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Testing and Analysis of Selected Operating Parameters of a Vehicle Powered by Fuel with the Addition of Biocomponents

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Abstract: The most common fuel used for powering compression ignition engines is diesel, whose main components are petroleum products. The constantly growing energy demand involves the implementation of new technical solutions and applying alternative fuels, including renewable ones, such as rapeseed oil, sunflower oil, peanut oil, and animal fats. The most commonly used biofuels are those obtained from chemically processed rapeseeds (transesterification) to provide them with physical–chemical properties similar to diesel fuel. The study presents the results of tests of a power unit fueled with different mixtures of diesel oil and fatty acid methyl esters. The experiment was carried out for a compression ignition engine of 81 kW power with direct fuel injection. Performance parameters of the vehicle power unit and its computer software were modified for the needs of the tests. Those modifications involved increasing the fuel dose and the fuel injection pressure. The test results were statistically analyzed. Based on the results, a simulation of power and torque was performed, depending on the vehicle computer system adjustment and the fuel mixture used. A simulation of the vehicle movement in a non-homogeneous environment (variable road conditions) was performed concerning the vehicle motion kinematics. The simulations were carried out in a V-SIM 5.0 program. The simulation was performed at five speeds, respectively: 0 km/h, 25 km/h, 50 km/h, 75 km/h, and 100 km/h. The simulation made it possible to determine speed, acceleration, time, and distance. The analysis shows that the highest acceleration of 3 m/s^2 was obtained for the BIO50 mixture, regulation V. The longest road section needed to achieve the maximum speed (100 km/h) was recorded for the BIO10 mixture, regulation II. The simulation duration ranged from 17.9 s to 17.74 s, depending on the adopted variant.

Keywords: transport; biofuels; exhaust components; combustion engine; road simulation

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Citation: Markiewicz, M.; Aleksandrowicz, P.; Muślewski, Ł.; Pająk, M. Testing and Analysis of Selected Operating Parameters of a Vehicle Powered by Fuel with the Addition of Biocomponents. *Energies* **2023**, *16*, 3159. https://doi.org/10.3390/en16073159

Academic Editor: Dimitrios C. Rakopoulos

Received: 3 February 2023
Revised: 28 March 2023
Accepted: 29 March 2023
Published: 31 March 2023

1. Introduction

Sustainable development assumes a balance between many branches of the economy, including transport. In accordance with the principle, the introduced changes and pro-ecological procedures aim at limiting the negative effects of this sector on the natural environment. The topic discussed in the manuscript coincides with the sustainable development strategy of the European Union.

Transport development has significantly increased the demand for non-renewable energy sources and air pollination. The growth of road transport leads to the degradation of the natural environment, necessitating the introduction of standardized legal regulations. The European Union and domestic legislation are supposed to reduce the negative environmental impact of transport [1,2]. The European Union Directives also set out rules for the application of renewable energy sources. The necessity of using alternative fuels to power combustion engines is caused by a high demand for fuel and diminishing deposits of natural resources. The design of engines enables their modernization and a return to the concept of plant-origin fuels. In terms of sustainability, try not to use your car, at least for short distances. This will help to reduce carbon dioxide emissions and thus protect the environment. You can ride a bike or scooter, walk, or use public transport. However, this will not eliminate the use of means of transport, which can become more ecological thanks to the use of biocomponent additives to fuels used in drive units. The first argument favoring plant-derived fuels is the exhaustibility of oil-derived fuels and the necessity to leave natural resources for the next generations [3,4]. The second argument is to relieve the market from oil-derived supplies. Natural fuels from the Earth's resources are exhaustible and difficult to access. It seems, however, that the predictions about the exhaustion of natural resources are too early. In 1948, an American geologist and geophysicist predicted the exhaustion of the world oil deposits by 2000. The next predictions, however, extended the time of oil exhaustion. According to current predictions, oil deposits will have finished in the next 41 years. The third argument for using plant-origin fuels is the utilization of rural areas [5–7]. Current prediction about a lack of fuel is far from consistent with those published in the middle of the previous century. However, political, economic, and social reasons speak for a return to research on using plant oil as a fuel for compression ignition engines. Advanced research on compression ignition engine fueling with plant oils is being carried out in the agricultural sector, where the rate of oil derivative fuels is very high. Another argument favoring plant oils is environmental protection, including CO_2 emission reduction [8]. Combustion engines mounted in vehicles are responsible for the emission of harmful substances into the natural environment. In the literature, there are several studies on internal combustion engines, conducted both in mechanical and ecological aspects, which indicate the legitimacy of using biofuel to power engines [9–12].

