

Article

Analysis of Biodiesel Influence on Unregulated Gaseous Emissions of Diesel Motor Vehicles

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Abstract: This scientific study is focused on the analysis of an influence of the experimental diesel fuel mixtures containing various portions of the biocomponent on the unregulated gaseous emissions generated by a diesel motor vehicle, which is equipped with the diesel engine utilizing the direct fuel injection system “common rail”. The main reason for the choice of this engine type was its wide usage in the current vehicles. The experimental diesel fuel mixtures were created as a mixture of the standard low-sulfur diesel fuel with the biodiesel, using various mixing ratios. The experiments were realized by means of a special 13-regime engine test cycle, which was intentionally developed for the diesel combustion engines. All the individual experiments were performed on the base of the given test cycle with 13 different operational modes. The obtained results offer a complex view on the generation of the unregulated emissions with regard to the operational conditions and taking into consideration operational loading of the given experimental engine.

Keywords: analysis; biodiesel; unregulated emissions; motor vehicles



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1. Introduction

Constantly growing energy consumption and the degradation of environmental quality require the search for alternative fuels in order to replace the petroleum fuels that are used nowadays in motor vehicles. One of the most often applied alternative fuels is biodiesel. The main advantage of biodiesel is its renewability and reduction in greenhouse gases [1]. Biodiesel can be used either in its pure form or in the form of diesel mixtures. For that reason, there have been various studies focused on diesel engines, which combust diesel mixtures. In general, it is possible to say that the application of biodiesel causes an increase in fuel consumption, reduction in HC emissions, CO emissions and particulate matter emissions as well as a moderate higher amount of NO_x emissions [2–6]. The influence of unregulated emissions was also investigated by Sharp et al. [7] using three diesel engines. They recorded the reduced emissions of hydrocarbon and acetaldehyde. The USEPA [8] also presents lower levels of acetaldehyde, formaldehyde and xylene. According to McGill et al. [9] the interesting unregulated emissions, namely aldehyde and 1,3-butadiene, are almost independent on the kind of fuel. Di et al. [10] performed investigations with the following results: the reduced amount of formaldehyde, 1,3-butadiene, toluene and xylene, and the increased amount of acetaldehyde and benzene. Lapuerta et al. [11] stated a lack of published scientific research information concerning the impact of biodiesel on unregulated emissions. Taking into consideration all the above-mentioned facts, we can say that it is necessary to carry out another scientific research works oriented around unregulated gaseous emissions of automotive diesel engines. In order to supplement a gap of knowledge in this area, in our study, the unregulated gaseous emissions of diesel engines are investigated by means of a special 13-regime test cycle, which was directly developed for the diesel engine. The analyzed unregulated emissions

include formaldehyde, acetaldehyde, 1,3 butadiene, propene, benzene, toluene and xylene. All these matters are classified as substances harmful for the atmosphere.

2. Experiment Conditions

The practical base for the experimental measurements created a diesel engine equipped with a direct fuel injection system of the common rail type, which is normally installed in a wide range of diesel engine vehicles. The tested diesel mixtures were achieved by mixing biodiesel with pure diesel using various mixing ratios. The pure diesel fuel contained less than 10 ppm of the sulfur, such that it was the so-called ultra-low sulfur diesel (ULSD-F). Biodiesel was obtained from waste oil according to the valid European standard EN-14214. The individual diesel mixtures were determined, taking into consideration the previous experiments, as follows: B-U (25:75) (25% biodiesel and 75% ULSD-F), B-U (50:50), B-U (75:25). The most important technical parameters of the tested diesel engine are summarized in Table 1.

Table 1. The experimental engine parameters.

Type	4-Cylinders, Common-Rail Diesel
Compression ratio (CR)	16.2:1
Bore × stroke	81 × 95.5 mm
Displacement	1968 cm ³
Rated output	110 kW
Engine speed	3500–4000 rpm

The experimental testing system was created by the placement of the tested diesel vehicle engine on the testing dynamometer according to Figure 1. The gas analyzer was used to perform analysis of regulated gaseous emissions, i.e., for the analysis of nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM).

