

Article

Modeling of Diesel Engine Fuel Systems Reliability When Operating on Biofuels

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Abstract: One of the main trends in the development of modern engine building is the use of biodiesel fuel, which can lead to a decrease in the reliability of engines that are not adapted to it. However, at present there is no general method for determining the reliability of fuel systems of internal combustion engines. In this paper, a reliability model of engine fuel systems when operating on biofuel has been developed. Comprehensive indicators for assessing the reliability of diesel engine fuel systems are the coefficient of readiness and technical use. The availability factor of the fuel system when operating on biodiesel fuel without the replacement of structural materials was 0.66, while with the replacement it was 0.71, and the coefficient of technical utilization without replacement of materials was 0.36, and with the replacement of 0.4. Recommendations are given to improve the reliability of the engine fuel system components. The resulting model allows for complex comparisons of the effectiveness of various ways to improve the reliability of engines running on biodiesel fuel.

Keywords: biodiesel; reliability modeling; fuel system; state graph

1. Introduction

The efficiency of agricultural production largely depends on the performance of agricultural machinery in various operating conditions. Modern agricultural machinery is a complex energy-saturated complexes, the performance of which, among other things, depends on the reliability of the engine fuel system [1,2]. One of the main trends in

the development of modern agricultural machinery is the search for alternative energy sources [3,4].

Non-fossil fuels are becoming increasingly important due to their positive impact on reducing exhaust emissions. Studies examining a wide range of biofuels, synthetic fuels, and regenerative fuels have shown that the reduction in carbon dioxide emissions is possible without major changes in the existing infrastructure of internal combustion engines of agricultural machinery [5,6].

Adaptation of modern fuel systems to new fuel types of plant or animal origin is an indispensable condition for ensuring the reliability of complex agricultural machinery [7,8]. This is the essence of the international problem at the stage of the struggle for the energy independence of the country [9,10]. Among the advantages of biodiesel compared to other energy sources, the following should be noted that biodiesel is obtained from renewable sources, its chemical properties are very close to oil [11]. The fuel has good lubricating properties and is quickly decomposed by bacteria when it enters the soil. The use of biodiesel significantly reduces the emissions of greenhouse gases, hydrocarbons, carbon monoxide, soot, and carcinogens; as a result, exhaust fumes are reduced [12,13]. These indicators can positively affect the service life of a diesel engine [14].

The analysis of different types of alternative fuels [15] has shown that fatty acid methyl esters attract more attention than other alternative fuels due to their biological properties and chemical structure. For central Europe as well as countries with similar climatic conditions, the most promising is the use of biofuels based on rapeseed oil, particularly rapeseed oil methyl ester [16,17]. These fuels have a liquid or gaseous state and are produced from green mass or plant seeds [18,19].

However, such fuels differ significantly from traditional liquid hydrocarbon fuels in their physical and chemical properties [20], which affect both the reliability of machine-tractor units and the organization of the working process of an internal combustion engine and the final technical, economic, and environmental indicators of thermal engine [21,22]. Therefore, modern scientific publications indicate that the use of biological fuel is one of the problems of modern society [23,24]. The essence of this problem lies in the fact that the fuel systems of agricultural machinery are designed to operate on diesel oil fuel, which provides a normalized resource. However, the use of biofuel increases the chemical wear of the materials of diesel engine parts, since it is more aggressive than conventional diesel fuel [25,26]. This leads to a decrease in the diesel engine resource, which was considered in [27–29]. However, the authors of these works did not provide the degree of quantitative assessment in the reduction in engine life, which was most significantly (up to 50%) influenced by the fuel system. That is, there is no general methodology for assessing the reliability of fuel systems.

Hönig, V. (2018) [30] proposed an improvement in the reliability of fuel systems by using light metals such as aluminum alloy for the manufacture of engine cylinder-piston group parts. However, in this case, a problem arises, which lies in the poor tribological properties of these light metals as well as in the lower strength compared to the cast iron construction. A similar approach was taken by Mosarof et al. (2016) [31] and Nag et al. (2019) [32], who proposed improving the tribological properties of cylinder liners and increased the mechanical efficiency of the engine when using biodiesel fuel through a thermal spray process and high-velocity oxyfuel coatings, the use of various nano-additives, and the addition of bioethanol to diesel–biodiesel mixtures. However, in all such works, there was no methodology for a comprehensive assessment of the reliability of fuel systems, thanks to which it is possible to compare the effectiveness of increasing the resource of internal combustion engines.

Similar approaches to improving reliability are described in [33] such as improving the tribological characteristics of biodiesel, [34] improved the quality indicators of mixtures of vegetable oils and biodiesel mixtures for diesel engine wear, and [35] increased the viscosity characteristics of engine oil. However, even in these works, there was no comprehensive

methodology for determining reliability, which does not take into account the simplicity of the technique, which led to an overestimation of resources.

Similar shortcomings can be traced in [36] of automated control of the temperature characteristics of systems, and [37] improved the quality of the operating parameters of the environmental performance of engines. However, such approaches complicated the design and increase the cost of equipment operation.

Another important aspect of the use of biofuels is the impact on the environment. Considering the environmental aspects of using biological fuel, researchers have come to the conclusion that such a fuel is more environmentally friendly than diesel fuel [28]. However, the presence of a large amount of methanol in it leads to the decomposition of the materials of the fuel system elements, which reduces the service life of the equipment. To solve this problem, various options are offered:

- the use of additives that reduce the activity of fuel methanols [38];
- reduced wear of precision pairs of the fuel system [39]; and
- periodic flushing of the fuel system [40,41].

However, the proposed options only solved the problem partially, that is, for special cases, without considering it as a whole, for example, only the durability of the engine [42], friction and wear for a diesel engine running on soybean oil [43], and fuel thermodynamics [44].

