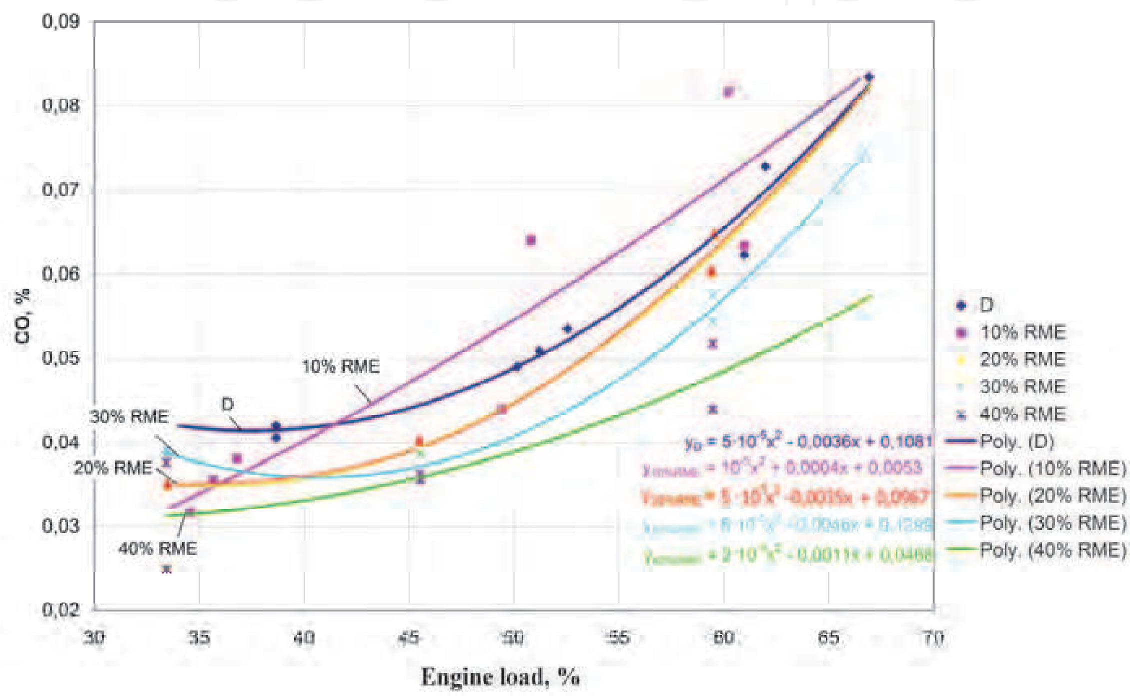


Fig. 12. Dependence of emission of CO on the engine power (% P_{max}) when using various fuel mixtures

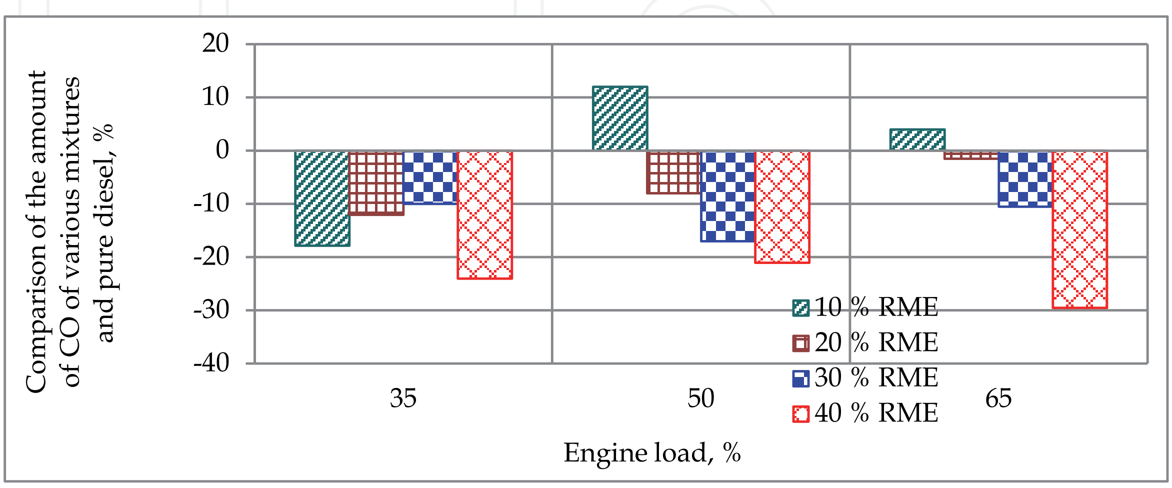


Fig. 13. Percentage comparison of the amount of CO to CO emission when using pure diesel