Using alternative fuels (biofuels) to power internal combustion engines makes it possible to reduce the consumption of fossil fuels and reduce the emission of toxic components contained in exhaust gases. The share of oil deposits transformed into fuel by physical-chemical processes in the transport sector is 40%. The application of alternative fuels from renewable energy sources in combustion engines involves a growing demand for these substances and decreasing consumption of fossil fuels. Plants are the most popular sources used for the production of biofuels. Alternative fuels of plant origin applied in compression ignition engines include rapeseed oil, peanut oil, soya oil, and animal fats [13]. These fuels are referred to as biofuels and must be subjected to chemical processes to provide properties similar to diesel. Physical-chemical characteristics of biodiesel produced from rapeseed oil are presented in Table 1. Due to its intrinsic properties and economic reasons, the most popular plant used for the production of biodiesels is rapeseed oil. Compression ignition engines can also be fueled by biogas produced from fruit and vegetable waste as well as pyrolysis oil, i.e., a mixture that is generated in the process of the thermal decomposition of organic substances from waste vehicle tires [14–17]. Microalgae can also be an alternative fuel of natural origin [18–22]. Leftover frying oil can be used for combustion engine fueling, though it requires applying a flexible fuel system that runs on more than one fuel [21,22].

Table 1. Physical–chemical properties of biodiesel and diesel oil [23].

Parameter	Biodiesel	Diesel Oil
viscosity [$m^2 \cdot s^{-1}$]	3.5–5.0	2.0–4.5
sulfur content [mg/m^3]	≤10	≤350
density [g/cm^3]	0.86–0.90	0.82–0.845
cetane number	≥47	≥51
solid content [mg/cm^3]	≤24	≤24
water content [mg/kg]	≤500	≤200
carbon residue [%]	≤0.3	≤0.3
flash point [°C]	≥101	≥55

Tests of the basic characteristics of compression ignition engines fueled by plant oils, or mixtures of plant oil and diesel, have been conducted in numerous Polish and foreign research centers. Analyses of the test results are focused on the problems connected with the application of these oils for combustion engine fueling [24–27]. There are numerical quantities characterizing the performance of internal combustion engines that are used for their assessment and comparison. An analysis of these quantities provides detailed information about the engine characteristics. The tests have revealed a 7.8% drop in the value of the engine performance parameters and smaller power drops, as compared to diesel oil, depending on the characteristics of the combustion engine injection system. This was caused by lower calorific value and higher density parameter value of fatty acid methyl esters. Basically, the overall efficiency found for an engine powered with fatty acid methyl esters was the same or even better than for diesel, regardless of the engine design, loads applied, and testing conditions [28,29].

The goal of the tests was to determine and analyze the value of power and torque of a biofuel-powered engine to determine its best performance parameters. The test results allowed us to analyze the vehicle motion and carry out a simulation in a V-SIM 5.0 program. A novelty in the conducted research is the combined analysis of the mixture change and the adjustment of the engine control system software. Combining these dependent variables has allowed power and torque to be maintained or improved while reducing exhaust emissions. Exhaust emission results are presented in other published works, which are included in the reference list. Running a simulation program to determine the vehicle motion parameters is also a new approach to this topic and an extension of the analyses carried out so far.

2. Materials and Methods

Pure oil with no biocomponent additive and fatty acid methyl esters were used in the tests. Proportions and symbols given to the tested fuel mixtures are presented in Table 2. Fatty acid methyl esters used in the tests were transesterified plant oils. The process of transesterification involves breaking triglycerides down into fatty acids. More generally, it is the process of exchanging an of an alcohol with an of an ester in the presence of a base catalyzer, creating fatty acid methyl esters used as an additive to diesel commonly referred to as a biofuel.

Table 2. Proportions of fuel mixtures used in the research.

Fuel Mixture Composition	Symbol
diesel fuel without the addition of fatty acid methyl esters	ON
90% diesel oil 10% fatty acid methyl esters	BIO10
70% diesel oil 30% fatty acid methyl esters	BIO30
50% diesel oil 50% fatty acid methyl esters	BIO50

The research object was a compression ignition combustion engine. The power unit was selected due to its wide application in road transport vehicles. 1.6 HDi compression ignition engine equipped with the Common Rail system and electromagnetic injector was used for the tests. The engine is presented in Figure 1.

The power unit was equipped with a dual mass flywheel and a variable geometry turbocharger, which affected its performance. The engine also had a filter of solid particles. The supply system was modified to allow a non-invasive fuel change. The adjustments were applied to the fuel supply system, and an additional fuel tank was installed. There was no direct tampering with the engine structure. Adaptations necessary to deliver fuel to the power unit involved fixing an external fuel tank and disconnecting the fuel supply from the manufacturer's tank. No additional filters or fuel pumps were installed. The fuel supply system was connected directly to the engine from the external fuel tank. The supply pump sucked the fuel from the fuel tank. The fuel that flowed through a pre-filter was then fed to the fine mesh filter, from where it went to the chamber of the Common Rail supply system and was fed to the injectors fixed on the engine head. The computer-controlled injector regulated the injection start and the fuel dose. The fuel mixture was injected directly into the cylinder chamber. Standard filters designed for this engine model were used. Fuel excess was returned to the external tank through a return fuel pipe. Each time, after a change of the fuel mixture, the engines were left operating on an idle gear for about 10 min to remove the remains of the previous fuel from the fuel filter and the supply system. The characteristics of the tested engines are presented in Figure 2. In the characteristics (Figure 2), the curve reflecting the power of the tested engine is marked in red, and the curve showing the drive torque of the unit is in blue.