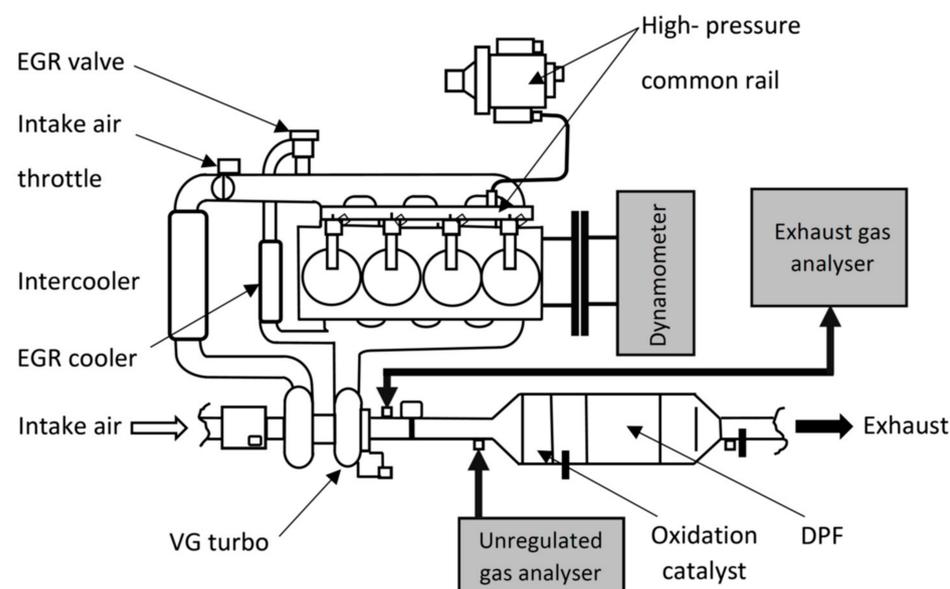


Figure 1. The experimental system.

Analysis of unregulated emissions (such as acetaldehyde, 1,3-butadiene, formaldehyde, ethene, propene and BTX hydrocarbons) was performed using the multi-component gas analyzer. The calibration of this analyzer was repeated before each measurement. The fuel consumption was measured by the electronic flowmeter. The characteristics of the experimental biodiesel and ULSD-F are presented in Table 2.

Table 2. The characteristics of the experimental fuels.

	Biodiesel	ULSD-F
Density, 15 ($\text{kg}\cdot\text{m}^{-3}$)	860 ÷ 920	820 ÷ 845
Viscosity (40 °C) ($\text{mm}^2\cdot\text{s}^{-1}$)	3.8 ÷ 5.1	1.9 ÷ 4.1
Cetane number	min 55	min 47
Sulphur content ($\text{mg}\cdot\text{kg}^{-1}$)	max 10	max 10
Heat of evaporation ($\text{kJ}\cdot\text{kg}^{-1}$)	252 ÷ 295	285 ÷ 338
Flash point (°C)	103	82
Carbon content (wt %)	81.6	97.2
Hydrogen content (wt %)	12.4	13.4
Oxygen content (wt %)	10.5	0

The European Stationary Cycle (ESC) was used in order to analyze the influence of the fuel mixtures on the gaseous emissions. The ESC testing parameters are described in Table 3 and in Figure 2. The first regime of the testing process measurement was the stable operation of the tested engine. This first phase is characterized by the constant temperature of the coolant, lubricating oil and exhaust gases. Afterwards, the engine operational parameters were monitored at five-minute intervals; namely in the form of mean values of the measured operational parameters. The experiments were repeated two times with regard to the elimination of potential random failures. The results obtained from the experiments agree with the 97% confidence level.

Table 3. The European Stationary Cycle (ESC) test regimes.

Mode	Engine Speed	Load (%)	Weight (%)	Duration (min)
1	Low idle	0	15	4
2	A	100	8	2
3	B	50	10	2
4	B	75	10	2
5	A	50	5	2
6	A	75	5	2
7	A	25	5	2
8	B	100	9	2
9	B	25	10	2
10	C	100	8	2
11	C	25	5	2
12	C	75	5	2
13	C	50	5	2

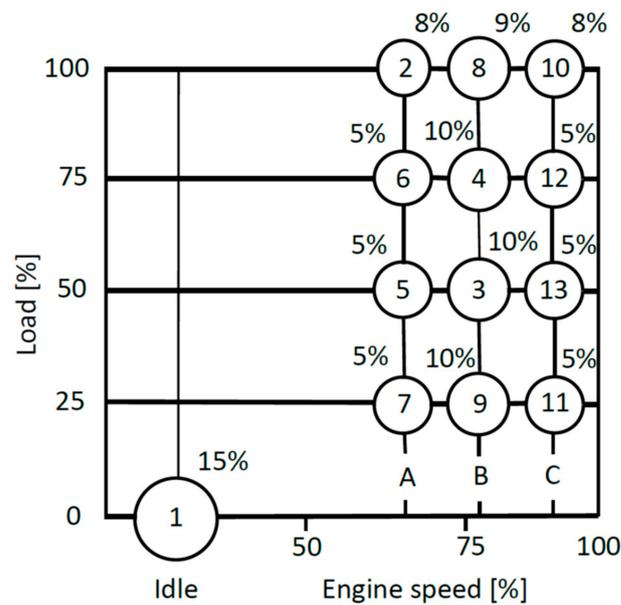


Figure 2. European Stationary Cycle (ESC).