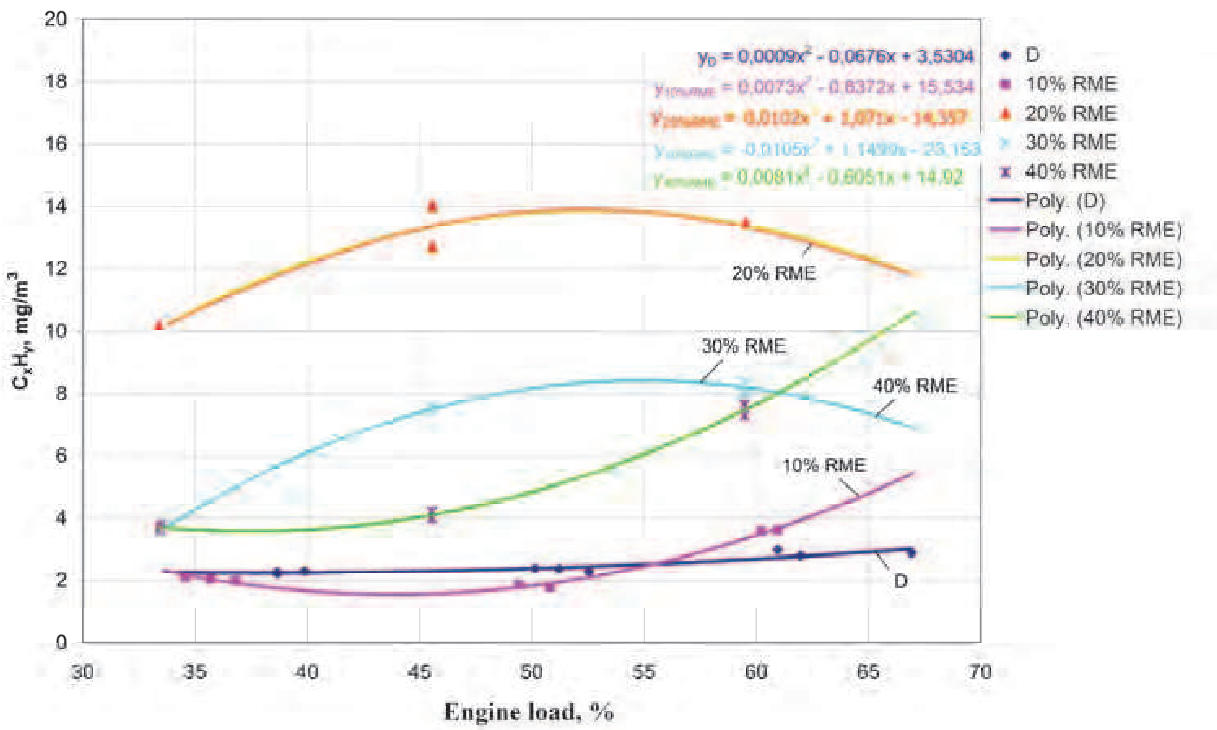


Fig. 14. Dependence of emission of CxHy on the engine power (% P_{max}) when using various fuel mixtures

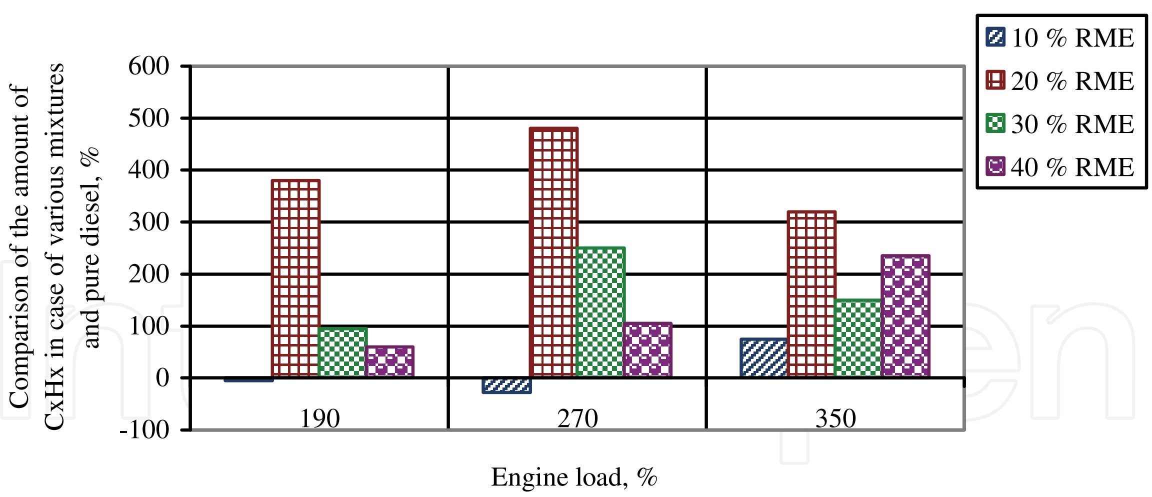


Fig. 15. Percentage comparison of CxHy emission to CxHy emission when using pure diesel

It can be seen from these charts that, as the engine load increases, these emissions increase too, excluding the mixtures containing 20 % and 30 % of RME. Emissions thereof reach maximum at the value 50 % P_{max} and keep decreasing afterwards. The load has the lowest impact on the CxHy emission when the engine operates using pure diesel. The values of CxHy of the mixture containing 10 % RME and diesel are ones of the lowest and close to the values of CxHy pollutants of diesel.

As the engines of diesel trains operate at idle run a lot of time, i.e. they are not turned off in railway stations, when waiting for the permissible traffic lights signal etc, it is rational to perform tests on the unloaded engine using mixtures of various compositions.
Percentage comparison of emission of solid particles when mixtures of various compositions (10 %, 20 %, 30 % and 40 % of RME) are combusted and the engine is unloaded to emissions when pure diesel is combusted is shown in fig. 16. We can see that exhaust smoke increases when the mixture contains 30 % and 40 % of RME; in all other cases, exhaust smoke is lower than exhaust smoke of pure diesel.

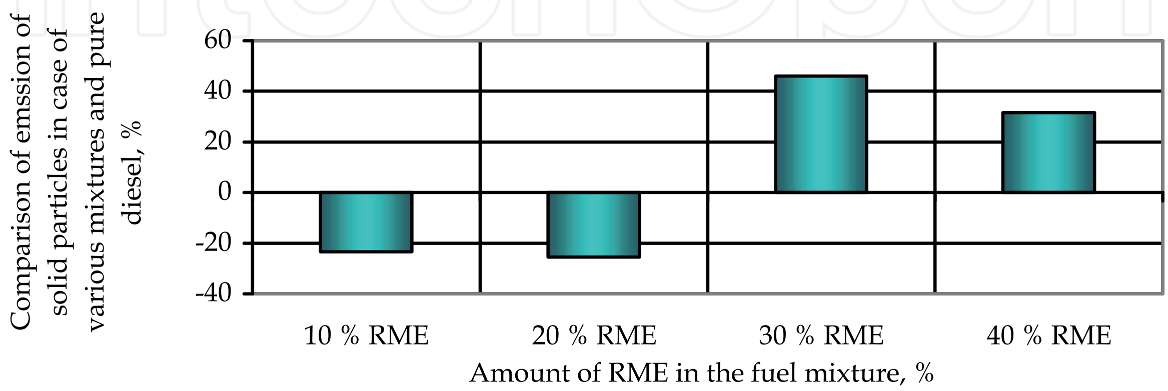


Fig. 16. Comparison of emission of solid particles in case of various mixtures to emission when using pure diesel

Naturally, it impossible to choose a different composition of the mixtures for all the engine loads; these values suggest that the most rational option is using biodiesel containing 20 % of RME, as, in this case, exhaust smoke is reduced by 25 % compared to exhaust smoke of pure diesel.
We can see from fig. 17 that the amount of nitrogen oxides in oxides increases significantly (up to 27 % compared to pure diesel) when the mixture contains 20 % of RME; in all other cases, emissions of these pollutants are significantly lower. With regard to these amounts of pollutants, the amounts of NOx are the lowest in case of the mixture containing 10 % of RME. They are lower by 15 % compared to the amount of NOx in case of pure diesel.