Figure 1. Example combustion engine used in the test.

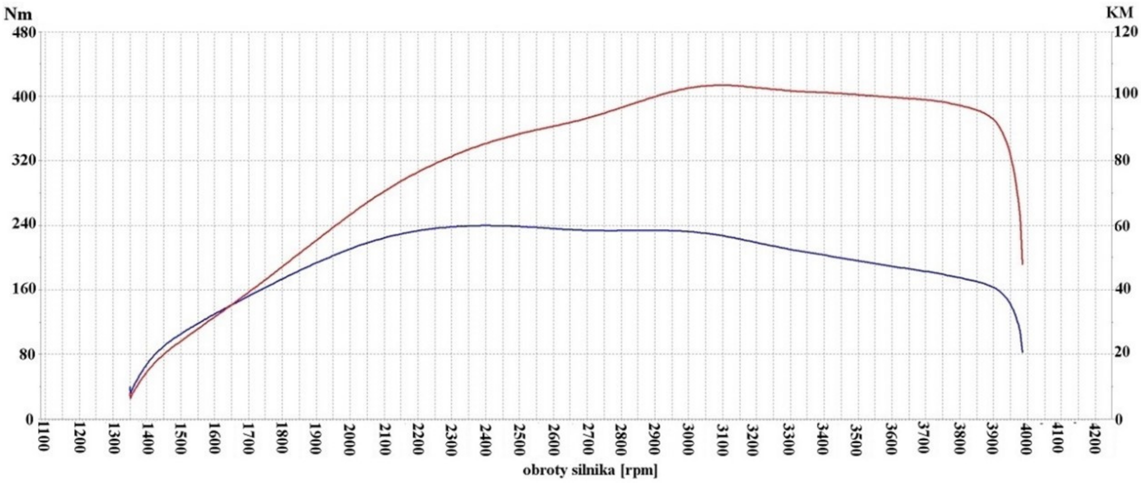

Figure 2. Characteristics of the tested test engine.

The engine computer software was modified. Before each test, the vehicle computer system was disassembled and connected to the test stand, where it was adjusted accordingly. Adjustments to the fuel injection control system were performed according to a preset schedule. Modifications involved increasing the fuel dose and the air intake. The changes and their symbols are presented in Table 3. An example of fuel injection for increased by 50 hPa air intake is presented in Figure 3. The presented fuel injection map shows the engine revolutions for which changes were made. The introduced modification is marked in yellow in the drawing. This is the map loaded into the engine after making the required adjustments.

Table 3. Settings of the engine computer control system.

Setting Number	Control System Settings
I	Standard setting
II	Fuel dose increased by 2%, air intake increased by 50 hPa
III	Fuel dose increased by 4%, air intake increased by 50 hPa
IV	Fuel dose increased by 6%, air intake increased by 50 hPa
V	Fuel dose increased by 6%, air intake increased by 150 hPa

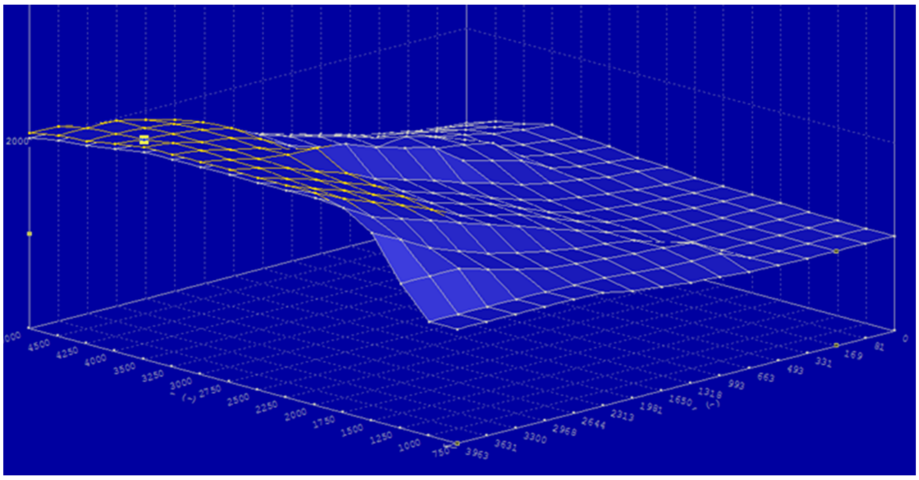

Figure 3. Fuel injection characteristics for air intake increased by 50 hPa from the nominal value.

The tests were conducted on a chassis load dynamometer with an eddy current brake. The chassis dynamometer made it possible to determine the engine performance characteristics such as power and torque. Torque transmitted to the crankshaft was measured, and the engine power was calculated based on the value of torque and the crankshaft rotational speed. To measure power and torque, road traffic conditions were simulated, and appropriate loads were applied. Measurements started with placing the vehicle on the rollers of the chassis dynamometer and immobilizing it. Measurement signals were transmitted to the computer system and transposed to selected performance parameters of the vehicle.