3. Results and Discussion

3.1. Parameters of the Experimental Engine

Table 4 presents the fuel consumption (FC), given in kg/h, for the individual fuel mixtures. The values of the brake thermal efficiency (BTE) were calculated using data of the engine speed, torque and fuel consumption. It is evident that the combustion of biodiesel increases the fuel consumption, because the biodiesel heat value is lower compared to the standard diesel fuel. At the same time, the combustion of biodiesel increases the BTE thanks to a higher amount of oxygen in this fuel, which has a positive effect on the speed and quality of the combustion process. It is also possible to say that a higher level of the engine speed also increases the fuel consumption and reduces the BTE values. On the other hand, the BTE values are higher if the engine loading is rising. The above-mentioned facts are valid for both kinds of the fuels, i.e., for diesel fuel and for biodiesel, as well.

Table 4. The FC and BTE.

Mode	ULSD-F		B-U (25:75)		B-U (50:50)		B-U (75:25)		Biodiesel	
	FC (kg/h)	BTE (%)	FC (kg/h)	BTE (%)	FC (kg/h)	BTE (%)	FC (kg/h)	BTE (%)	FC (kg/h)	BTE (%)
1	0.68		0.70		0.73		0.77		0.85	
2	2.18	25.01	2.21	25.30	2.25	25.62	2.35	25.92	2.43	26.12
3	3.31	33.15	3.32	33.40	3.44	33.52	3.54	33.82	3.69	34.31
4	0.67		0.70		0.72		0.77		0.83	
5	3.64	23.31	3.70	23.51	3.81	23.52	3.98	23.69	4.14	23.83
6	5.49	31.04	5.56	31.25	5.70	31.43	5.92	31.73	6.15	31.92
7	8.02	27.22	8.25	27.32	8.37	27.62	8.37	27.62	9.02	28.01
8	11.00	30.19	11.18	30.38	11.36	30.48	11.36	30.48	12.18	31.05
9	7.62	33.61	7.79	33.87	7.92	34.00	7.92	34.00	7.97	34.93
10	9.73	35.13	9.89	35.33	10.11	35.52	10.11	35.52	10.87	36.12
11	11.21	34.24	11.38	34.20	11.72	34.19	11.72	34.19	12.60	34.78
12	14.78	29.95	14.91	30.19	15.24	30.29	15.24	30.29	16.41	30.79
13	2.18	9.52	2.31	9.34	2.46	9.14	2.46	9.14	2.65	9.32

3.2. The Regulated Emissions

The regulated emissions that are analyzed in this article include: HC, CO and NO_x. The obtained results are shown in Figures 3–5.

It is evident from the analysis presented in Figure 3 that combustion of the fuel with a portion of biodiesel reduces the HC emissions under all conditions due to the oxygen, which is contained in biodiesel; thus, it increases the fuel combustion efficiency [12].

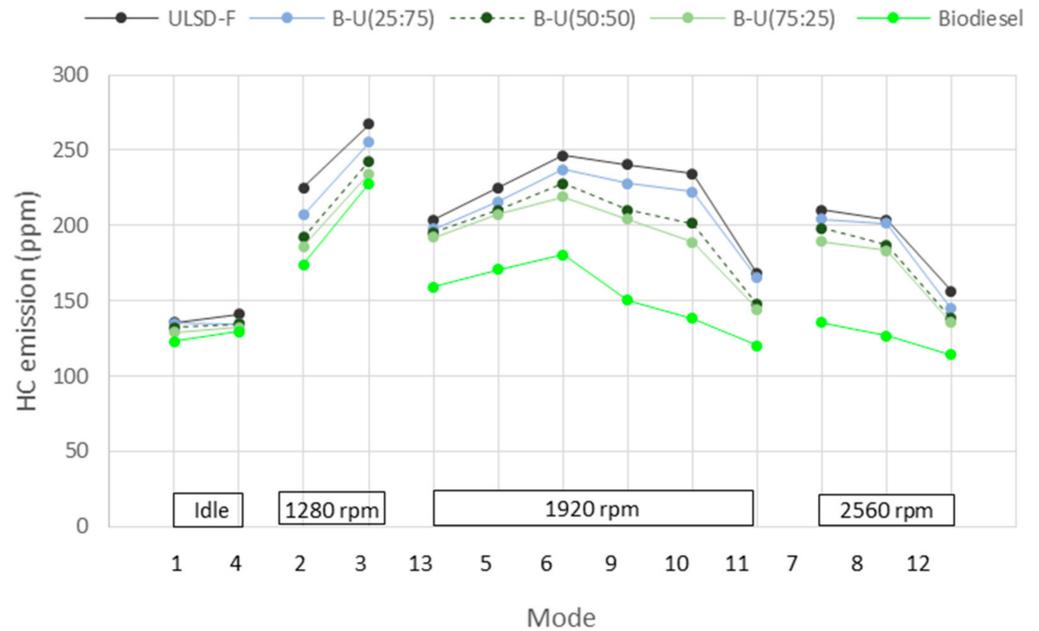


Figure 3. Experimental fuels and the HC emissions.