As a result of the analysis of possible theoretical and experimental ways to study the increase in the reliability of diesel engines when operating on bio-diesel fuel, two main methodological directions have been established. The first includes design and technological methods that require changes in the design parameters of precision joints and improvement in the manufacturing technology of individual parts [45,46]. The second is operational and technological methods associated with ensuring favorable operating conditions for rubbing parts by improving the existing repair and maintenance technology [47,48]. Moreover, the choice of a rational way to increase the resource of diesel engines should be based on data on the wear nature and operating conditions of parts of the assemblies and assemblies. At the heart of both ways to improve the reliability of biodiesel engines of agricultural machinery is the need for its correct assessment. However, the above analysis of the studies carried out in this area showed the least study of issues related to determining the reliability of diesel engine fuel systems operating on various types of fuel. Thus, the purpose of this article was to develop a complex analytical model to determine the reliability of engine fuel systems when operating on biofuels.

To achieve this goal (development of a fuel system reliability model), it is necessary to:

- conduct analytical studies by developing a system of equations to determine the degree of influence of biodiesel fuel on the reliability of the diesel engine fuel system;
- determine complex indicators that will allow to assess the reliability of diesel engines running on biodiesel fuel; and
- conduct experimental studies of the effect of biodiesel fuels on the fuel system of diesel engines, according to the developed model.
- The fulfillment of the tasks set will make it possible to develop a methodology to predict the resource of fuel systems of diesel engines when operating on biodiesel fuel.

2. Materials and Methods

To conduct analytical studies to determine whether the fuel system is in working or non-working condition with the appropriate probability, the Kolmogorov system method was used. Kolmogorov's differential equations are used to describe the variability of the state probabilities of a multi-element system with failures and restorations. In this case, it is assumed that the system operates in continuous time, and its elements change their state under the influence of discrete flows of failures and restorations with intensities λ_k and μ_k , respectively; here, $k = 1, m$, where m is the number of system elements. With the simplest flow of these events (i.e., with an ordinary flow and no after-effect), a Markov process of

system transitions from one state to another arises, which can be described by a system of differential equations.

Experimental studies were carried out in accordance with the plan, which provided for the use of agricultural units during work in the field with a sufficient degree of reliability. The most common MTZ-80 tractors of traction class (1.4) were used as agricultural units. Their number was chosen from the condition of obtaining the required confidence level for this type of agricultural machinery—0.8–0.9, which corresponds to 12 tractors. In accordance with the statistics, the average annual operating time of the MTZ-80 tractors was 1200 moto-hours of operation, and the total resource to failure was 16,000 h of operation. The research was carried out both on new tractors and on tractors with different resources. However, for all 12 tractors, the initial resource of the engine fuel systems was the same. Thus, at the time of the start of the tests, all fuel systems of the studied tractors were in the same conditions.

Operational studies were conducted on biodiesel fuel B-70, which is based on 70% mineral fuel and 30% methyl esters of rapeseed oil. The machines that reached the limiting state were removed from further observation, and the resulting operational failures were eliminated without removing the machines from observation. The obtained information was processed in the following sequence: a statistical series was built and the values of the displacement of the beginning of scattering were determined; the average value and root-mean-square deviation of reliability indicators were determined; the state graph for the nodes of the fuel system of diesel engines was built; the Kolmogorov differential equations were made up and the availability and technical utilization factors were determined; the dependences of the failure probabilities were built, that is, of the transition of the state of the fuel system nodes from one to another, both with the replacement of structural materials and without replacement.

For the integral assessment, complex indicators of the reliability of agricultural machines were used: the coefficients of readiness (K_a) and technical use (K_{tu}). The readiness factor is the ratio of the operating time of the machine (assembly unit) for the pre-repair or overhaul period to the sum of this time and downtime to eliminate operational failures for the same period of operation. The coefficient of technical use allows one to estimate the percentage or fraction of the total downtime duration of the machine during its operation. For tractors, agricultural machines, and their assembly units, this ranged from 0.6 to 0.8, which indicates a low level of maintainability of these machines.

3. Results

3.1. Results of Analytical Studies on the Development of a Fuel System Reliability Model

The fuel system can be represented as several subsystems. Such subsystems that perform independent functions include a fuel tank, a booster pump, a filter, a high-pressure fuel pump, injectors, pipelines, a valve, and seals.

The reliability of the unit depends on the reliability of each of the subsystems as well as on the use of various types of fuel (finely dispersed [36–38]), in particular, biofuel and the adaptation of the fuel system to it. These subsystems can be both in good and faulty condition. Quantitatively, this can be established by the corresponding probability. For the convenience of the mathematical description of the process, it can be represented as a state graph. Event streams characterizing transitions from one state to another have intensities λ_{ij} and $\mu_{1,0}$, and hence the fuel system can have a limited number of discrete states. Therefore, all transitions of the system from the state S_i to the state S_j occur under the influence of the simplest flows of events with intensity λ_{ij} ($i, j = 0, 1, 2, 3 \dots$). The transition of the system from state S_0 (fuel system is in good working order) to S_2 (fuel system is out of order and not working) will occur under the action of the failure flow of the first node, and the reverse transition from state S_2 to S_0 will occur under the action of the end of repair flow.

In our case, the fuel system has eleven possible states. The system under consideration has eleven possible states: $S_0, S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_9$, and S_{10} .

The random process of transition from one state to another can be carried out on the basis of determining the probabilities of the state, which are functions of time $P_0(t)$, $P_1(t)$... $P_{10}(t)$.

Or $P_1(t) = P\{S(t) = S_i\}$, where $P_1(t)$ is the probability that at time t , the system S is in the state S_i .

A schematic graph of the state for the fuel system of a diesel engine is shown in Figure 1.