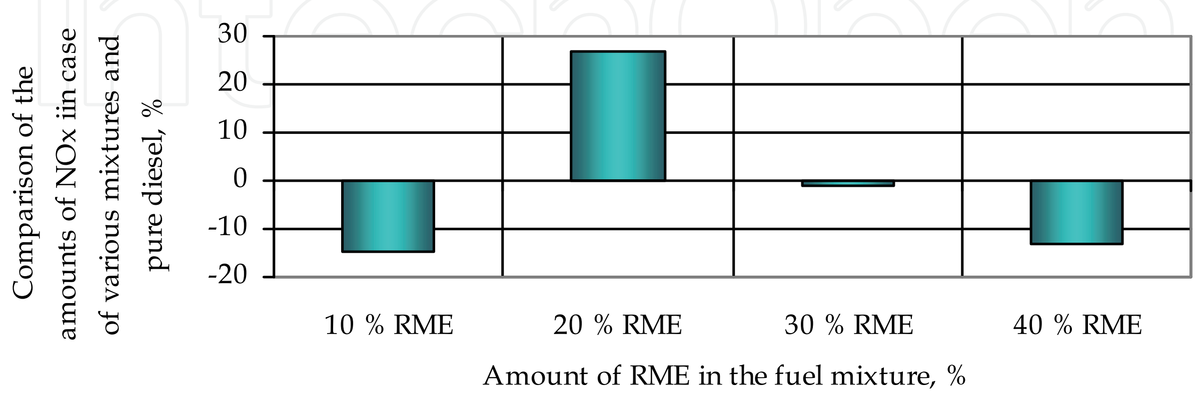


Fig. 17. Comparison of NOx emission in case of various mixtures to emission when using pure diesel

We can see CO_2 emissions to the environment at idle run and different composition of fuel in fig. 18. It can be clearly seen here that CO_2 emissions to the environment increase by up to 3 % when the mixture contains 20 % of RME compared to pure diesel. In all other cases, CO_2 decreases and, when the mixture contains 40 % of RME, CO_2 decreases by up to 10 % compared to emissions when using pure diesel.

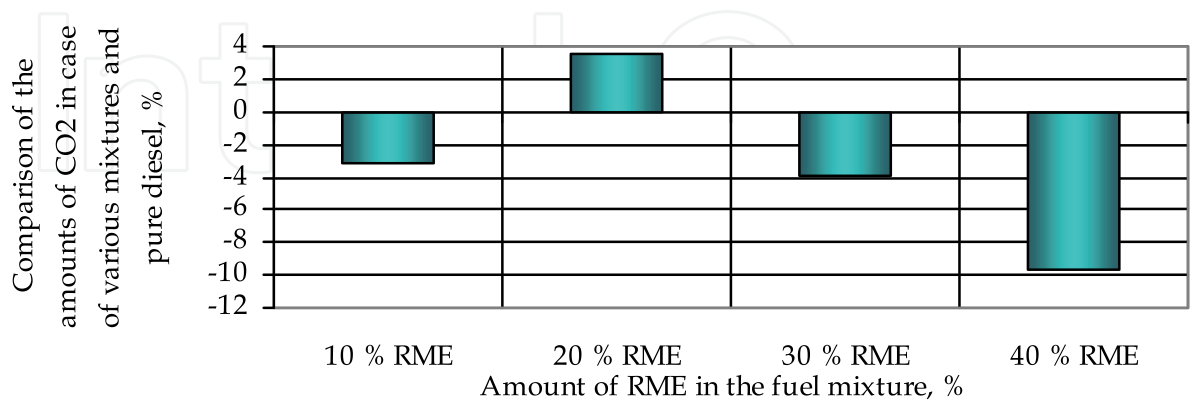


Fig. 18. Comparison of CO_2 emission in case of various mixtures to emission when using pure diesel

The amount of charcoal fumes (CO) emitted to the environment decreased from 5 to 26 percent in all cases compared to emissions when using pure diesel (fig. 19). The amount of CO decreased in the oxides the most when the engine operated using a mixture containing 20 % of RME and diesel: even up to 26 % compared to CO emission when using pure diesel.

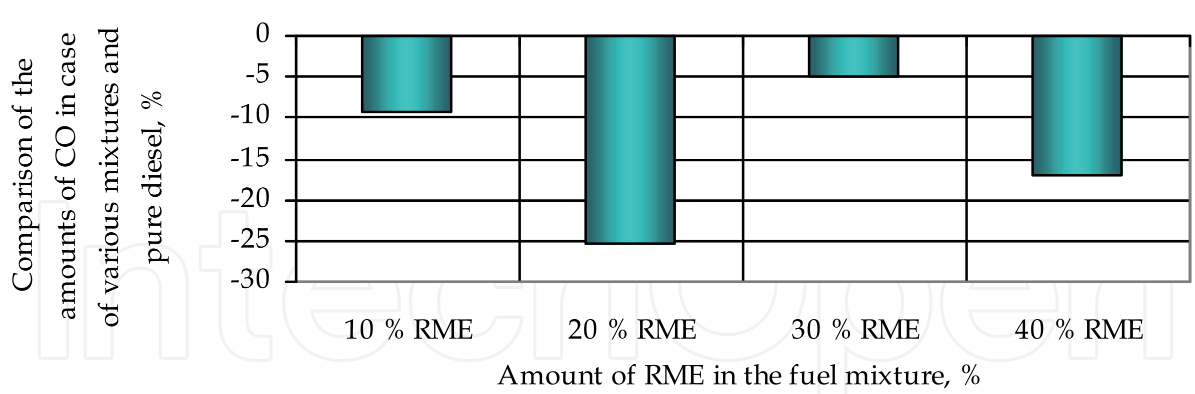


Fig. 19. Comparison of CO emission in case of various mixtures to emission when using pure diesel

When adding RME to diesel, the amount of carbohydrates (CxHy) in the oxides increases from 151 % to 290 % compared to emissions when using pure diesel (fig. 20), excluding the mixture where the amount of RME is 10 %. In this case, the amount of CxHy emitted to the environment is reduced by approximately 30 %.

Generalizing the results obtained, an optimal composition of the mixture should be chosen in accordance with all the criteria analyzed and not only the pollutants emitted to the environment together with oxides should be taken into account but also the level of toxicity of these pollutants and fuel consumption.