The test results were statistically analyzed, and a simulation of the vehicle was performed in a non-homogeneous environment (variable traffic conditions) utilizing the V-SIM 5.0 program. The V-SIM program is used for the simulation of a vehicle motion in a complex traffic environment taking into consideration potential accidents. The vehicle model in the V-SIM program is presented in Figure 4.

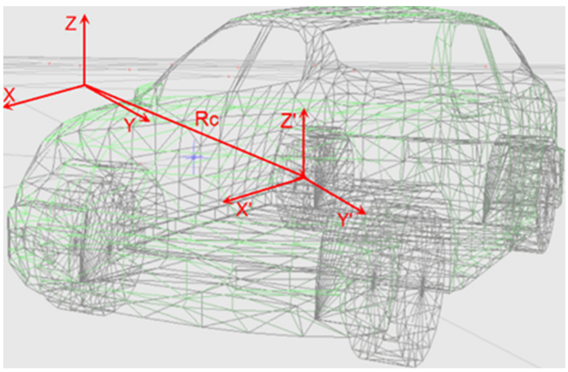

Figure 4. Vehicle model in the V-SIM program.

The program was used to analyze the vehicle motion in a three-dimensional space, consistent with the laws of dynamics. The vehicle model considered the inertia moments of the wheels and elements of the drive unit. Additional freedom degrees were provided by the wheel's rotational motion. In the V-SM program, the numerical model of the analyzed vehicle had 10 freedom degrees. A kinematic model of an independent suspension, including the vertical motion of the wheels, was used for the analysis. Furthermore, the suspension reaction forces affecting the vehicle's overall motion dynamics were determined for each wheel, considering damping for the compression and tension phase of and stiffness of the stabilizer rods. In a descriptive model of the vehicle motion dynamics, the vehicle steering system was based on Ackerman's rules, whereas the brake system was equipped with the main braking system and an auxiliary one with optional ABS and ESP functions [30]. The vehicle model included parametrically assigned characteristics obtained from simulations of road traffic conditions to provide real accelerations. Thus, the engine model enables introducing data into the characteristics in the form of power and torque obtained based on the tested fuel mixtures. By entering the data obtained from the experiment performed on the dynamometer, taking into account the fuel composition, it is possible to obtain simulations showing the effect of the fuel composition on the acceleration and speed of the car. The vehicle presented in the program also included models of the power transmission system, i.e., a clutch, gearbox with the possibility to change gears, main gearbox, and a differentiating mechanism. The program enabled force-oriented modeling and classical impulse response modeling using other vehicles and road infrastructure elements [31–37]. Basic technical specifications of the simulated vehicle numerical model and the road traffic environment are included in Table 4.

Table 4. Changes to the software of the control system of the tested engine computer.

Vehicle	Car
engine type	1.6 HDI
gross vehicle weight	1433 kg
vehicle length/width/height	4.030 m/1.720 m/1.472 m
vehicle wheelbase	2.540 m
front/rear axle track of the vehicle	1.467 m/1.468 m
wheel model and size	TM-easy 195/55 R16
braking system	hydraulic with ABS
gearbox	mechanical, 6 stages
task—pressure on the gas pedal	100%
type of surface	dry asphalt
adhesion coefficient	0.80/075

3. Analysis and Results

The experiment results were statistically analyzed to acquire information about the analyzed dependencies. The statistical analysis is divided into two parts. The first part includes the share of fatty acid methyl esters in diesel fuel. The second part of the analysis covers the statistical results of the vehicle fuel injection control system modification.

In the first place, a hypothesis assuming equality of all the values of the considered parameters was accepted to provide the possibility of comparing the fuel blends and the computer control system adjustments and determining their significance for further statistical analysis. In this way, the information that all the variants were statistically significant was provided. Next, dependencies of the parameters were analyzed (power and torque), depending on the blend composition and the computer control system setting. The blend composition and computer system adjustments were independent variables in the regression analysis, whereas the values of power and torque were dependent variables. A sample regression equation for the blend composition is presented in the study. For the ON blend, the regression equation is expressed in the form of the following dependency:

$$y = 0.944x + 101.074 \quad (1)$$

The correlation coefficient for the above regression equation was r = 0.7097. Testing of the H0 hypothesis yielded: a = 0 $p < 0.0001$, which means that the considered dependency is statistically significant. A straight regression was obtained by plotting the empirical points on a graph, which is presented in Figure 5. Prior to the simulation, a statistical analysis was performed to obtain the necessary information about the analyzed dependencies.