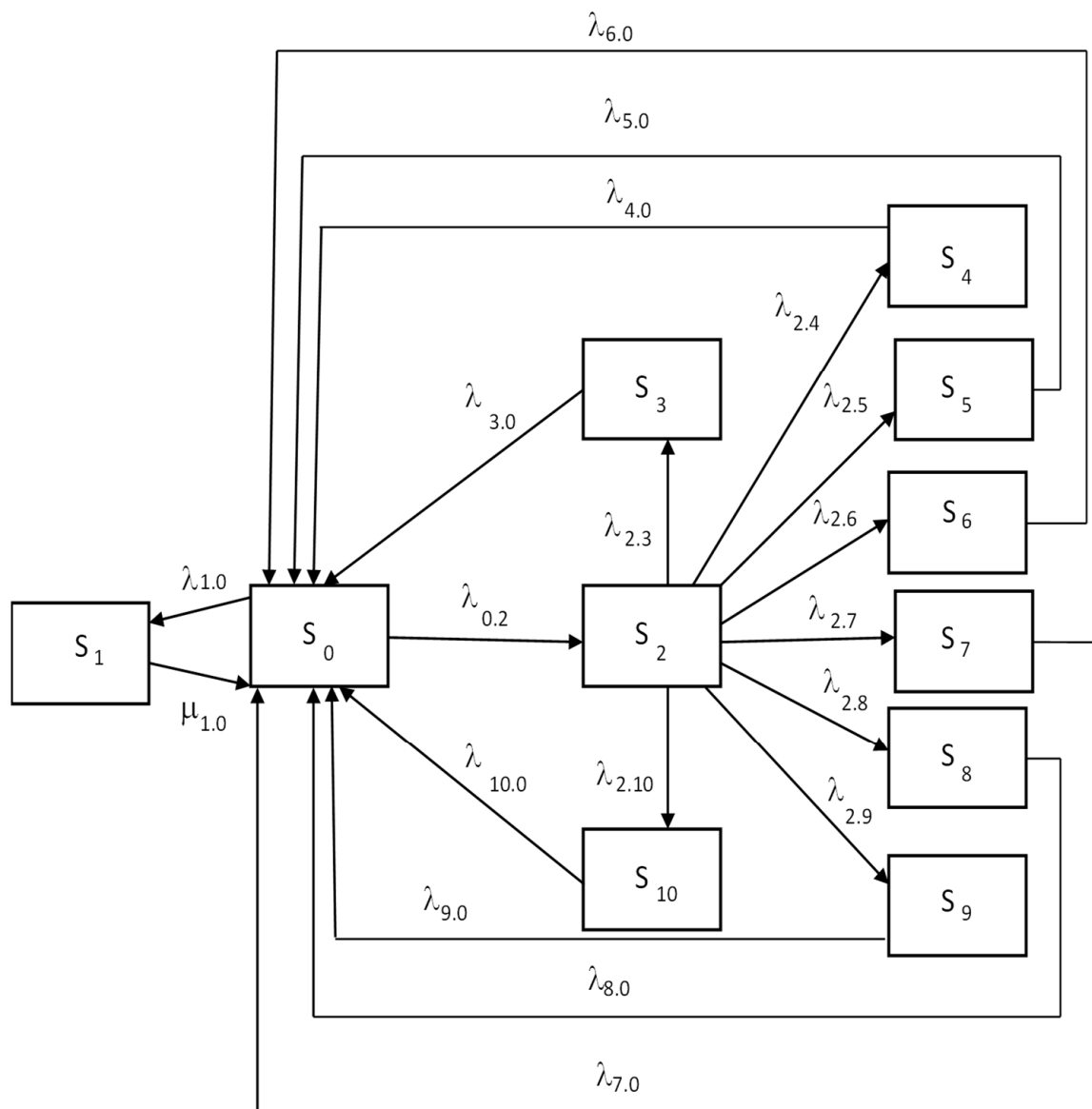


Figure 1. Graph of states of the diesel engine fuel system (FS). S_0 —serviceable and working FS; S_1 —serviceable but not working (downtime) FS; S_2 —faulty and not work (the failure is diagnosed) FS; S_3 —faulty due to fuel tank failure FS; S_4 —faulty due to the failure of the booster pump FS; S_5 —defective due to filter failure FS; S_6 —defective due to failure high pressure fuel pump (HPFP) FS; S_7 —faulty due to injector failure FS; S_8 —faulty due to pipeline failure FS; S_9 —faulty due to valve failure FS; S_{10} —defective due to seal failure FS.

We obtained a system of Kolmogorov differential equations for the probabilities of states. The right side of the equations is the sum of the products of the probabilities of all possible states of subsystems, taking into account the intensity of the corresponding flows

of events that bring the system out of an idle state and multiplied by the probability of this state.

