TRANSPORT PROBLEMS 2025 Volume 20 Issue 1
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2025.20.1.14

Keywords: exhaust gases; pollutant; diesel fuel; rapeseed methyl ester

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REDUCING THE ENVIRONMENTAL AGGRESSIVENESS OF DMU ENGINES' EXHAUST GASES BY USING BIODIESEL

Summary. Many research results have been published in scientific works on the effect of rapeseed methyl ester diesel fuel additives on the composition of pollutants. This article examines this effect using multi-criteria decision-making methods. This study also evaluates the aggressiveness of various diesel engine pollutants. The findings identify the optimal RME proportion in diesel fuel, considering the overall harmfulness of pollutants. The results before and after assessing pollutant aggressiveness are compared.

1. INTRODUCTION

Studies have shown that using rapeseed methyl ester (RME) as a fuel additive in diesel can reduce the toxicity of engine emissions [1]. If diesel fuel with alcohol-based additives is used, a decrease in carbon monoxide and oxides of nitrogen pollution is observed, but hydrocarbon emissions increase [2]. RME has been found to have favorable combustion properties, which can lead to efficient engine performance [3]. The high cetane number of RME improves ignition quality and combustion efficiency [4]. RME is biodegradable and non-toxic, reducing the environmental impact of spills. RME is prone to oxidation, affecting fuel stability and storage [5]. Various scientific researches are carried out not only on two-component but also on three-component fuels [6].

Studies have shown that when fuel additives are used in a spark ignition engine, their effectiveness can be easily adjusted by the ignition angle, while in a diesel engine, this process is more difficult to control [7]. Meanwhile, in a diesel engine, it is possible to change the injection moment, which, as research shows, also affects the reduction of pollution [8]. Changing the injection moment works differently with different fuel mixtures [9]. Most studies indicate that it is necessary to adjust the engine parameters when using alternative fuels and their additives in a diesel engine [10].

It has been established that the toxicity of exhaust gases depends on the composition and quality of the diesel fuel (specifically, on the sulfur content in the diesel fuel) and the effectiveness of the nanoparticle additives used [3]. Low-sulphur diesel fuel can be used as an emulsion with water, which significantly reduces the number of solid particles emitted [11]. The number of solid particles also decreases when diesel fuel is mixed with kerosene [12]. The emission of solid particles can be reduced by using a catalyst system, but depending on the fuel type, the corresponding catalyst systems are required [13].

Using an artificial neural network, a 2% isopropanol + RBME additive is the best for achieving optimum diesel engine performance [14]. It has been observed that the multi-layer perception neural network is well suited for this [15]. Nanoparticle additives can be used in diesel engines, depending on their operating conditions. Sometimes, they produce a similar effect as the RME additive [16]. It has been observed that the amount of solid particles is effectively reduced by adding aluminum nanoparticles to diesel fuel [17]. It has been found that different nanoparticles are suitable for different fuels – for

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example, calcium oxide particles can be used for a mixture of diesel with sunflower oil [18]. However, when sunflower oil is used, the engine's performance parameters change, and it needs to be adjusted [19]. In addition, fuels with nanoparticle additives sometimes have instability problems [20]. Other additives can be used to increase stability, but these affect combustion properties [21].

Railways operate electric and diesel passenger trains. Wagons can be pulled by a diesel locomotive or can be formed by a diesel multi-unit (DMU). DMUs are generally used to transport suburban passengers. Since DMUs operate in densely populated areas, it is critical to minimize their impact on the environment. A crucial factor is the environmental impact of diesel engine emissions. One of the aspects is the effect of the use of alternative fuels in the DMU (including the RME ratio in the fuel) and its exhaust gas composition. The purpose of the present study is to determine the most environmentally friendly ratio of diesel fuel to RME based on estimated changes in the amount of pollutants in question. Experimental research was carried out on behalf of the Lithuanian Railways in cooperation with VILNIUS TECH scientists. Experimental studies were carried out in closed rooms. The engines used in DMUs can vary in size, construction, and power.

The 12VFE17/24 diesel train engine was used in this experiment. Such an engine is used in DMUs with up to three wagons; if a DMU has more than three wagons, two engines can be used (installed in the rear wagon of the DMU with a driver's cabin). The main characteristics of the engine are given in Table 1.