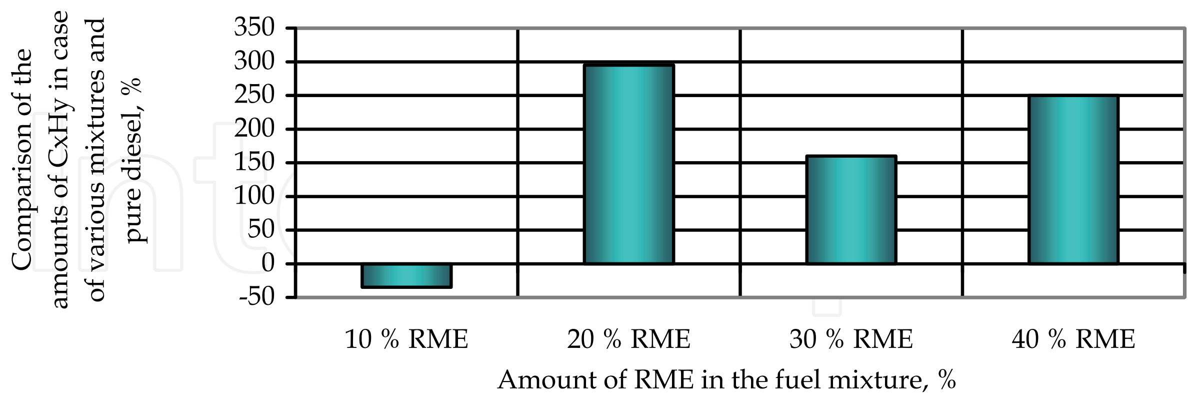


Fig. 20. Comparison of CxHy emission in case of various mixtures to emission when using pure diesel

Mixtures containing 5 % of fatty acid methyl esters with mineral diesel are used in a lot of EU countries. They conform to the requirements of the standard LST EN 590 and do not cause any operational issues. Biodiesel is used in such mixtures as an addition to mineral diesel, such mixtures must not be specially market at the selling spots and are sold as ordinary diesel.

Higher-concentration biodiesel mixtures containing mineral diesel are used in Italy (25 % of RME) and the Czech Republic (30 % of RME). It was determined that a mixture containing 30 % of biodiesel and mineral diesel is optimal with regard to the operating and environment protection features. When using such a mixture, fuel consumption increases slightly and engines do not need special preparation (this is a must when using pure biodiesel). Besides, less nitrogen oxides that are characterized by features causing the greenhouse effect are emitted to the environment and biologic decomposition of the mixture in the nature conforms to the requirements established for biofuel. The rules on trade in oil products, biofuel, bio oil and other combustible liquid products in the Republic of Lithuania stipulate that pure RME and mixtures containing 5 % and 30 % (volume) of RME with mineral diesel may be sold in our Republic.

3. Generalization of stand tests

Having processed the results obtained during these tests, mathematic dependence of fuel consumption of the engine power and the amount of RME was designed:

$$B = 2.92481 + 0.27641 \cdot P + 0.10377 \cdot 10^{-3} \cdot P^2 + 0.25431 \cdot B_{RME\%} - 5.07103 \cdot 10^{-3} \cdot B^2_{RME\%}; \quad (1)$$

here: P – engine power, kW; $B_{RME\%}$ – amount of RME in total volume of fuel, %.

The graphic form of this mathematic expression is presented in fig. 21.

We can see in the chart presented that, as the engine power increases, fuel consumption increases rapidly, as more fuel is needed for obtaining energy and the amount of biofuel influences fuel consumption slightly.

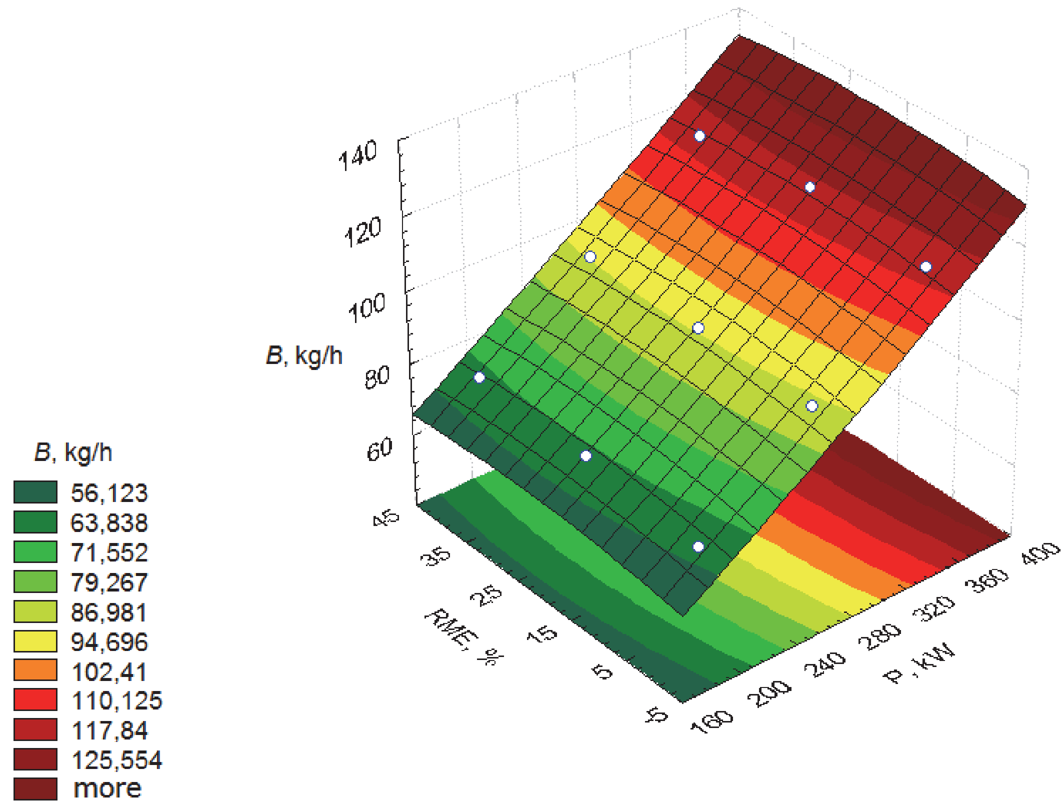


Fig. 21. Dependence of total fuel consumption *B* (when using a mixture of diesel and RME) on the amount of RME and the engine power *P*

4. Economic calculations

We calculate annual expenses for fuel of diesel passenger trains. It is complicated to calculate accurately the economic effect that may be achieved when using RME, as fuel consumption varies and prices fluctuate constantly.

Annual (year 2004...2006) fuel consumption of passenger trains of AB (Public Limited Liability Company) "Lietuvos gelezinkeliai" is presented in table 4.

Year	Fuel consumption, t
2004	1301.5
2005	1632.1
2006	3251.5

Table 4. Annual fuel consumption of diesel passenger trains, year 2004...2006

Having assessed annual increase of fuel consumption, it may be forecasted that it shall amount to 3251.5 t/m in 2007 (fig. 22).

Knowing the amount of fuel consumed Bdyz and prices of fuel Kdyz, we can calculate annual expenses for fuel Z, (EUR/y.):

$$Z = B_{dyz} \cdot K_{dyz}; \tag{2}$$

here: B_{dyz} – annual fuel consumption of diesel trains, t/m.; K_{dyz} – price of diesel paid by the company, EUR/t.