$$\left\{ \begin{array}{l} \frac{dP_0(t)}{dt} = \mu_{10}P_1(t) + \lambda_{30}P_3(t) + \lambda_{40}P_4(t) + \lambda_{50}P_5(t) + \lambda_{60}P_6(t) + \\ \lambda_{70}P_7(t) + \lambda_{80}P_8(t) + \lambda_{90}P_9(t) + \lambda_{100}P_{10}(t) - \lambda_{01}P_0(t) - \lambda_{02}P_0(t) \\ \frac{dP_1(t)}{dt} = \lambda_{01}P_0(t) - \mu_{10}P_1(t) \\ \frac{dP_2(t)}{dt} = \lambda_{02}P_0(t)(\lambda_{2.3} + \lambda_{2.4} + \lambda_{2.5} + \lambda_{2.6} + \lambda_{2.7} + \lambda_{2.8} + \lambda_{2.9} + \lambda_{2.1}) \\ \frac{dP_3(t)}{dt} = \lambda_{2.3}P_2(t) - \lambda_{30}P_3(t) \\ \frac{dP_4(t)}{dt} = \lambda_{2.4}P_2(t) - \lambda_{40}P_4(t) \\ \frac{dP_5(t)}{dt} = \lambda_{2.5}P_2(t) - \lambda_{50}P_5(t) \\ \frac{dP_6(t)}{dt} = \lambda_{2.6}P_2(t) - \lambda_{60}P_6(t) \\ \frac{dP_7(t)}{dt} = \lambda_{2.7}P_2(t) - \lambda_{70}P_7(t) \\ \frac{dP_8(t)}{dt} = \lambda_{2.8}P_2(t) - \lambda_{80}P_8(t) \\ \frac{dP_9(t)}{dt} = \lambda_{2.9}P_2(t) - \lambda_{90}P_9(t) \\ \frac{dP_{10}(t)}{dt} = \lambda_{2.1}P_2(t) - \lambda_{100}P_{10}(t) \end{array} \right. \quad (1)$$

Obviously, for any moment of t , the sum of the probabilities of all states is equal to one:

$$\sum_{i=0}^{i=10} P_i(t) = 1 \quad (2)$$

To solve the system of equations, let us set the initial conditions. In this case, the system is in state S_0 with probability $P_1(0) = 1$. Then, according to the normalization condition, the remaining probabilities of states are equal:

$$P_1(0) = P_2(0) = P_3(0) = P_4(0) = P_5(0) = P_6(0) = P_7(0) = P_8(0) = P_9(0) = P_{10}(0) = 0$$

Using the Kolmogorov equations, it is possible to find the probabilities of states as a function of time. In this case, of interest are the probabilities of the system $P_i(t)$ in the limiting stationary mode ($t \rightarrow \infty$):

$$P_i = \lim_{t \rightarrow \infty} P_i(t) \quad (3)$$

For stationary operation, this is typical. In this mode, the fuel system goes from one state to another, but the probabilities of being in them remain constant. Since the limiting probabilities are constant,

$$\frac{dP_i}{dt} = 0 \quad (4)$$

then, replacing their derivatives in the Kolmogorov equations by zero values, we obtain a system of algebraic equations:

$$\left\{ \begin{array}{l} (\lambda_{01} + \lambda_{02})P_0 = \mu_{10}P_1 + \lambda_{30}P_3 + \lambda_{40}P_4 + \lambda_{50}P_5 + \lambda_{60}P_6 + \\ \lambda_{70}P_7 + \lambda_{80}P_8 + \lambda_{90}P_9 + \lambda_{100}P_{10} \\ \mu_{10}P_1 = \lambda_{01}P_0 \\ (\lambda_{2.3} + \lambda_{2.4} + \lambda_{2.5} + \lambda_{2.6} + \lambda_{2.7} + \lambda_{2.8} + \lambda_{2.9} + \lambda_{2.1})P_2 = \lambda_{02}P_0 \\ \lambda_{30}P_3 = \lambda_{2.3}P_2 \\ \lambda_{40}P_4 = \lambda_{2.4}P_2 \\ \lambda_{50}P_5 = \lambda_{2.5}P_2 \\ \lambda_{60}P_6 = \lambda_{2.6}P_2 \\ \lambda_{70}P_7 = \lambda_{2.7}P_2 \\ \lambda_{80}P_8 = \lambda_{2.8}P_2 \\ \lambda_{90}P_9 = \lambda_{2.9}P_2 \\ \lambda_{100}P_{10} = \lambda_{2.1}P_2 \end{array} \right. \quad (5)$$

Thus, a system of algebraic equations was obtained in which there are eleven unknowns P_0 – P_{10} .

We supplemented these equations with the condition (2) and obtained from the second equation of the system:

$$P_0 = P_2 \left(\frac{\lambda_{2.3} + \lambda_{2.4} + \lambda_{2.5} + \lambda_{2.6} + \lambda_{2.7} + \lambda_{2.8} + \lambda_{2.9} + \lambda_{2.1}}{\lambda_{02}} \right). \quad (6)$$

Furthermore,

$$P_3 = P_2 \left(\frac{\lambda_{2.3}}{\lambda_{30}} \right). \quad (7)$$

$$P_4 = P_2 \left(\frac{\lambda_{2.4}}{\lambda_{40}} \right). \quad (8)$$

$$P_5 = P_2 \left(\frac{\lambda_{2.5}}{\lambda_{50}} \right). \quad (9)$$

$$P_6 = P_2 \left(\frac{\lambda_{2.6}}{\lambda_{60}} \right). \quad (10)$$

$$P_7 = P_2 \left(\frac{\lambda_{2.7}}{\lambda_{70}} \right). \quad (11)$$

$$P_8 = P_2 \left(\frac{\lambda_{2.8}}{\lambda_{80}} \right). \quad (12)$$

$$P_9 = P_2 \left(\frac{\lambda_{2.9}}{\lambda_{90}} \right). \quad (13)$$

$$P_{10} = P_2 \left(\frac{\lambda_{2.1}}{\lambda_{100}} \right). \quad (14)$$

We solved the system by substituting all probabilities in the normalization condition, expressed in terms of P_2 :

$$P_2 \frac{(\lambda_{2.3} + \lambda_{2.4} + \lambda_{2.5} + \lambda_{2.6} + \lambda_{2.7} + \lambda_{2.8} + \lambda_{2.9} + \lambda_{2.1})}{\lambda_{02}} + \frac{\lambda_{01}}{\mu_{10}} \cdot \frac{(\lambda_{2.3} + \lambda_{2.4} + \lambda_{2.5} + \lambda_{2.6} + \lambda_{2.7} + \lambda_{2.8} + \lambda_{2.9} + \lambda_{2.1})}{\lambda_{02}} + P_2 + P_2 \left(\frac{\lambda_{2.3}}{\lambda_{30}} \right) + P_2 \left(\frac{\lambda_{2.4}}{\lambda_{40}} \right) + P_2 \left(\frac{\lambda_{2.5}}{\lambda_{50}} \right) + P_2 \left(\frac{\lambda_{2.6}}{\lambda_{60}} \right) + P_2 \left(\frac{\lambda_{2.7}}{\lambda_{70}} \right) + P_2 \left(\frac{\lambda_{2.8}}{\lambda_{80}} \right) + P_2 \left(\frac{\lambda_{2.9}}{\lambda_{90}} \right) + P_2 \left(\frac{\lambda_{2.1}}{\lambda_{100}} \right) = 1. \quad (15)$$