Table 1

Technical specifications of diesel train engine 12VFE17/24

No	Indicator	Meaning
1.	Type	four-stroke, V-shaped
2.	Number of cylinders	12
3.	Engine revolutions, min^{-1}	550–1250
4.	Degree of compression	13.6
5.	Rated power, kW	538
6.	Engine displacement capacity, l	65.3
7.	Comparative fuel consumption, g/(kW h)	225+8%

Table 1 shows that the engine is more powerful than usual in car transport. The engine consists of 12 cylinders, and the power reaches more than 500 kW (we can meet such power of diesel engines on ships). The engine is a four-stroke engine (two-stroke engines also occur on railway rolling stock). There is an impressive engine displacement of more than 60 liters. The speed of the crankshaft is relatively small, at up to 1250 revolutions per minute. The fuel consumption of 225 g/(kWh) is neither very high nor very low compared to other diesel engines. In other words, the utilized engine is a typical rolling stock diesel engine.

2. THE COURSE OF THE EXPERIMENT

The course of the ongoing research is depicted in Fig. 1. The engine was anchored in the engine test stand. The control panel of the stand regulated the engine load and speed. Diesel fuel that meets the requirements of the LST LT EN 590 standard and biodiesel (RME) that meets the requirements of the LST EN 14214 standard were used for the tests. The proportions of RME in biodiesel were 10%, 20%, 30% and 40%. A chromatograph (SRI 8610) and an electrochemical device (Testo 350-M/XL) were used for the exhaust gas composition analysis. The amount of solid particles (SP), nitrogen oxides (NO_x), hydrocarbons (C_xH_y), carbon monoxide (CO), and carbon dioxide (CO_2) were measured. During the tests, the temperature of the engine cooling thermal agent varied from 70 to 80 °C. Tests were performed with different RME mixtures (RME content from 10–40%) and four different engine load modes. Each test was repeated three times, and the arithmetic mean of the results was taken for further research.

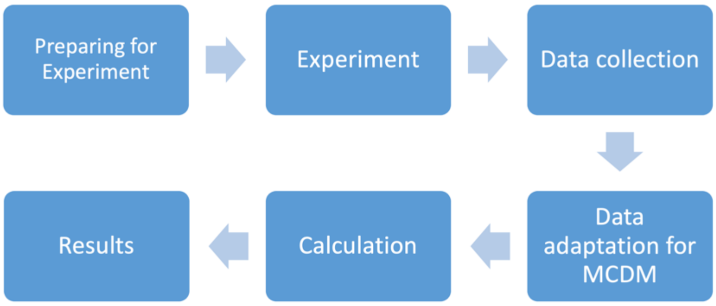

Fig. 1. Block scheme of the study

The results of the DMU engine experiment are presented in Table 2. Changes occurred in the quantities of SP, NO_x, C_xH_y, CO, and CO_2 compared to the corresponding emissions using pure diesel fuel.

Table 2

Variation in DMU engine emissions using different fuel mixtures of diesel and RME

	Engine load, %	Amount of RME of the fuel mixture, %			
		10	20	30	40
Difference CO, %	0	-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 2 reveals that the pollutant levels from diesel and RME fuel mixtures did not consistently decrease or increase. Consequently, Table 2 contains both positive and negative values. When applying multi-criteria evaluation methods, it is necessary to eliminate the negative values, as these methods typically do not handle negative numbers.

3. DATA PROCESSING METHODOLOGY

To eliminate the negative values of the indicators in the table, the authors proposed a methodology by introducing a pollution change indicator. This indicator was calculated for each pollution component separately:

$$Q_{ij} = -(P_{ij} - P_{max}), \quad (1)$$

where: P_{ij} – the difference in the amount of the pollution component compared to the emissions of an engine using pure diesel, % (indexes i and j correspond to the column and row number of the amount of RME of the fuel mixture values in Table 2 and Table 3), P_{max} – the maximum value of the difference in the amount of the pollution component, %.

Calculation results of the pollution change indicator (PCI) according to the methodology developed by the authors are presented in Table 3 below.