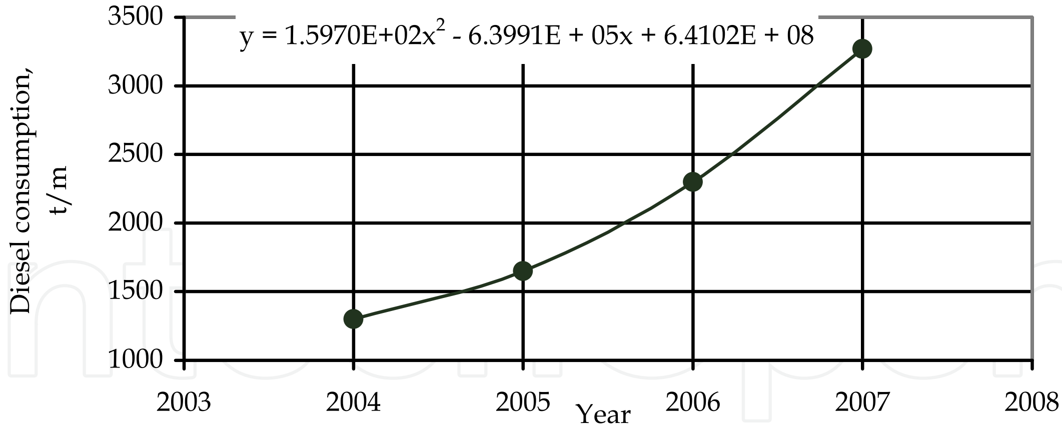


Fig. 22. Annual fuel consumption of diesel passenger trains (the fact and prognosis for the year 2007)

Having performed experimental tests, it was determined that fuel consumption increased by 2.95 % at an average when using RME compared to consumption of pure diesel; therefore, this increase must be assessed when calculating annual expenses for fuel. When using RME, total fuel consumption changes not in proportion to the amount thereof but in accordance with a certain law which is presented in fig. 23.

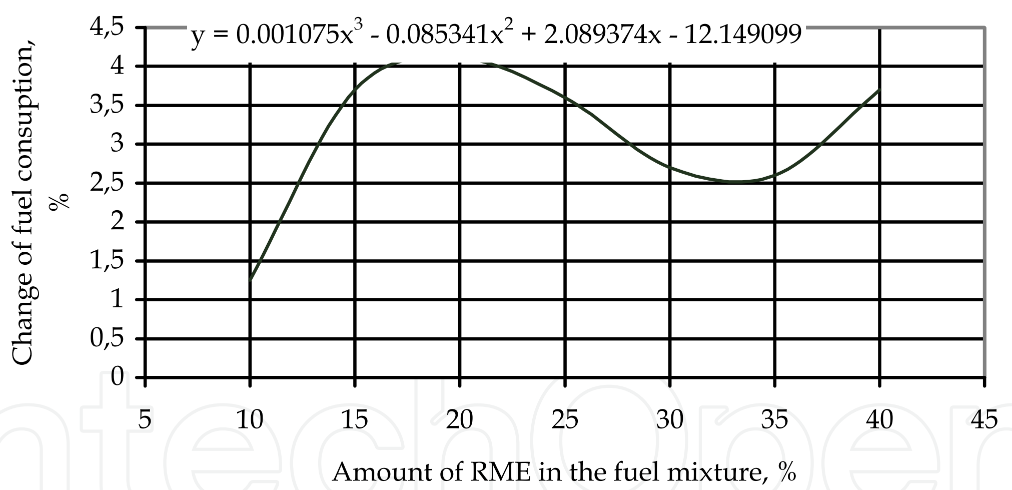
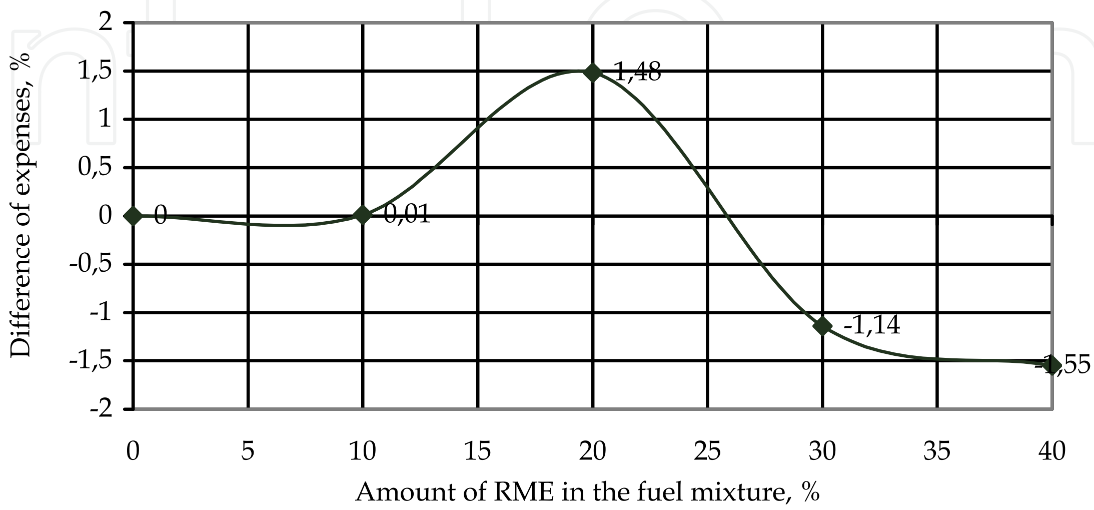


Fig. 23. Dependence of the change of fuel consumption on the amount of RME compared to consumption of pure diesel

The chart presented in fig. 23 shows that fuel consumption increases by up to 4 % when using a mixture containing 20 % of RME compared to consumption of pure diesel, it increases by up to 2.5 % using a mixture containing 30 % of RME and consumption keeps increasing when the amount of RME in the mixture is increased.
Knowing that total fuel consumption is:

$$B = B'_{dyz} + B_{RME}; \tag{3}$$

here: B'_{dyz} – amount of diesel when using biodiesel and having assessed total increase of fuel consumption due to the difference in calorific value.
The chart of the change of expenses for fuel is presented in fig. 24. The calculations were carried out at the prices of fuel and taxes in the 4th quarter of 2006 and having assessed the change of fuel consumption due to usage of RME.