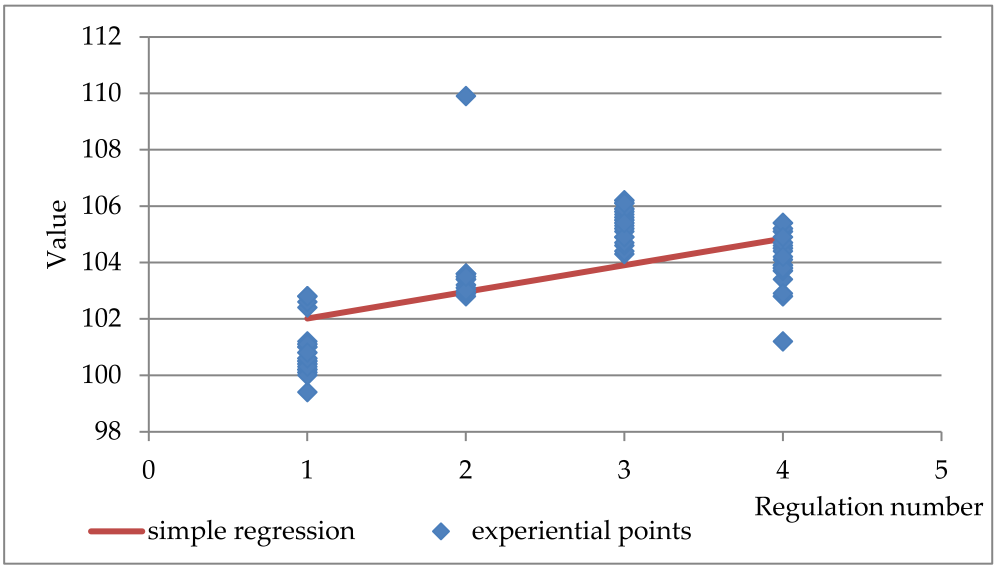

Figure 5. Linear regression plot of the tested power parameter for the ON mixture.

The test results were also simulated in the VSIM 5.0 program, which allowed us to reach the required speed, acceleration, and distance in relation to time. The simulations were conducted for four blends of diesel and fatty acid methyl esters and five computer control system settings, 20 variants overall. Mean values, taken from 30 measurements performed on the chassis dynamometer, were used for the simulations. The mean results of power and torque found for each fuel blend and the computer control system setting are demonstrated in Tables 5 and 6.

Table 5. Power measurement results used for simulation.

	Setting Number				
	I	**II**	**III**	**IV**	**V**
ON	100.95 KM	103.56 KM	104.48 KM	105.42 KM	105.36 KM
BIO10	100.49 KM	101.71 KM	104.17 KM	104.65 KM	104.95 KM
BIO30	100.11 KM	100.15 KM	104.79 KM	105.74 KM	106.26 KM
BIO50	100.99 KM	104.22 KM	104.91 KM	105.40 KM	106.33 KM

Table 6. Torque measurement results used for simulation.

	Setting Number				
	I	**II**	**III**	**IV**	**V**
ON	238.88 Nm	243.72 Nm	244.22 Nm	241.30 Nm	245.85 Nm
BIO10	246.87 Nm	235.27 Nm	242.26 Nm	241.67 Nm	241.68 Nm
BIO30	233.59 Nm	229.76 Nm	241.49 Nm	246.89 Nm	239.03 Nm
BIO50	239.497 Nm	241.747 Nm	248.17 Nm	254.213 Nm	247.773 Nm

The simulated vehicles were accelerated on a dry asphalt road up to 100 km/h. Based on this, time changes were determined for acceleration, speed, and distance covered. The simulation time was from 16.82 s to 17.76 s, depending on the given variant. The simulation results obtained for particular blends were similar, proving that the fuel change had only a slight impact on the engine performance. The computer control system settings increased the power and torque, proven by the simulations, though the changes were insignificant. However, the ON blend and setting I variant, compared to the BIO10 blend and setting II, is characterized by a higher speed in each gear and reached 100 km/m in about 0.22 s shorter. However, the best results obtained for the BIO50 blend and gear setting V are even greater than ON blend and setting I, and 100 km/h was reached 0.58 s sooner. The study presents changes in acceleration, speed, and distance for three variants: ON blend and setting I, BIO10 blend and setting II, and BIO50 blend and setting V. The charts depicting changes in selected variants are presented in Figures 6–8.

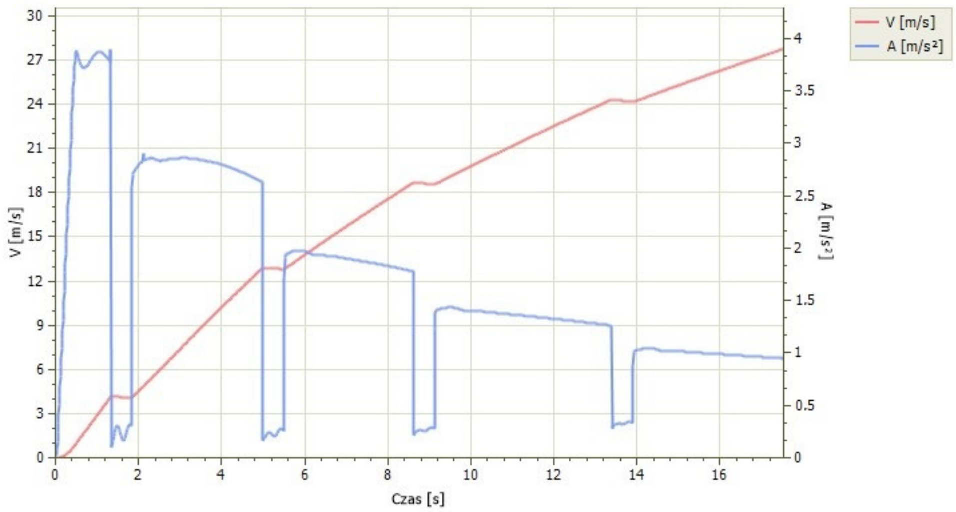

Figure 6. Cumulative time courses of speed, acceleration, and distance traveled for the variant ON mixture and control I.