Table 3

Values of the pollution change indicator

	Engine load, %	Amount of RME of the fuel mixture, %			
		10	20	30	40
Difference CO, %	0	20.9	34.3	16.8	28.7
	25	65.2	29.2	9.8	47.9
	50	0	20.1	28.4	32.3
	75	19.1	10.1	16.8	47.4
Difference CO_2, %	0	20.8	22.3	21.6	27.3
	25	23	15.2	34.3	19.5
	50	14.4	17.8	17.4	19.7
	75	14.7	0	11.8	12.4
Difference C_xH_y, %	0	510.1	194.8	318.7	226.7
	25	404.8	327.7	536.6	376.3
	50	501.1	0	235.6	374.4
	75	331.4	326.4	459.3	149.8
Difference NO_x, %	0	19.8	0	5.8	18
	25	11.6	38.1	44.1	45.6
	50	11.2	22.2	25.9	28.4
	75	11	11.5	13	16.4
Difference SP, %	0	284.4	287.9	215	229.5
	25	259.5	272.2	333.1	316.7
	50	260.9	276.4	4.2	0
	75	251.3	276.9	344.4	320.2

It is recommended to apply multi-criteria decision-making methods when generalizing the influence of RME on the formation of pollutants. There are several suitable methods for this, such as sum of ratings (SoR), geometrical means (GM), and simple additive weighting (SAW). The authors opine that the method of geometric means would be the most suitable for the preliminary evaluation of the research results.

The first step was to assess the effect of RME as a percentage of engine load. For this purpose, the average values of the indicator were calculated for all the fuel blends considered. The results of this generalization are shown in Table 4.

It is convenient to analyze the data in Table 4 for each row since the logical meaning and scale of the numbers given in each line are mutually adequate. Comparing numbers in different rows may seem impossible since their scale varies substantially, and it is impossible to summarize such figures. However, in mathematics, there is a way to summarize the results in this case—namely, by normalizing them. That is, the amounts can be calculated based on each line, and each value can be taken as its ratio to the string sum. In this way, the numbers will be from 0 to 1 in all rows, and their proportions will be the same as the numbers before normalization. Such figures can also be summarized.

Table 4

Mean of the pollution change indicator after aggregation by fuel composition

	Difference CO, %				Difference CO_2, %				Difference C_xH_y, %				Difference NO_x, %				Difference SP, %			
Engine load, %	0	25	50	75	0	25	50	75	0	25	50	75	0	25	50	75	0	25	50	75
Mean of pollution change indicator	25.175	38.025	20.2	23.35	23	23	17.325	9.725	312.575	411.35	277.775	316.725	10.9	34.85	21.925	12.975	254.2	295.375	135.375	298.2

As the values in the table are scaled differently (some values are measured in tens, others in hundreds), it is appropriate to analyze them graphically in a normalized form. The normalized values of the pollution change indicator after aggregation by fuel composition are shown in Fig. 2.