Hence

$$P_2 \frac{(\lambda_{2.3} + \lambda_{2.4} + \lambda_{2.5} + \lambda_{2.6} + \lambda_{2.7} + \lambda_{2.8} + \lambda_{2.9} + \lambda_{2.1})}{\lambda_{02}} \cdot \left(1 + \frac{\lambda_{01}}{\mu_{10}} \right) + P_2 + \left(\frac{\lambda_{2.3}}{\lambda_{30}} \right) + P_2 \left(\frac{\lambda_{2.5}}{\lambda_{50}} \right) + P_2 \left(\frac{\lambda_{2.6}}{\lambda_{60}} \right) + P_2 \left(\frac{\lambda_{2.7}}{\lambda_{70}} \right) + P_2 \left(\frac{\lambda_{2.8}}{\lambda_{80}} \right) + P_2 \left(\frac{\lambda_{2.9}}{\lambda_{90}} \right) + P_2 \left(\frac{\lambda_{2.1}}{\lambda_{100}} \right) = 1. \quad (16)$$

After conversion, we have:

$$P_2 \left[\frac{\lambda_{2.3} + \dots + \lambda_{2.9} + \lambda_{2.1}}{\lambda_{02}} \left(1 + \frac{\lambda_{01}}{\mu_{10}} \right) + 1 + \left(\frac{\lambda_{2.3}}{\lambda_{30}} + \dots + \frac{\lambda_{2.9}}{\lambda_{90}} + \frac{\lambda_{2.1}}{\lambda_{100}} \right) \right] = 1 \quad (17)$$

From here, P_2 is

$$P_2 = \frac{1}{\left[\left[\frac{\lambda_{2.3} + \dots + \lambda_{2.9} + \lambda_{2.1}}{\lambda_{02}} \left(1 + \frac{\lambda_{01}}{\mu_{10}} \right) + 1 + \left(\frac{\lambda_{2.3}}{\lambda_{30}} + \dots + \frac{\lambda_{2.9}}{\lambda_{90}} + \frac{\lambda_{2.1}}{\lambda_{100}} \right) \right] \right]} \quad (18)$$

$$P_2 = \left[\frac{\lambda_{2.3} + \dots + \lambda_{2.9} + \lambda_{2.1}}{\lambda_{02}} \left(1 + \frac{\lambda_{01}}{\mu_{10}} \right) + 1 + \left(\frac{\lambda_{2.3}}{\lambda_{30}} + \dots + \frac{\lambda_{2.9}}{\lambda_{90}} + \frac{\lambda_{2.1}}{\lambda_{100}} \right) \right]^{-1} \quad (19)$$

Having P_2 , we can define P_0 , P_3 , P_4 , P_5 , P_6 , P_7 , P_8 , P_9 , and P_{10} .

The probability P_1 is found from the normalization condition as the difference:

$$P_1 = 1 - (P_0 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 + P_9 + P_{10}) \quad (20)$$

The obtained probabilities of states can be used as the basis for determining the integrated reliability indicators of the diesel engine fuel system. Therefore, the availability coefficient K_a is the sum of the probabilities of working states, with a serviceable and working fuel system as well as with a serviceable but not working fuel system (idle), for some reason, of a non-technical nature:

$$K_a = P_0 + P_1 \quad (21)$$

We entered the value of probabilities into the formula and obtained:

$$K_a = P_0 + [1 - (P_0 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 + P_9 + P_{10})] \quad (22)$$

Converting the expression, we obtained:

$$K_a = 1 - P_2 - P_3 - P_4 - P_5 - P_6 - P_7 - P_8 - P_9 - P_{10} \quad (23)$$

Expressing the probabilities in terms of P_2 , we have:

$$K_a = 1 - P_2 \left(1 - \frac{\lambda_{2.3}}{\lambda_{30}} + \frac{\lambda_{2.4}}{\lambda_{40}} + \frac{\lambda_{2.5}}{\lambda_{50}} + \frac{\lambda_{2.6}}{\lambda_{60}} + \frac{\lambda_{2.7}}{\lambda_{70}} + \frac{\lambda_{2.8}}{\lambda_{80}} + \frac{\lambda_{2.9}}{\lambda_{90}} + \frac{\lambda_{2.1}}{\lambda_{100}} \right) \quad (24)$$

Substituting into the equation the values of P_2 expressed in terms of intensities, we have the final formula:

$$K_a = \frac{\lambda_{2.3} + \lambda_{2.4} + \lambda_{2.5} + \lambda_{2.6} + \lambda_{2.7} + \lambda_{2.8} + \lambda_{2.9} + \lambda_{2.1}}{\lambda_{2.3} + \dots + \lambda_{2.9} + \lambda_{2.1} + \frac{\lambda_{02}}{(1 + \frac{\lambda_{01}}{\mu_{10}})}} \cdot \left(1 + \frac{\lambda_{2.3}}{\lambda_{30}} + \dots + \frac{\lambda_{2.9}}{\lambda_{90}} + \frac{\lambda_{2.1}}{\lambda_{100}} \right) \quad (25)$$