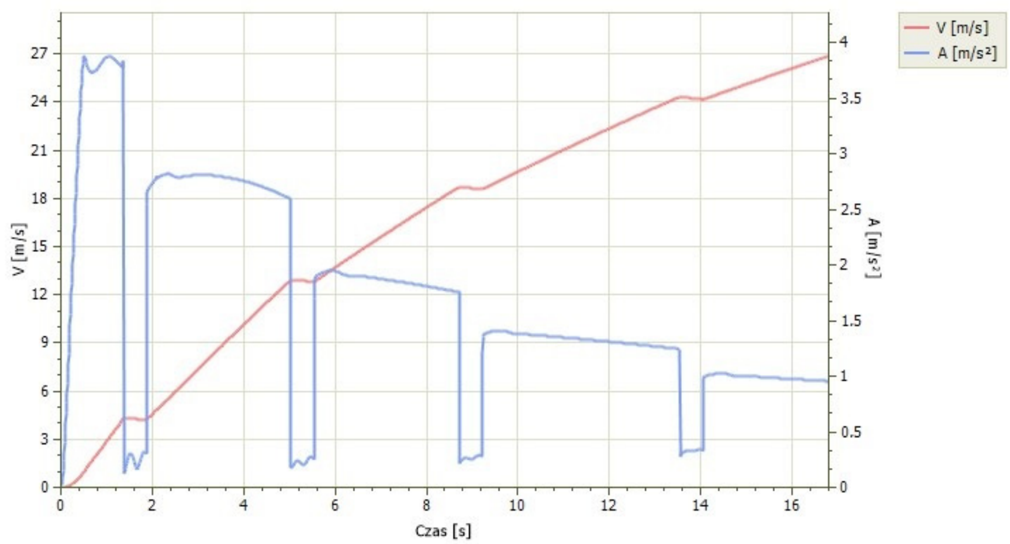

Figure 7. Cumulative time courses of speed, acceleration, and distance traveled for the variant BIO10 mixture and control II.

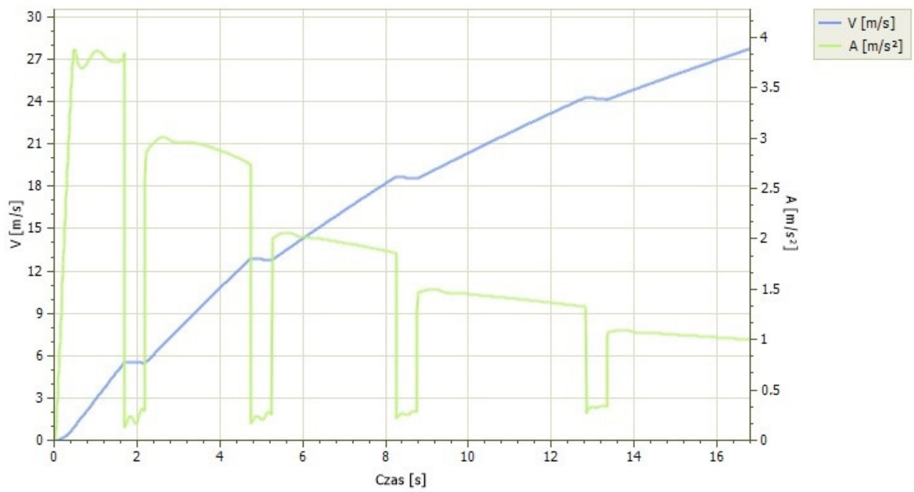

Figure 8. Cumulative time courses of speed, acceleration, and distance traveled for the variant BIO50 mixture and control V.

The use of the BIO50 blend and setting V mixture allows for the best traction parameters of the vehicle, and the comparison of the discussed acceleration and speed courses is shown in Figures 9 and 10. The graphs show the values of velocity and acceleration related to time. Due to similar values for all the analyzed variants, the lines defining the course of velocity and acceleration overlap. This proves that the parameters of the mixtures with the biocomponent are similar to those of diesel fuel.