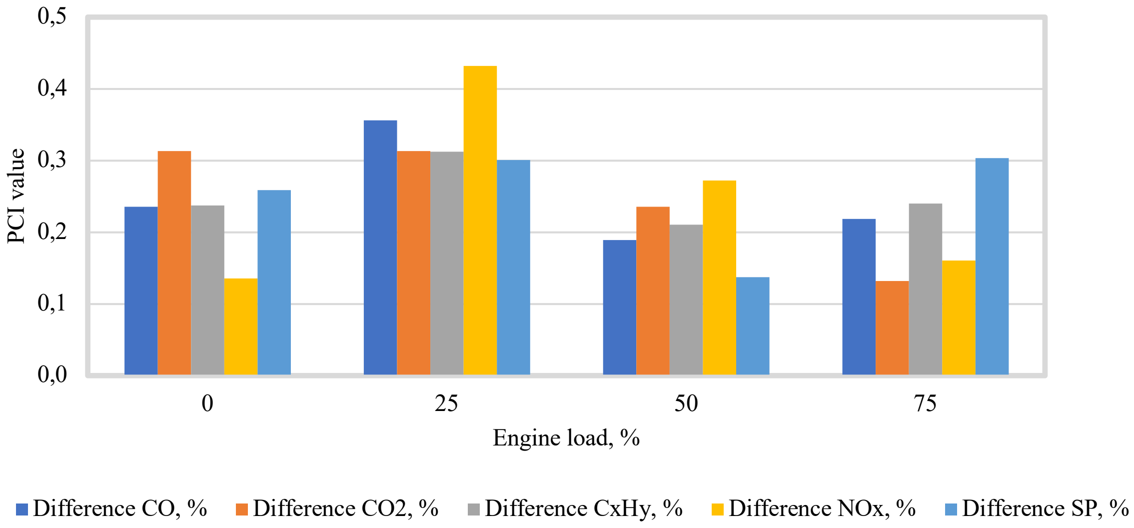

Fig. 2. Normalized values for the PCI after aggregation by fuel composition

The graph shows that the greatest reduction in CO emissions occurred at 25% engine load. The same applies to the reduction in CO_2 and C_xH_y emissions. The greatest reduction in NO_x emissions was also observed at average engine loads of 25% and 50%. The reduction in solid particulate emissions was the greatest at maximum engine power (75% and above) and was significant at 25% engine load.

The impact of RME was then assessed by observing the percentage composition of the fuel. For this purpose, the average values of the indicator were calculated for all engine loads. The results of this aggregation are shown in Table 5.

Table 5

Mean of the pollution change indicator after aggregation by engine load

	Amount of RME of the fuel mixture, %			
	10	20	30	40
Difference CO, %	26.30	23.43	17.95	39.08
Difference CO_2, %	18.23	13.83	21.28	19.73
Difference C_xH_y, %	436.85	212.23	387.55	281.80
Difference NOx, %	13.40	17.95	22.20	27.10
Difference SP, %	264.03	278.35	224.18	216.60

Before the data in Table 5 can be summarized, they need to be normalized for the same reason as the data in Table 4. This process transforms all table values to a scale of 0 to 1 while preserving their proportions, allowing for effective summarization. The normalized values of PCI after aggregation by engine load are shown in Fig. 3.

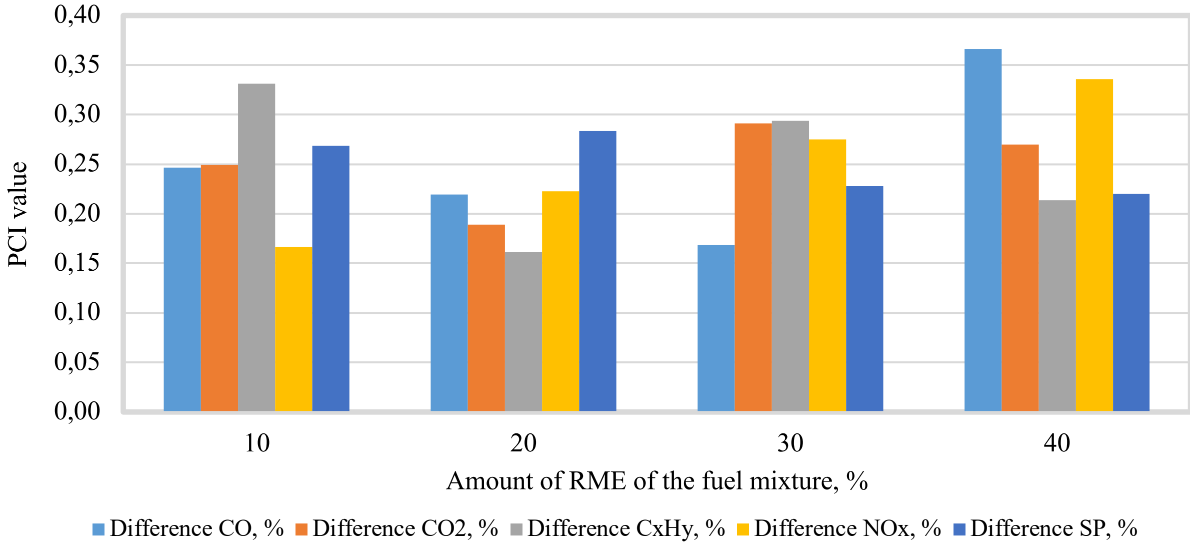

Fig. 3. Normalized values for PCI after aggregation by engine load

The graph shows that the greatest reduction in CO emissions occurred when the diesel and RME mixture comprised 40% RME. The greatest reductions in CO_2 and NO_x emissions were observed at 30% and 40% RME. The reduction in C_xH_y emissions was highest at 10% and 30% RME. The reduction in solid particulate emissions was highest at 10 to 20 % RME.