Considering the issues of the reliability of fuel systems, attention should be paid to another comprehensive indicator of reliability—the coefficient of technical use (K_{tu}). Based on the theory of reliability, the coefficient of technical utilization represents the probability that at any arbitrary moment the fuel system is in use and not idle for repair or diagnostics.

$$K_{tu} = K_a - (P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 + P_9 + P_{10}) \quad (26)$$

We substituted the availability factor into the equation:

$$K_{tu} = 1 - 2(P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 + P_9 + P_{10}) \quad (27)$$

Hence:

$$K_{tu} = 1 - 2P_2 \cdot \left(+ \frac{\lambda_{2.3}}{\lambda_{30}} + \frac{\lambda_{2.4}}{\lambda_{40}} + \frac{\lambda_{2.5}}{\lambda_{50}} + \frac{\lambda_{2.6}}{\lambda_{60}} + \frac{\lambda_{2.7}}{\lambda_{70}} + \frac{\lambda_{2.8}}{\lambda_{80}} + \frac{\lambda_{2.9}}{\lambda_{90}} + \frac{\lambda_{2.1}}{\lambda_{100}} \right) \quad (28)$$

Replacing the probability P_2 in terms of intensities, we obtained:

$$K_{tu} = 1 - \frac{2 \cdot \left(1 + \frac{\lambda_{2.3}}{\lambda_{30}} + \frac{\lambda_{2.4}}{\lambda_{40}} + \frac{\lambda_{2.5}}{\lambda_{50}} + \frac{\lambda_{2.6}}{\lambda_{60}} + \frac{\lambda_{2.7}}{\lambda_{70}} + \frac{\lambda_{2.8}}{\lambda_{80}} + \frac{\lambda_{2.9}}{\lambda_{90}} + \frac{\lambda_{2.1}}{\lambda_{100}} \right)}{\frac{\lambda_{2.3} + \dots + \lambda_{2.9} + \lambda_{2.1}}{\lambda_{02}} \cdot \left(1 + \frac{\lambda_{01}}{\mu_{10}} \right) + 1 + \left(\frac{\lambda_{2.3}}{\lambda_{30}} + \dots + \frac{\lambda_{2.9}}{\lambda_{90}} + \frac{\lambda_{2.1}}{\lambda_{100}} \right)} \quad (29)$$

To determine the intensities of transitions λ_i and μ_{10} of the observed fuel system from one state to another, we used the following correlation:

$$\lambda_i = (T_i)^{-1} \quad (30)$$

$$\mu_{10} = T_{10}^{-1} \quad (31)$$

where T_i is the average time of the i -th operation, h .

Thus, the developed system of equations describing the reliability model makes it possible to give a probabilistic assessment of the presence of fuel system subsystems in two fixed positions: working or non-working, due to a failure in waiting or a repair state.

3.2. Results of Experimental Studies

Experimental studies enabled determining the time for technological maintenance and repair of individual units of the fuel equipment as well as the availability factor of the entire mechanism as a whole. For this, the results of operational studies were used as well as expert assessments of specialists in the repair and maintenance of fuel equipment (Tables 1 and 2).

Table 1. The average values of the time for performing technological operations on the diagnostics of fuel equipment.

Name of Operations	The Nature of the Use of Fuel Biodiesel Systems			
	No Replacement of Materials		With the Replacement of Materials	
	Average Operation Time T_i [h]	Intensity Transition from One State to Another λ_{ij}	Average Operation Time T_i [h]	Intensity Transition from One State to Another λ_{ij}
1. Diagnosing malfunction and preparing for the repair of the fuel tank	$T_{2,3} = 40$	0.025	$T_{2,3} = 30$	0.033
2. Diagnosing malfunction and preparation for repair of the booster pump	$T_{2,4} = 50$	0.02	$T_{2,4} = 40$	0.025
3. Diagnosing fault and preparation for filter repair	$T_{2,5} = 20$	0.05	$T_{2,5} = 15$	0.067
4. Diagnosing malfunction and preparation for repair of the high pressure fuel pump	$T_{2,6} = 80$	0.0125	$T_{2,6} = 65$	0.0153
5. Diagnosing fault and preparation for repair of injectors	$T_{2,7} = 70$	0.0143	$T_{2,7} = 50$	0.02
6. Diagnosing fault and preparation for pipeline repair	$T_{2,8} = 16$	0.063	$T_{2,8} = 10$	0.1
7. Diagnosing fault and preparation for valve repair	$T_{2,9} = 20$	0.05	$T_{2,9} = 18$	0.056
8. Diagnosing fault and preparation for repair of seals	$T_{2,1} = 55$	0.018	$T_{2,1} = 65$	0.015

Next, we calculated the probabilities of transitions of the fuel system from one state to another on biofuel, without replacing the structural materials using Equation (19):

$$P_2 = \left[\left(\frac{0.025+0.02+0.05+0.0125+0.0143+0.063+0.05+0.018}{0.01} \right) \left(1 + \frac{0.19}{1} \right) + \frac{1}{1 + \frac{0.025}{0.0185} + \frac{0.02}{0.0084} + \frac{0.05}{0.067} + \frac{0.0125}{0.0042} + \frac{0.0143}{0.0084} + \frac{0.063}{0.2} + \frac{0.05}{0.034} + \frac{0.018}{0.0084}} \right]^{-1} = 0.022$$

Table 2. Average values of time for performing technological operations for the repair of fuel equipment.