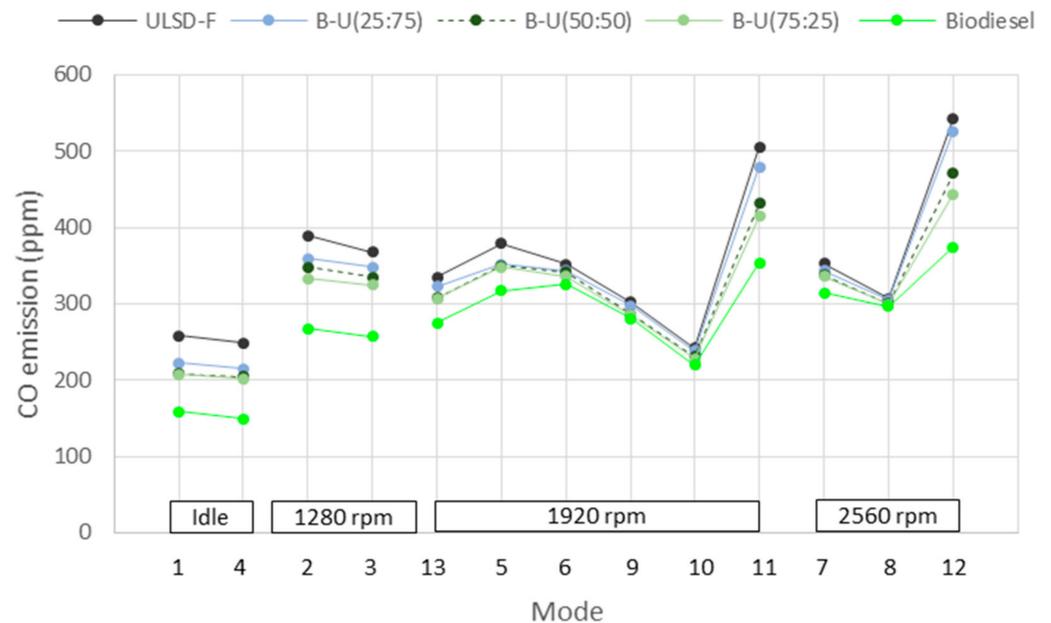


Figure 4. Experimental fuels and the CO emissions.

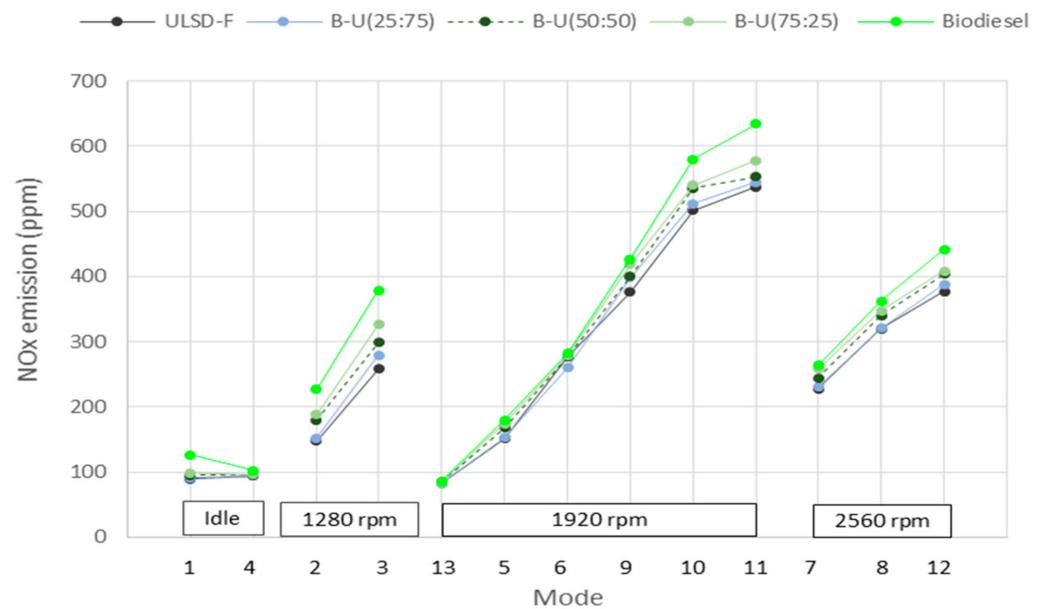


Figure 5. Experimental fuels and the NO_x emissions.