The geometric mean Π_j of the normalized values of all indicators (Table 6) was determined using the following formula:

$$\Pi_j = \sqrt[m]{\prod_{i=1}^{m} \omega_i}, \tag{2}$$

where m is the quantity of pollutant types (SP, NO_x, C_xH_y, CO_2, and CO; equal to 5). When maximizing, the largest value of the criterion Π_j is the best. The results of the calculations using the multi-criteria decision-making method are presented in Table 6. A diagram of the normalized PCI based on the data presented in Table 6 is provided in Fig. 4.

Fig. 4 shows that the optimal result was achieved with a diesel and RME mixture containing 40% RME. The second-best result was achieved with 10% RME, followed by 30% RME, and the least effective result was achieved with the 20% RME mixture. More detailed studies on the use of RME in diesel engines for railway rolling stock should evaluate emission levels and their environmental harmfulness. This can be assessed using the aggressiveness indicator [22], with normalized values provided in Table 7.

The simple additive weighting method was used for further evaluation. The sums S_j of the normalized values of all indicator estimates (SAW) for each j-th object were calculated using the formula below:

$$S_j = \sum_{i=1}^{m} \omega_i \cdot r_{ij}, \tag{3}$$

where: ω_i – the size of the i-th indicator estimate; r_{ij} – the importance coefficient of the i-th indicator for the j-th object. The best value of the criterion S_j is when it is the largest. The results of the calculations using the SAW multi-criteria decision-making method are given in Table 8.

Fig. 5 shows that, considering the aggressiveness of pollutants, the best result was achieved when the mixture of diesel and RME contained 20% RME. The next-best result was achieved by the mixture with 10% RME, followed by the mixture with 40% RME and the mixture with 30% RME. The results were obtained before and after the assessment of whether the aggressiveness of pollutants was fundamentally different. Thus, determining the amount of emissions and accurately assessing the aggressiveness of pollutants remains a critical issue.

Table 6
Calculation results using the GM multi-criteria decision-making method

Pollutant	Fuel mixture			
	10 % RME	20 % RME	30 % RME	40 % RME
SP	0.269	0.283	0.228	0.220
NO_x	0.166	0.223	0.275	0.336
C_xH_y	0.331	0.161	0.294	0.214
CO_2	0.249	0.189	0.291	0.270
CO	0.246	0.219	0.168	0.366
Geomean Π_j	0.2464	0.2113	0.2461	0.2747

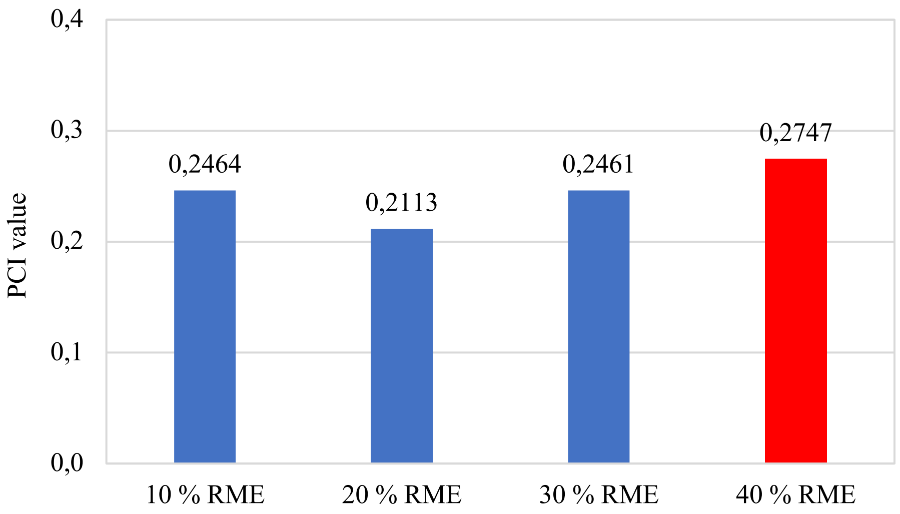

Fig. 4. Diagram of the change in normalized PCI

Table 7
Indicators of the aggressiveness of pollutants

Pollutant	Indicator of aggressiveness	Normalized indicator of aggressiveness
CO	1.0	0.0029
NO_x	41.1	0.1190
C_xH_y	3.16	0.0092
SP	300	0.8689