Name of Operations	The Nature of the Use of Fuel Biodiesel Systems			
	Without Replacement of Materials		With the Replacement of Materials	
	Average Operation Time T_i [h]	Intensity Transition from One State to Another λ_{ij}	Average Operation Time T_i [h]	Intensity Transition from One State to Another λ_{ij}
1. Fuel tank repair	$T_{30} = 80$	0.0125	$T_{30} = 80$	0.0125
2. Booster pump repair	$T_{40} = 120$	0.0084	$T_{40} = 120$	0.0084
3. Filter repair	$T_{50} = 15$	0.067	$T_{50} = 15$	0.067
4. HPFP repair	$T_{60} = 240$	0.0042	$T_{60} = 240$	0.0042
5. Injector repair	$T_{70} = 120$	0.0084	$T_{70} = 120$	0.0084
6. Pipeline repair	$T_{80} = 5$	0.2	$T_{80} = 5$	0.2
7. Valve repair	$T_{90} = 30$	0.034	$T_{90} = 30$	0.034
8. Seals repair	$T_{100} = 120$	0.0084	$T_{100} = 1$	0.0084
9. Preparation for the diagnosis of repair work	$T_{02} = 100$	0.01	$T_{02} = 90$	0.011

From here, according to Equations (7)–(14), we calculated the probabilities:

$P_3 = 0.044$; $P_4 = 0.052$; $P_5 = 0.0165$; $P_6 = 0.066$; $P_7 = 0.0374$; $P_8 = 0.00693$; $P_9 = 0.032$; $P_{10} = 0.047$.

Through Equation (6), we find that $P_0 = 0.022 \cdot 25.3 = 0.56$.

P_1 , according to Equation (20), is equal to $P_1 = 1 - 0.9 = 0.1$.

Hence, the availability factor for the fuel system, using biofuel, without replacing structural materials, is calculated according to Equation (21), and the technical utilization coefficient according to Equation (26)

$$K_a = 0.056 + 0.1 = 0.66$$

$$K_{tu} = 0.66 - 0.30 = 0.36$$

Figures 2 and 3 show the probability diagrams of transitions from one state to another of the fuel equipment subsystems without replacement and with replacement of the structural materials.

We calculated the probabilities of transitions of the fuel system from one state to another when operating on biofuel and replacing structural materials with a biodiesel fuel inert to an aggressive environment using Equation (19):

$$P_2 = \left[\frac{(0.033+0.025+0.067+0.0153+0.02+0.1+0.056+0.025)}{0.011} \left(1 + \frac{0.19}{1}\right) + 1 + \frac{0.033}{0.0185} + \frac{0.025}{0.0084} + \frac{0.067}{0.067} + \frac{0.0153}{0.0042} + \frac{0.02}{0.0084} + \frac{0.01}{0.2} + \frac{0.056}{0.034} + \frac{0.015}{0.0084} \right]^{-1} = 0.011$$

From here, according to Equations (7)–(14), we calculated the probabilities:

$P_3 = 0.045$; $P_4 = 0.05$; $P_5 = 0.017$; $P_6 = 0.062$; $P_7 = 0.04$; $P_8 = 0.0025$; $P_9 = 0.028$; $P_{10} = 0.02$. Using Equation (6), we found that P_0 is

$$P_0 = 0.011 \times 34.13 = 0.38$$

P_1 , according to Equation (20), is equal to $P_1 = 1 - 0.825 = 0.175$.

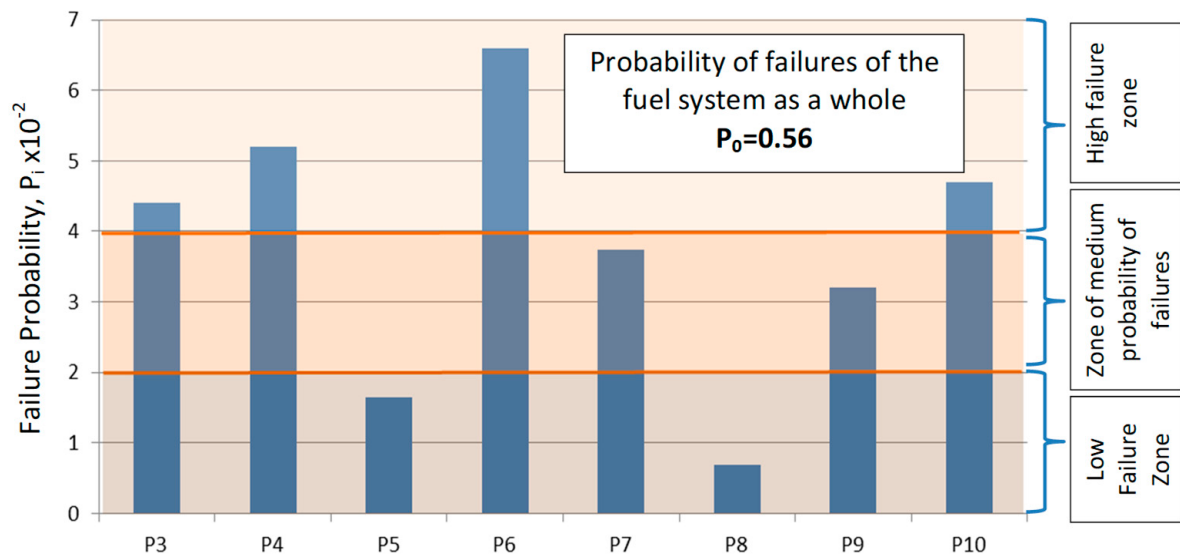


Figure 2. Diagram of failure probabilities of engine fuel system elements without the replacement of structural materials: P_3 —fuel tank failure probability; P_4 —the probability of a booster pump failure; P_5 —probability of filter failure; P_6 —the probability of failure of the high-pressure fuel pump; P_7 —probability of injector failure; P_8 —the probability of pipeline failure; P_9 —the probability of valve failure; P_{10} —probability of seal failure.