It can be stated, according to the measured data, that the profile of HC emissions reaches its maximum at the average engine speed of 1920 rpm in the case of medium engine loading and for both types of fuels (100% diesel fuel and biodiesel). However, it should be also mentioned that in the case of low engine loading levels and at the engine speed of 1280 rpm, the HC emissions increased with higher engine loading; thereby, the HC emissions were reduced at high engine loading levels and at the engine speed of 2560 rpm. A similar situation was also recorded at engine speeds of 1920 rpm and 1280 rpm. In this case, the HC emissions increased if the engine loading raised from 20% to 40%. Higher fuel consumption causes also a higher amount of HC emissions. At the same time, the rising engine loading generates increased temperatures of the burned gas in the cylinder as well as increased temperature of the exhaust gases. In this way, there is also a reduced volume of the unburned fuel components. The HC emissions are lower at higher engine speeds thanks to the improved oxidation of HC due to the high level of the exhaust gas temperatures.

Analogous to the HC emissions, we can say that a higher amount of biodiesel reduces the CO emissions, according to Figure 4.

It can be stated, according to the obtained results, that an increase in the CO emissions is essential in the operational modes 11 and 12, namely due to the higher value of the fuel/air ratio, which is necessary at a high engine loading level. At the same time, the CO emissions rise with the increasing engine speed. It is visible from Figure 4 that the addition of biodiesel to the standard diesel fuel causes an increase in NO_x emissions. The generation of NO_x emissions is a function of the local oxygen concentration, combustion temperature and ignition delay [10]. The engine operational mode has a significant influence on the combustion process temperature and thus it can significantly affect the amount of generated NO_x emissions. A higher engine speed at lower engine loading reduces NO_x emissions. On the other hand, higher engine loading requires a higher amount of the injected fuel, which causes higher combustion temperature and, finally, an increase in NO_x emissions.

Figure 6 illustrates the particulate matter (PM) emissions in the operational modes 3, 6, 7, 8, 12. The PM emissions are reduced in the case of a larger volume of biodiesel in the fuel mixture during the operational modes 6, 7, 8, 12. The reason for this reduction consists in the following factors: the absence of aromatic content in biodiesel and the presence of oxygen in biodiesel, which improves the oxidation of the carbon particles.

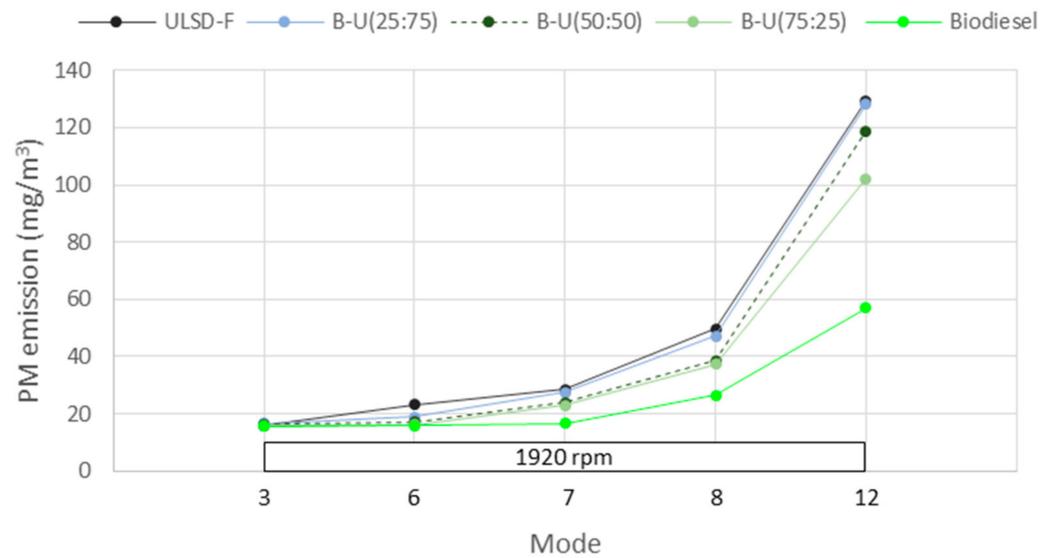


Figure 6. Experimental fuels and the PM emissions.

The PM emissions increase with higher engine loading due to a larger amount of the injected fuel. Another relevant factor for the increase in PM emissions is the higher engine speed level, which causes a decrease in the volumetric efficiency [13]. The reduced volumetric efficiency means the higher AFR value, which leads to the production of PM emissions.

3.3. The Unregulated Emissions

The emissions of acetaldehyde and formaldehyde (Figures 7 and 8) grow with the increasing portion of biodiesel in the fuel mixture. This dependence is caused mainly due to the fact that short-chain chemicals, which are contained in the biodiesel produced from the home waste oil, are able to create the shortest carbonyl chain during the combustion process, i.e., acetaldehyde and formaldehyde [14].