Fig. 6 shows that locomotives operate mostly with medium and maximum engine loads, which made it possible to assess emission changes based on the maximum engine load. However, for a more accurate study, it is necessary to evaluate the percentage distribution of engine load time. Calculations were made where previously obtained values were multiplied by the obtained engine operating time coefficient values. Considering the distribution of engine load time, it can be seen how the indicator changes according to the composition of RME mixtures (Fig. 7).

Table 8

Calculation results using the SAW multi-criteria decision-making method

Pollutant	Fuel mixture			
	10 % RME	20 % RME	30 % RME	40 % RME
CO	0.00071	0.00064	0.00049	0.00106
NOx	0.02756	0.03702	0.04565	0.05578
C_xH_y	0.00305	0.00148	0.00270	0.00197
SP	0.23373	0.24590	0.19811	0.19116
SAW	0.26505	0.28503	0.24695	0.24996

A graphical interpretation of the data in Table 8 is presented in Fig. 5.

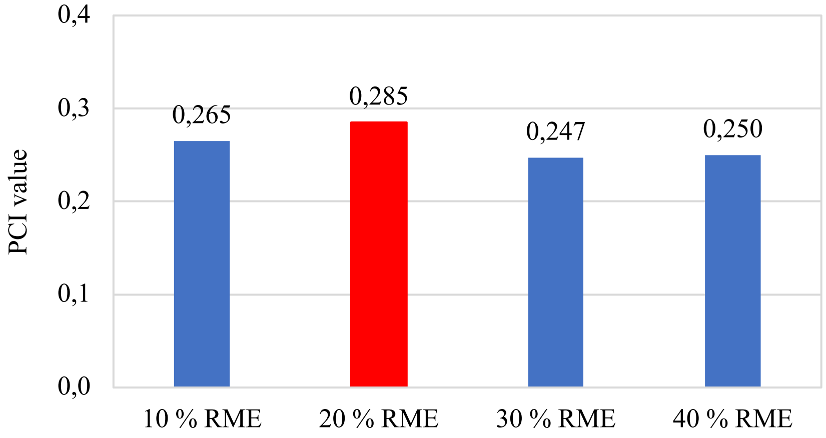

Fig. 5. Diagram of the change in normalized PCI according to the pollutant's aggressiveness

As shown in Fig. 7, the largest PCI changes occurred with a 40% RME and diesel mixture, followed by a 30% RME mixture. Comparing this with the data presented in Fig. 5 shows that without considering the engine load working time distribution, the best PCI occurred at 20% RME; when considering it, the best PCI occurred at 40% RME. Fig. 8 was created to illustrate the impact of engine load on PCI changes, taking into account its duration.