*The prices of fuel valid in the end of 2006 were used for the calculations

Fig. 24. Difference of expenses for fuel when using a different amount of RME and having assessed the change of fuel consumption due to usage of RME compared to expenses when using pure diesel

The figure (fig. 24) shows that expenses for fuel (and environmental taxes) shall change insignificantly when using a fuel mixture containing 10 % of RME compared to expenses when using pure diesel; expenses shall increase by 1.48 % when using a fuel mixture containing 20 % of RME; expenses shall decrease by 1.14 % when using a fuel mixture containing 30 % of RME; expenses shall decrease by 1.5 % when using a fuel mixture containing 40 % of RME.

5. Environment protection calculations

When analyzing data concerning pollutants obtained during the experiment (fig. 6, 21 and 23), a calculation was carried out in accordance with the "Methodology of assessment of pollutants emitted to the atmosphere by locomotives and diesel trains" presented in the normative instrument LAND 18-2003/M-03 for environment protection.
This instrument is a corrected methodology of calculation of pollutants emitted by the railway transport presented in the normative instrument LAND 18-96/M-03 compiled having assessed the recommendations of the program CORINAIR of the European Union (EU) and other methodologies of calculation of pollutants emitted to the atmosphere by traction rolling-stock.
The calculation methodology was corrected having additionally assessed the fact that the amount of pollutants emitted to the atmosphere depends on the currently changed operation conditions of traction rolling-stock with diesel engines in Lithuania, comparatively high average mass of freight trains, change of the engines of old traction

rolling-stock by new engines conforming to the standards of emission of pollutants (UIC I and UIC II) established by UIC (International Union of Railways).
The purpose of this calculation is to present comparable estimates of various pollutants that would enable determining the most ecological ration of diesel and RME.
The difference of the averages of all the amounts of pollutants analyzed during the experiment is calculated based on the available results of the tests compared to pollutants emitted by an engine using pure diesel. The data about the differences calculated is presented in table 5.

	Engine load, %	Amount of RME in the fuel mixture, %			
		10	20	30	40
Difference CO, %	0[1]	-9.1	-22.5	-5.0	-16.9
	25	-53.4	-17.4	2.0	-36.1
	50	11.8	-8.3	-16.6	-20.5
	75	-7.3	1.7	-5.0	-35.6
Difference CO_2, %	0	-3.1	-4.6	-3.9	-9.6
	25	-5.3	2.5	-16.6	-1.8
	50	3.3	-0.1	0.3	-2.0
	75	3.0	17.7	5.9	5.3
Difference C_xH_y, %	0	-31.6	283.7	159.8	251.8
	25	73.7	150.8	-58.098	102.2
	50	-22.6	478.5	242.9	104.1
	75	147.1	152.1	19.2	328.7
Difference NO_x, %	0	-14.5	5.3	-0.5	-12.7
	25	-6.3	-32.8	-38.8	-40.3
	50	-5.9	-16.9	-20.6	-23.1
	75	-5.7	-6.2	-7.7	-11.1
Difference SP, %	0	-23.4	-26.9	46.0	31.5
	25	1.5	-11.2	-72.1	-55.7
	50	0.1	-15.4	256.8	261.0
	75	9.7	-15.9	-83.4	-59.2

Table 5. Comparison of various pollutants when using different amounts of RME in diesel to pollutants emitted by an engine using pure diesel (the values are presented in %)

The amount of fuel Q (t/h) consumed at different engine load modes is presented in table 6.

Fuel	Engine load, %			
	0	25	50	75
diesel	0.0031	0.0095	0.0180	0.0146
10 % of RME	0.0030	0.0100	0.0182	0.0146
20 % of RME	0.0032	0.0116	0.0183	0.0153
30 % of RME	0.0031	0.0105	0.0184	0.0145
40 % of RME	0.0031	0.0116	0.0184	0.0141

Table 6. The amount of fuel Q (t/h) consumed at different engine load modes

[1]The engine was operating at idle run.

The values of comparative pollution by trains D1 depending on the amount of fuel consumed when the engine operates at different modes is presented in table 7.

Pollutant	Engine load, %			
	0	25	50	75
CO	3.5	5.0	5.7	6.0
NOx	12.0	25.0	35.0	86.0
CxHy	0.7	0.8	0.9	1.1
SP	1.6	2.2	2.5	3.2

Table 7. Comparative values of various pollutants

Amounts of various pollutants *W*(*t*) are calculated then:

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

here: $l_{k,\,j,\,i}$ – comparative portion of the pollutant "*k*" at the load mode "*j*" in a locomotive, engine unit of a diesel train or automotrice of series "*i*" in kilograms per one ton of fuel consumed (table 8).
The *W* values calculated are presented in table 8.

Fuel	CO, t/h				C_xH_y, t/h				NO_x, t/h				SP, t/h			
	Engine power, %				Engine power, %				Engine power, %				Engine power, %			
	0	25	50	75	0	25	50	75	0	25	50	75	0	25	50	75
diesel	0.011	0.047	0.102	0.087	0.002	0.008	0.016	0.016	0.037	0.237	0.629	1.254	0.005	0.021	0.045	0.047
10% of RME	0.010	0.022	0.115	0.081	0.001	0.013	0.013	0.040	0.031	0.222	0.592	1.182	0.004	0.021	0.045	0.051
20% of RME	0.008	0.039	0.094	0.089	0.008	0.019	0.094	0.040	0.039	0.159	0.522	1.177	0.004	0.019	0.038	0.039
30% of RME	0.010	0.048	0.085	0.083	0.006	0.003	0.055	0.019	0.037	0.145	0.500	1.157	0.007	0.006	0.160	0.008
40% of RME	0.009	0.030	0.081	0.056	0.008	0.015	0.033	0.069	0.032	0.141	0.483	1.115	0.006	0.009	0.162	0.019

Table 8. Amounts of various pollutants *W*

Having performed these calculations, different harmful effect of pollutants to the environment is assessed. It is assessed in accordance with the aggressiveness indicator that is presented in table 9.

Pollutant	Aggressiveness indicator A
CO	1.0
NOx	41.1
CxHy	3.16
SP	300

Table 9. Aggressiveness indicators of pollutant

Conditional amounts of pollutants M assessing the different effect of each pollutant to the environment are calculated (table 10).