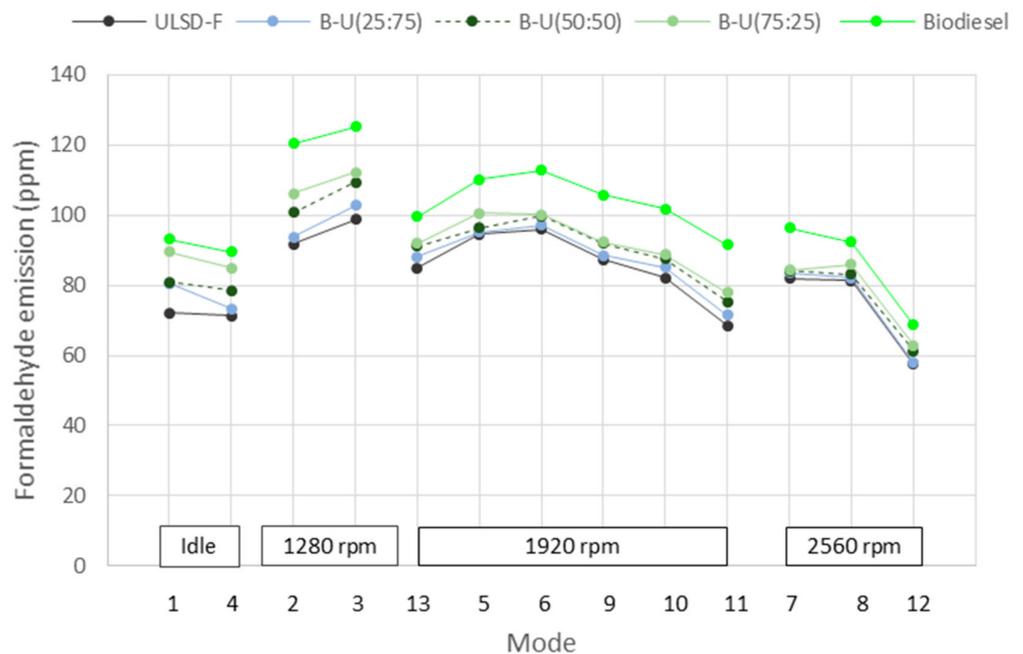


Figure 7. Experimental fuels and the formaldehyde emissions.

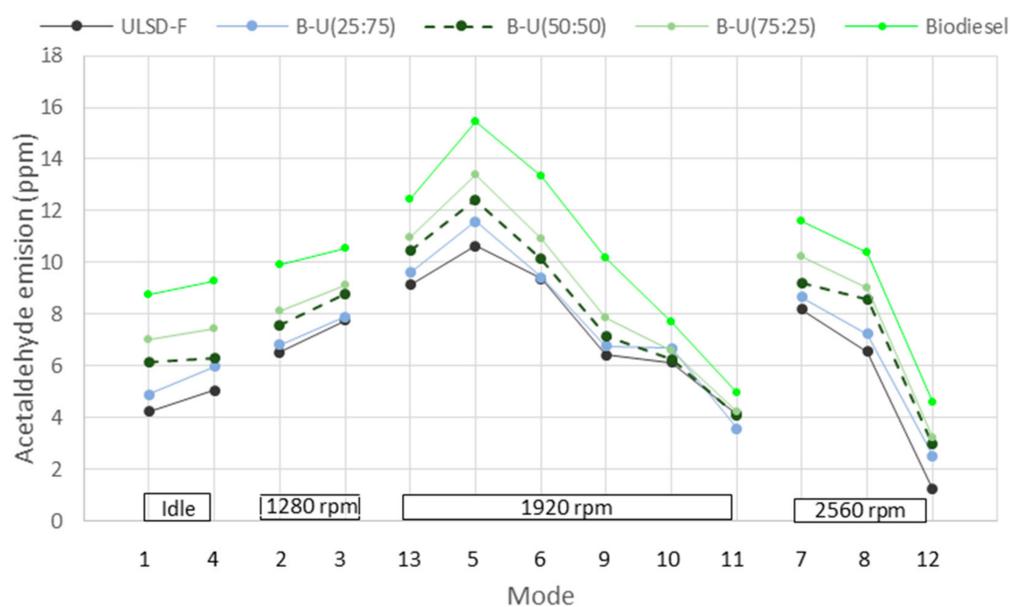


Figure 8. Experimental fuels and the acetaldehyde emissions.

At the same time, the operational or working conditions also have a major impact on these emissions. An increase in formaldehyde emissions was recorded within the interval from low to middle engine loading level. A decrease in this kind of emissions was monitored in the range from middle to high engine loading level and for all the tested fuels, according to Figure 7, at the engine speed 1920 rpm. The developed trend concerning acetaldehyde emissions is very similar, as seen in Figure 8. A higher volume of carbonyl emissions in the case of low engine loading level is caused due to increased fuel consumption. A reduction in these emissions at high engine loading level is a positive consequence of the rising combustion temperature as well as the exhaust gas temperature. Higher engine speed reduces acetaldehyde and formaldehyde emissions thanks to higher combustion temperatures.

The unsaturated alkenes, i.e., propene, ethene and 1,3-butadiene, are the chemical precursors of diesel soot. 1,3-butadiene is one of the most harmful substances that pollutes air with regard to its carcinogenic impact [15].