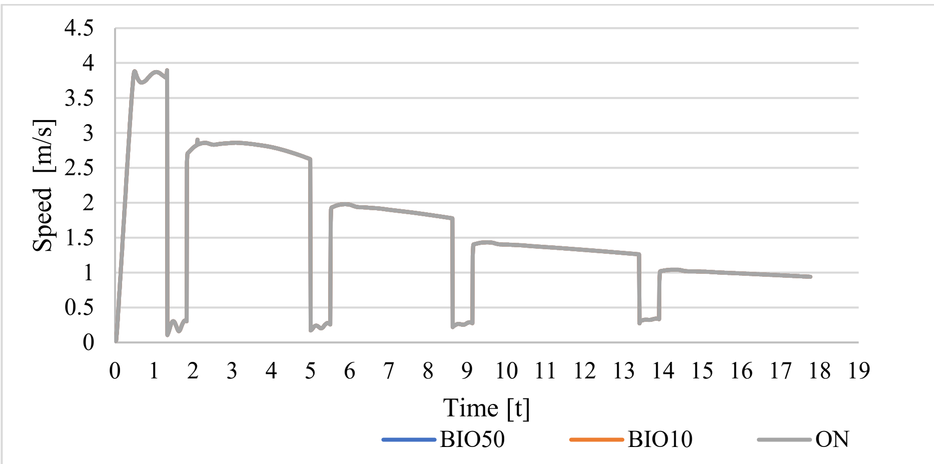

Figure 9. Comparison of velocity values over time for the analyzed mixtures.

Moreover, the simulation allowed us to analyze the motion of a vehicle with power and torque assigned to it. Road traffic tests were conducted for vehicles fueled with the analyzed blends and the engine computer control system settings. Each test was conducted for 0 km/h to 100 km/h. speed. A simulation model of a vehicle in motion was generated for the above-presented variants, representing the acceleration and distance traveled in the respective period. Five speeds were used for each vehicle model: 0 km/h, 25 km/h, 50 km/h, 75 km/h, and 100 km/h, respectively. The time and acceleration results for the analyzed speeds are presented in Table 7.

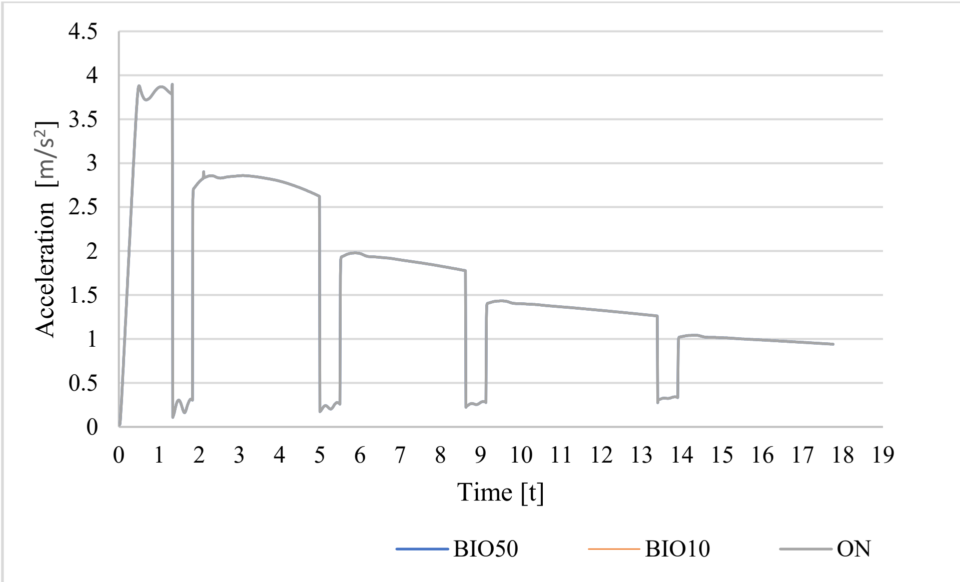

Figure 10. Comparison of acceleration values over time for the analyzed mixtures.

Table 7. The obtained results of time, distance, and acceleration for the analyzed speeds.

Variant	**V [km/h]**	**t [s]**	**S [m]**	**A [m/s^2]**
mixture ON setting I	25	2.86	10.01	2.90
	50	6.06	45.29	2.00
	75	10.76	128.70	1.40
	100	17.54	295.10	0.90
mixture BIO10 setting II	25	2.86	10.09	2.80
	50	6.10	45.78	1.90
	75	10.86	130.24	1.40
	100	17.76	299.64	1.20
mixtureBIO50 setting V	25	2.70	9.96	3.00
	50	5.80	44.14	2.00
	75	10,32	124.33	1.40
	100	16.82	283.85	1.00

The results presented in the table were obtained from an analysis of motion performed for a vehicle provided with appropriate torque and power according to a given variant. The simulation effects depending on the fuel mixture used are presented in Figure 11. The blue color stands for the ON mixture and setting I; red is for the BIO10 mixture and regulation II; and green is for the BIO50 mixture and regulation V. Positions of simulated vehicles from 0 km/h to 100 km/h by a vehicle (green) powered by the BIO50 mixture and regulation V is shown every 1000 s.

Figure 11. Simulation of vehicle traffic depending on the type of fuel—blue ON mixture and setting I; red—BIO10 mixture and regulation II; green—BIO50 mixture and regulation V.