Fuel	CO, t/h				C_xH_y, t/h				NO_x, t/h				SP, t/h			
	Engine power, %				Engine power, %				Engine power, %				Engine power, %			
	0	25	50	75	0	25	50	75	0	25	50	75	0	25	50	75
diesel	0.011	0.047	0.102	0.087	0.007	0.024	0.051	0.051	1.511	9.730	25.847	51.534	1.471	6.250	13.476	13.997
10% of RME	0.010	0.022	0.115	0.081	0.005	0.042	0.040	0.125	1.292	9.121	24.321	48.596	1.127	6.344	13.487	15.349
20% of RME	0.008	0.039	0.094	0.089	0.026	0.060	0.296	0.128	1.591	6.536	21.467	48.357	1.074	5.551	11.396	11.774
30% of RME	0.010	0.048	0.085	0.083	0.018	0.010	0.175	0.060	1.503	5.953	20.531	47.568	2.146	1.745	48.087	2.330
40% of RME	0.009	0.030	0.081	0.056	0.024	0.048	0.104	0.217	1.320	5.806	19.866	45.818	1.934	2.772	48.644	5.708

Table 10. Conditional amounts of pollutants *M* having assessed aggressiveness

By adding these conditional amounts of pollutants *M*, it is possible to determine the most ecological composition of fuel: the lower the value *M*, the more ecological the fuel (table 11).

Fuel	Total amounts of pollutants
diesel	124.197
10 % of RME	120.075
20 % of RME	108.485
30 % of RME	130.333
40 % of RME	132.438

Table 11. Total amounts of pollutants M having assessed aggressiveness

Dependence of the total amount of pollutants on the percent of RME may be determined in accordance with the data of the table (fig. 25).

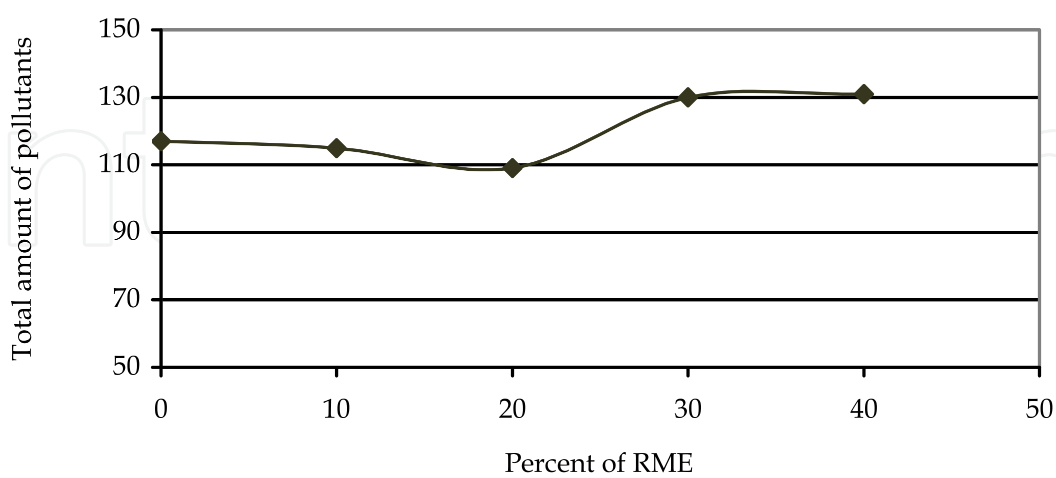


Fig. 25. Dependence of the total amount of pollutants on the percent of RME

It is obvious from table 11 and figure that the lowest total amount of pollutants is obtained when RME amounts to 20 %.

6. Conclusions

Having analyzed the results of the tests obtained, the following conclusions and recommendations may be presented:

1. Technically, there are no obstacles for using biodiesel in an engine that is not adapted to it, as physical characteristics of diesel and biodiesel (RME) are very similar. The only problem that may occur is shorter useful life of the rubber parts of the engine (hoses, sealing parts etc), which are not adapted specially, that have direct contact with fuel due to the acids contained in biodiesel.
2. Technologically, the ratio of RME and diesel is not important at all, as this fuel mixes well, does not form layers and stable mixtures are obtained.
3. Economic aspect.
   a. Under a low (up to 50 % P_{max}) load, fuel consumption increases in proportion to the amount of RME in the mixture; however, when the load increases more, fuel consumption approaches consumption of pure diesel, whereas it decreases by over 2 % when using the mixture containing 40 % of RME and diesel. Only the mixture containing 20 % of RME and diesel may be distinguished, as fuel consumption using it is 4 % higher than when using pure diesel at an average.
   b. An economic calculation assessing the pollution tax and the change of fuel consumption due to lower calorific value of biodiesel was carried out in order to determine expenses for fuel and showed that the highest expenses shall be incurred when using the mixture containing 20 % of RME (they shall increase by 1.48 % compared to diesel at an average), whereas the lowest shall be incurred when using the mixture containing 40 % of RME and diesel (they shall decrease by 1.55 % compared to diesel at an average). Expenses for fuel shall decrease by 1.14 % compared to diesel at an average when using the mixture containing 30 % of RME and diesel.
4. Environment protection aspect. Having measured the composition of oxides, calculated the values of pollutants and assessed different aggressiveness of pollutants, a total amount of pollutants was determined which showed that the most ecological fuel, having assessed all components of oxides, is the mixture containing 20 % of RME and diesel (value: 108.485), whereas the most polluting one is the mixture containing 40 % of RME and diesel.

With regard to fuel consumption measured, expenses calculated and having assessed harmfulness of pollutants, it may be maintained that the most rational option is to use the mixture containing 30 % of RME and diesel. Although expenses incurred when using this mixture are not the lowest and this mixture is not the most ecological one, it differs from the mixture containing 40 % of RME and diesel (expenses are the lowest for this mixture) only by 0.5 % with regard to expenses, whereas it is in the middle with regard to the estimates of harmfulness of pollutants: between the most ecological and the most polluting mixtures when calculating in one manner and is only by approximately 3.5 % more polluting than then most ecological mixture when calculating in another manner.

7. References

A Comprehensive Analysis of Biodiesel Impact on Exhaust Emissions. Draft Technical Report. Environmental Protection Agency, EPA420-P-02-001. October 2002

ADEME (1999). Referentiel pour le calcul des bilans energetiques. Production Agricole. Project de brochure. Paris, 1999

Available from http://biodiesel.ag.uidaho.edu/main/information.html

Available from http://www.greenfuels.org

Available from http://www.vegievan.org/biodiesel.html

Available from http://www.caddet–ee.org

Available from http://www.oceanairenvironmental.com

Council Directive 2003/96/EC of 27 October 2003 on restructuring the Community framework for the taxation of energy products and electricity. OJ L283, 2003, p. 51–70

Council Regulation (EC) No. 1782/2003 of 29 September 2003 on establishing common rules for direct support schemes under the common agricultural policy and establishing certain support schemes for farmers and amending Regulations (EEC) No. 2019/93, (EC) No. 1452/2001, (EC) No. 1453/2001, (EC) No. 1454/2001, (EC) No. 1868/94, (EC) No. 1251/1999, (EC) No. 1254/1999, (EC) No. 1673/2000, (EEC) No. 2358/71 and (EC) No. 2529/2001. OJ L203, 2003, p. 1