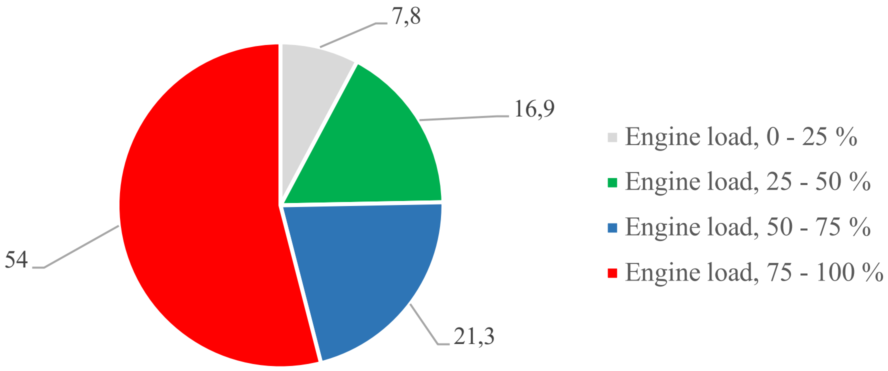

Fig. 6. Diagram of distribution of locomotive operating time by engine loads

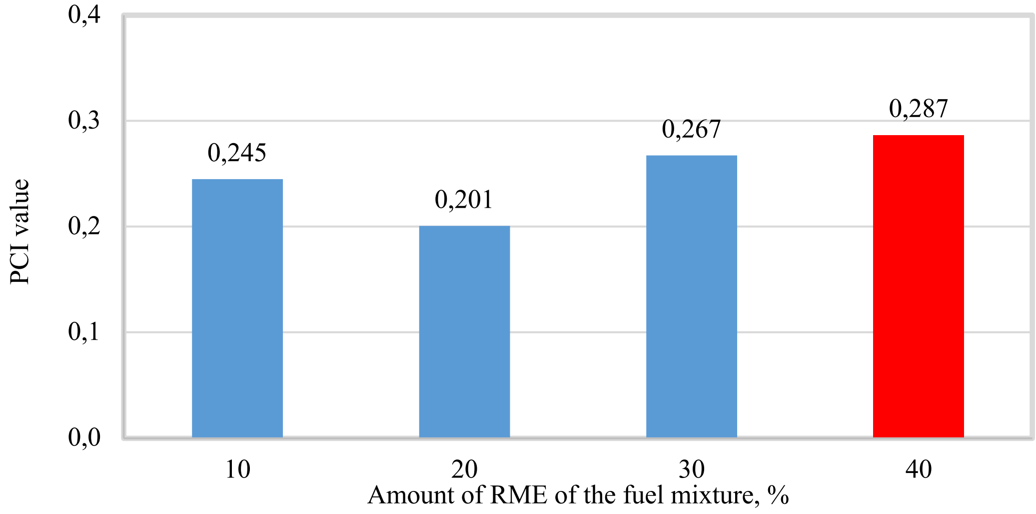

Fig. 7. Diagram of the change in normalized PCI according to the amount of RME

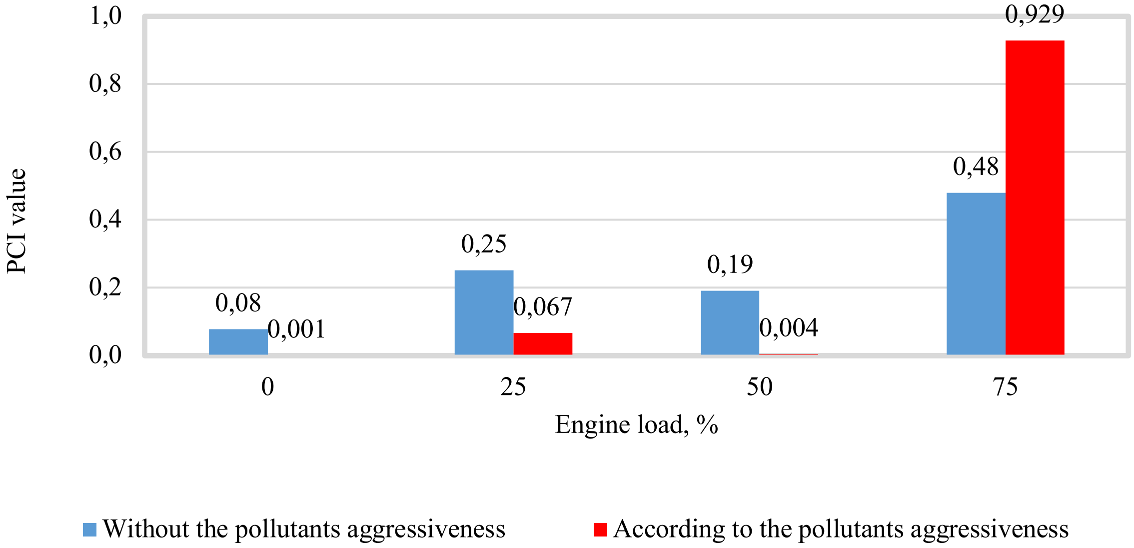

Fig. 8. Diagram of the change in normalized PCI according to the distribution of operating time

The data in Fig. 8 show that the largest variation in the pollution change indicator, both considering and not considering the aggressiveness of pollutants, occurred when the engine load was 75% or more. Based on this load, there is a need to evaluate the changes in PCI according to the percentage of RME. Fig. 9 presents the PCI results obtained after calculations were performed at a 75% engine load.