In the case of variant I (ON mixture and setting I), the overall simulation time was 17.54 s, in which time the vehicle traveled a distance of 295.10 m and reached an acceleration of 2.86 m/s^2 at the speed of 25 km/h. For variant II (BIO10 mixture and regulation II), the overall simulation time was 17.76 s, in which time the vehicle traveled a distance of

299.64 m and reached a maximal acceleration of 2.8 m/s^2 for a speed of 25 km/h. In the case of variant III (BIO50 mixture and regulation V), the overall simulation time was 16.82 s, during which time the vehicle traveled a distance of 283.85 and reached a maximal acceleration of 3.0 m/s^2 for a speed of 25 km/h.

The simulation models show differences in the distance traveled, time of travel, and maximal acceleration of the vehicle. The value of acceleration decreased along with the increasing speed. The analysis showed that, out of the twenty variants (changes of fuel blend and the power unit computer control system), it was the vehicle fueled with BIO10 mixture and computer control system setting II that needed the longest time and traveled the longest distance to reach a speed of 100 km/h (fuel dose increased by 2% air intake increased by 50 hPa) powered with fatty acid methyl esters.

4. Discussion

The test results and literature data [24–29,37–40] have confirmed the assumption that fuel blends with biocomponent additives can be used without the risk of changing the basic performance parameters of drive units. Other studies, which concern changes in fuel mixtures and changes in the vehicle computer software, show that the composition of the mixture has a positive effect on emissions, while modifications to the control system software maintain the expected parameters [38–41]. The analysis of the literature shows that the impact of the use of biofuels on power, torque, fuel consumption, and engine start-up conditions is known, an argument for undertaking this type of research. Research results show that using mixtures of diesel oil and fatty acid methyl esters reduces the number of components emitted to the environment, which has been confirmed by many authors [23–25,42,43]. In addition, the obtained results indicate that with the use of the V-SIM simulation program, it is possible to obtain not only time courses of changes in acceleration, speed, and distance traveled by the vehicle for different fuel mixtures. Based on the obtained results, it is also possible to efficiently plan future road tests, taking into account the selection of the appropriate track length and predicting the parameters for experimenting while maintaining safety and rationalizing costs. At the same time, it should be considered whether adding biocomponents to fuel is so effective, in terms of the use of means of transport, that other sectors of the economy should be adapted to them. Agriculture, including the adaptation of land use or the engineering of renewable energy sources, and with it, the indispensable carbon footprint, also generates additional costs and losses for food and people. Therefore, taking these aspects into account is necessary regarding adding biocomponents to power the drive units of transport means.

5. Conclusions

Real tests conducted on a chassis dynamometer and a statistical analysis showed that all values of the analyzed parameters were statistically equal. The tests allowed us to compare fuel blends and adjustments of the engine computer control system and determine their significance for further analysis. Previous studies conducted in various scientific units on the use of fuel mixtures with biocomponent additives confirm the desirability of their use.

- Statistical analysis was carried out, and all tested variants were statistically significant.
- Additionally, a regression analysis was used to determine the parameter dependencies (power and torque) for the blend composition and the control system setting. The correlation coefficient values of the determined regression equations and tests of the H0 hypothesis showed that the analyzed dependencies were statistically significant.
- An important element of the work were simulation tests carried out using the V-SIM program, which confirmed the analyses.
- The simulations revealed differences in the distance traveled, the time needed to travel the distance, and the maximal acceleration of the vehicle reached for the fuel blend used and for the computer control system setting.

- An analysis of the variants shows that there are, but only slight differences in the tested parameter values, so it can be assumed that using an optional fuel blend BIO30 (for which the parameter values were the most similar to pure diesel ON), has no significant impact on the tested power unit performance parameters. To check the adequacy of the test results and generalize them to a larger population of vehicles, conducting comparative tests of different types and kinds of power units is planned. Additionally, the possibility of applying plant-origin additives in engine oils is being investigated.
- The results from the simulation show that with the use of the V-SIM simulation program, it is possible to obtain not only time courses of changes in acceleration, speed, and distance traveled by the vehicle for different fuel mixtures. Based on the obtained results, it is also possible to efficiently plan future road tests, taking into account the selection of the appropriate track length and predicting the parameters for experimenting while maintaining safety and rationalizing costs.
- The results of the obtained simulation in the case of the diesel mixture and regulation I show that the vehicle needed 17.55 s to cover 295.10 m. During this time, the simulated vehicle obtained a maximum acceleration of 2.86 m/s^2 at 25 km/h. For the variant BIO10 mixture and regulation II, the total simulation time was 17.76 s for a distance of 299.64 m. The vehicle obtained a maximum acceleration of 2.8 m/s^2 at 25 km/h. For the BIO50 mixture and regulation V variant, the distance traveled was 283.85 m, and the total simulation time was 16.82 s, during which time the vehicle obtained a maximum acceleration of 3.0 m/s^2 at a speed of 25 km/h.

Author Contributions: Conceptualization: M.M., Ł.M. and P.A.; formal analysis: M.M.; investigation: M.P. and M.M.; methodology: M.M. and Ł.M.; resources: M.M.; visualization: P.A. and M.M.; writing—original draft: M.M.; writing—review and editing: M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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