Directive 2003/03/EC of the European Parliament and the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport. OJ L 123, 2003, p. 42–46

Energy for the future: Renewable sources of energy. White paper for a Community strategy and action plan. Communication from the Commission (COM (97) 0599-C4-0047/98)

Engler, C. R.; Lepori, W. A.; Johnson, L. A.; Yarbrough, C. M. (1992). Processing requirements form plant oils as alternative diesel fuels // *Proc. of an Alternative Energy Conference. Liquid fuels from renewable resources.* St. Joseph, MI, p. 79–88

European Biodiesel Board. Avenue de Tervuren, 363 - 1150 Bruxelles – Belgium. Available from http://www.ebb-eu.org/ebbstyle.css

Industrial use of rape for biodiesel production in the Czech Republic. Prague, 1997

Janulis, P.; Makarevičienė,V. (2004). Biodegalų ir bioalyvų naudojimas Lietuvoje (Use of biofuel and bio oils in Lithuania). Vilnius. p. 72

Kerstin, G. (1999). H–D Vehicle Exhaust Emissions and Alternative Fuels // MTC AB

Krahl, J.; Munack, A.; Bahadir, M.; Schumacher, L. (1996). Survey about biodiesel exhaust emissions and their environmental effects // Liquid fuels and industrial products from renewable resources: *proceedings of the Third fuel conference*. Michigan, p. 136–148

Kyoto Protocol to the United Nations Framework Convention on Climate Change. UNFCCC, 1997 (FCCC/CP/1997/L.7/Add.1, December 1997)

Labeckas, G.; Slavinskas, S. (1998). Biodegalų naudojimo dyzeliniame variklyje tyrimas // Transporto technologijų tyrimai, kūrimas, energetinių resursų taupymas ir aplinkosauga (Research on use of biogas in a diesel engine // Research and development of transport technologies, saving energetic resources and environment protection). *Material for the national conference*. Vilnius, p. 409–415

Lingaitis, L. P.; Pukalskas, S. (2008). Ecological aspects of using biological diesel oil in railway transport / Leonas Povilas Lingaitis, Saugirdas Pukalskas // *Transport*. Vilnius: Technika. ISSN 1648-4142. 23(2): 138–143

Lingaitis, L. P.; Pukalskas, S. (2008). The economic effect of using biological diesel oil on railway transport / Leonas Povilas Lingaitis, Saugirdas Pukalskas // *Transport*. Vilnius: Technika. ISSN 1648-4142. 23(4): 287–290

Lingaitis, L. P.; Pukalskas, S. (2007). Determining the consumption of biodiesel by locomotive engines / L. P. Lingaitis, S. Pukalskas // *Transport Means - 2007: proceedings of the 11th international conference*, 18–19 October 2007. Kaunas University of Technology, Lithuania / Kaunas University of Technology, IFTOMM National Committee of Lithuania, SAE Lithuanian Branch, The Division of Technical Sciences of Lithuanian Academy of Sciences, Klaipėda University, Vilnius Gediminas Technical University. Kaunas: Technologija. ISSN 1822-296X. 2007, p. 194–197

LST EN 14214 Automotive fuels. Fatty acid methyl esters (FAME) for diesel engines. Requirements and test methods.

LST EN 590:2004 Automotive fuels. Diesel. Requirements and test methods

Makarevičienė, V. (2001). Rapsų aliejaus riebalų rūgščių etilesterio gavimas, vartojimas degalais ir poveikis aplinkai (Production of rapeseed oil fatty acid methyl ester, use as a fuel and impact on environment): *doctoral thesis*. Kaunas: LŽŪU. p. 113

Makarevičienė, V.; Pukalskas, S.; Janulis P. (2001). Palyginamieji rapsų aliejaus etil- ir metilesterių deginių emisijos tyrimai // *Aplinkos inžinerija* (Comparative research on emission of oxides of rapeseed oil ethyl- and methyl esters // *Environmental engineering*). Vilnius: Technika, 9(3): 158–163

Makarevičienė, V.; Sendzikiene, E.; Janulis, P. (2005). Solubility in multicomponent biodiesel fuel system // *Bioresource technology*. 96(5): 611–616

Peterson, C. L.; Reece, D. I.; Cruz, R.; Thompson, J. (1992). A comparison of ethyl and methyl esters of vegetable oils as diesel fuel substitutes // *Proc. of an Alternative Energy Conference.* Liquid fuels from renewable resources. St. Joseph, MI, p. 99–110

Rules on trade in oil products, biofuel, bio oil and other combustible liquid products in the Republic of Lithuania. "*Žin.*", 2001, No 37-1269, 2003 No 36-1596, No 121-5506

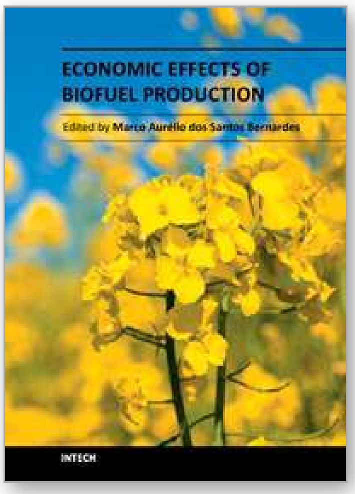
Wang, W. G.; Clark, N. N.; Lyons, D. W. (1997). Emissions comparisons from alternative fuel buses and diesel buses with a chassis dynamometer testing facility // *Environmental Science & Technology*. ISSN: 0013–936X., 31: 3132–3137

Worldwide Review on Biodiesel Production. (2003). IEA Bioenergy Task 39 Subtask "Biodiesel". Austrian Biofuels Institute. p. 92

Xiao, Z.; Ladommatos, N.; Zhao, H. (2000). The effect of aromatic hydrocarbons and oxygenates on diesel engine emissions // Proceedings of the institution of mechanical engineers part D-*Journal of automobile engineering*. ISSN: 0954-4070., 214(D3): 307–332

Zelenka, P.; Kriegler, W.; Herzog, P. L.; Cartellieri, W. P. (1990). Ways toward the clean heavy-duty diesel // SAE Tech. Pap. Ser. Nr. 900602. p. 13

Zubr, J.; Matzen, R. (1996). Mixed vegetable and diesel oil as fuel // 9th European Bioenergy Conference, 1st European Technology Exhibition on Biomass for Energy, Copenhagen, 24–27 June. p. 10



Economic Effects of Biofuel Production

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