Fig. 9 shows that the best results were achieved with a 40% RME and diesel mixture, followed by a 30% mixture. The 20% RME mixture had the weakest impact on the PCI value.

In summary, this study first evaluated the reduction of individual engine pollutants at different engine loads while varying the RME and diesel mixture composition from 10% to 40% RME. Multi-criteria decision-making methods were applied to summarize the results under the assumption that all pollutants have an equal impact on the environment. Subsequently, the aggressiveness of these pollutants was assessed. The final results were obtained by evaluating the time distribution of engine operation under different loads.

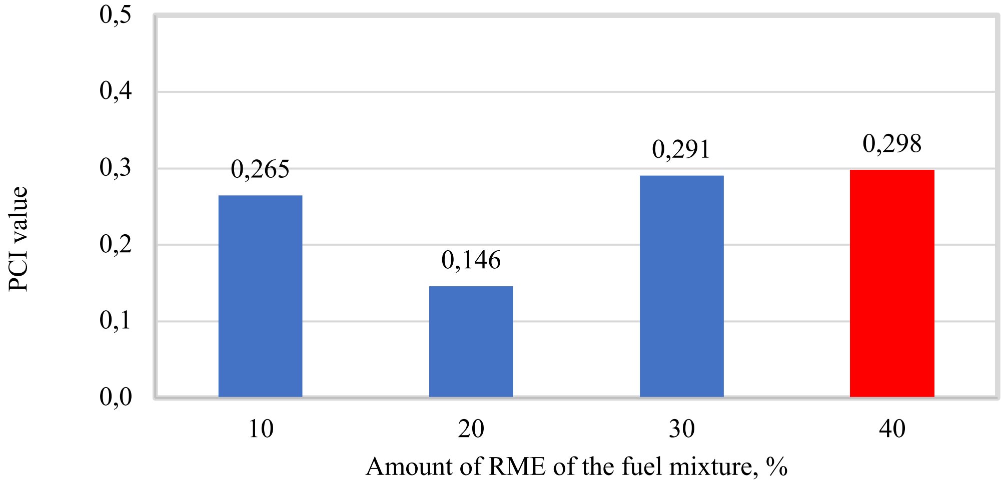

Fig. 9. Diagram of the change in normalized PCI according to the amount of RME when engine load was 75%

4. CONCLUSIONS

1. The analysis of scientific works showed that the problem of diesel engine emissions is studied in the example of car engines, but less attention is paid to diesel engines used in rolling stock. Therefore, an exhaust gas research experiment with a diesel train engine was carried out to examine the use of RME mixtures.
2. During the experiment, the difference in the amount of pollutants released when using fuel mixtures was determined and compared with the pollutants of the engine using pure diesel. These differences were expressed as both positive and negative numbers. Regarding the adaptation of the test results to multi-criteria evaluation methods, the authors propose a methodology that introduces the pollution change indicator Q_{ij}, which is always expressed only in positive numbers.
3. The analysis of the experimental data using the GM multi-criteria method revealed that the best results were achieved with a mixture containing 40% RME, followed by the 10% RME mixture, 30% RME mixture, and 20% RME mixture.
4. Studies on the use of RME in rolling stock diesel engines evaluated the amount of emissions and their aggressiveness index to more accurately determine the harmfulness of emissions to the environment.
5. The evaluation of the aggressiveness of pollutants revealed that the best result was achieved when the mixture of diesel and RME contained 20% RME, followed by 10% RME, 40% RME, and 30% RME.
6. The analysis of the time distribution of engine operation under different loads revealed that the engine usually operated at 75% load or higher (more than 54% of the time). The best results were achieved with a mixture containing 40% RME, followed by 30% RME, 10% RME, and 20% RME.
7. The results obtained before and after assessing the aggressiveness of pollutants were fundamentally different, indicating the importance of assessing the aggressiveness of pollutants.

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Received 25.08.2023; accepted in revised form 12.03.2025