It is possible to say, according to the measured results presented in Figures 9–11, that the emissions of 1,3-butadiene grow with the increasing amount of biodiesel.

Emissions of the three above-described toxic substances are reduced in the case of increased engine loading, but their concentration rises during the operational modes 11 and 12 [16].

Taking into consideration the emissions of benzene, xylene and toluene (BXT), a phenomenon that just the unburned fuel molecules generate these kind of gaseous emissions is observed. Table 5 documents the influence of biodiesel on the BXT emissions in the operational modes 5, 9 and 11 within the 13-regime experimental test cycle at the engine speed 1920 rpm. Benzene emissions grow when the content of biodiesel in the fuel is higher, whereby this relation is valid in the case of every engine loading level. However, the emissions of xylene and toluene are reduced if the volume of biodiesel is increased [16].

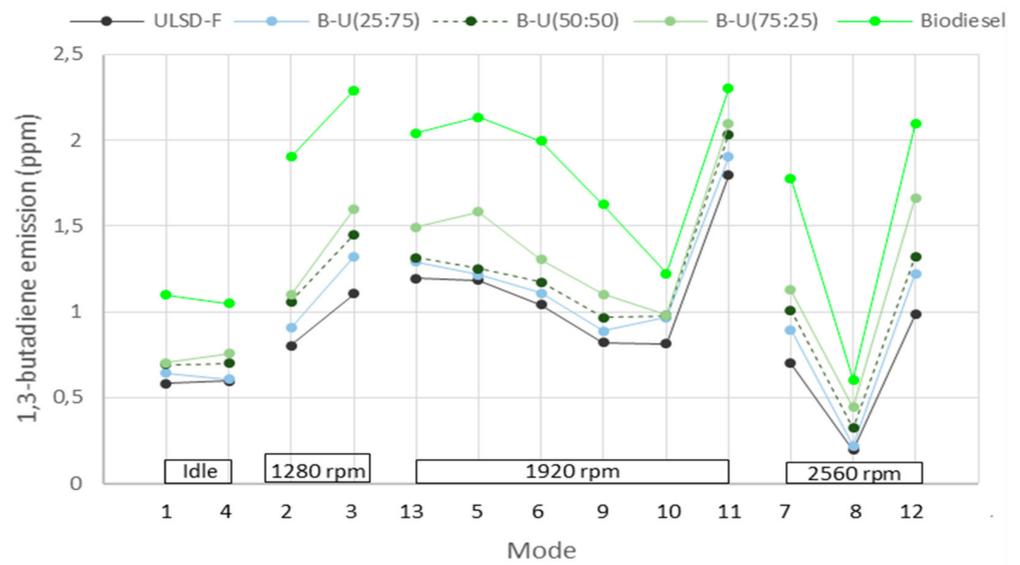


Figure 9. Experimental fuels and the 1,3-butadiene emissions.

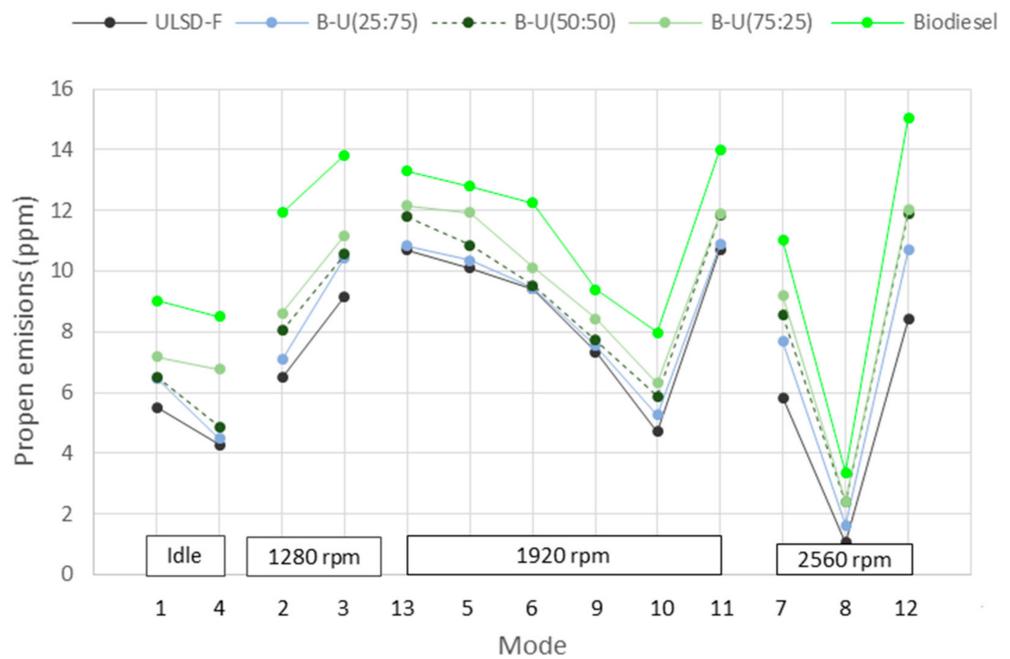


Figure 10. Experimental fuels and the propene emissions.

The total amount of BXT emissions is based on the measured data and is summarized in Table 5. The global volume of BXT emissions is lower if the engine loading increases, at the engine speed of 1920 rpm, because the higher temperature of the combustion process (due to higher level of engine loading) improves the oxidation process of the BXT emissions. The analogous results were obtained using another two engine speed levels: 1280 rpm and 2560 rpm. However, no relevant influence of the engine speed on BXT emissions was monitored.

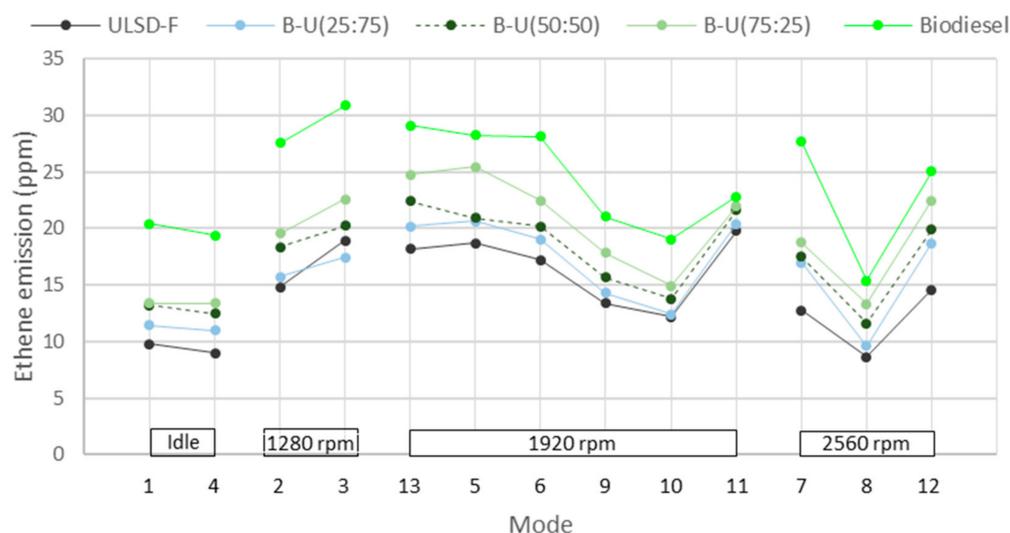


Figure 11. Experimental fuels and the ethene emissions.

Table 5. The benzene, toluene and xylene emissions.

Mode	Fuel	Benzene (mg/kWh)	Toluene (mg/kWh)	Xylene (mg/kWh)
5	ULSD-F	79.0	9.5	34.1
	B-U (25:75)	83.8	8.2	27.0
	B-U (50:50)	88.2	6.7	22.7
	B-U (75:25)	91.5	5.4	20.2
	Biodiesel	95.1	4.3	8.5
9	ULSD-F	43.2	3.6	12.8
	B-U (25:75)	44.3	3.0	9.9
	B-U (50:50)	45.9	2.5	8.0
	B-U (75:25)	47.2	2.0	5.9
	Biodiesel	49.8	1.7	3.5
11	ULSD-F	21.0	1.7	5.3
	B-U (25:75)	22.1	1.5	4.2
	B-U (50:50)	22.5	1.4	3.1
	B-U (75:25)	23.4	1.2	2.5
	Biodiesel	25.2	1.0	1.8

4. Conclusions

The article is focused on the influences of biodiesel, which is mixed with standard diesel fuel, and on gaseous emissions (both on regulated and unregulated) in the case of diesel engine, taking into consideration the infamous emission scandal, named “dieselgate”. The results of the experiments performed with the fuel mixture biodiesel–diesel, concerning the controlled emissions, point out a relevant fact that during all the engine operational modes, CO emissions and also hydrocarbon emissions were reduced, and NO_x emissions were increased in comparison with the combustion of pure diesel fuel.

With regard to the unregulated emissions, it was noted that the emissions of acetaldehyde and formaldehyde increased together with the growing volume of biodiesel contained in the fuel mixture. An analogous situation is also characteristic for the emissions of propene, ethene and 1,3-butadiene. Biodiesel also increases benzene emissions, but at the same time it also reduces xylene and toluene emissions. However, no significant

changes relating to the BXT emissions were monitored, thanks to the fact that a higher volume of benzene emissions were simultaneously compensated by the lower xylene and toluene emissions. It is important to emphasize the reality that gaseous emissions, whether regulated or unregulated, are predominantly influenced by engine operational modes that are required according to the changing engine loading [17].

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