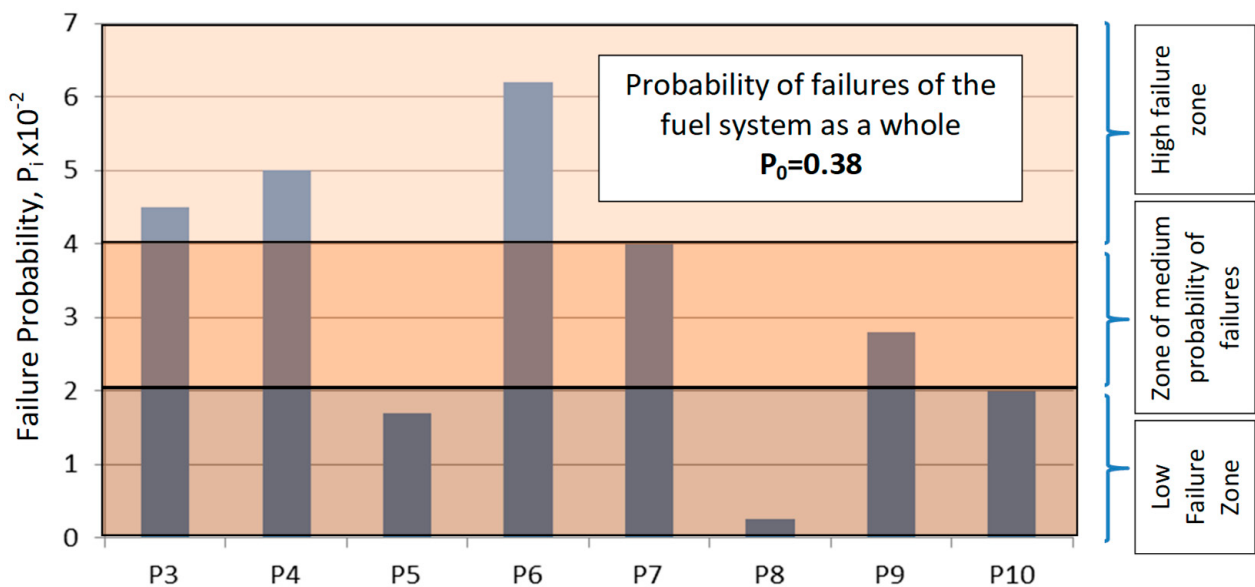


Figure 3. Diagram of failure probabilities of engine fuel system elements with the replacement of structural materials: P_3 —the probability of a fuel tank failure; P_4 —the probability of a booster pump failure; P_5 —probability of filter failure; P_6 —the probability of failure of the high pressure fuel pump; P_7 —probability of injector failure; P_8 —the probability of pipeline failure; P_9 —the probability of valve failure; P_{10} —the probability of failure of the seals.

Hence, the availability factor for the fuel system on biofuel, with the replacement of structural materials, can be calculated according to Equation (21) and the technical utilization coefficient according to Equation (26):

$$K_a = 0.53 + 0.175 = 0.71,$$

$$K_{tu} = 0.71 - 0.31 = 0.40.$$

The analysis of the influence of individual subsystems on the overall performance and reliability of the fuel system showed that the highest probability of being in a state of repair before replacing materials occurred due to the failure of the high pressure fuel pump and seals, and the failure probabilities were $P_6 = 0.066$ and $P_{10} = 0.047$, respectively. The probability of resource decline was due to the low resistance to methanol of the biodiesel fuel materials of plunger pairs of fuel pumps and seals. Furthermore, the booster pump $P_4 = 0.052$, injectors $P_7 = 0.0374$, and valves $P_9 = 0.032$ had high failure rates.

After the replacement of structural materials, the probability of failure decreases, respectively: high-pressure fuel pump $P_6 = 0.062$, seals $P_{10} = 0.02$, booster pump $P_4 = 0.05$, injector $P_7 = 0.04$, and valve $P_9 = 0.028$. The probability of failures of the fuel system as a whole decreased by more than 32%.

The analysis of the diagram showed that increasing the service life of the fuel system in working mode is possible by reducing the downtime of machine-tractor units.

It is obvious that the replacement of some construction materials does not completely solve the problem of ensuring the reliability of the fuel system when operating on biodiesel. To increase the reliability, namely, the coefficient of readiness and the coefficient of technical use as complex indicators, it is necessary to carry out additional measures, both technical, operational, and structural. Among the factors that cause a decrease in reliability, the most significant are working conditions (15–20%), operating modes (50–60%), and the physical and chemical properties of structural materials used to manufacture individual elements (25–30%).

4. Discussion

The main function of any system (including diesel engine fuel system) is to operate without fail during the specified service life while maintaining the parameters within the established norms. A more important property of reliability is non-failure operation, that is, the possibility of non-failure operation [10]. Considering the fuel systems of tractors as complex technical systems prone to various types of failures, we proposed a reliability model that allows, according to the statistical characteristics of the time between failures of their elements, to obtain averaged time values normalized in the technical conditions for performing technological operations for the maintenance and repair of fuel equipment [fourteen], which were evaluated by K_a and K_{tu} .

Availability factor (K_a) characterizes the probability that the tractor will be in working condition at any time when it should be working. This coefficient characterizes unscheduled repairs—the elimination of failures—and its value is determined by two indicators, only reliability and maintainability, therefore, depends on the number and complexity of failures and the fuel system's ability to eliminate them. This coefficient reflects the negative fact that the preventive maintenance and repair system does not adequately fulfill its purpose—complete prevention and elimination of failures between maintenance.

The technical utilization coefficient (K_{tu}) is similar to the availability coefficient, but unlike it, it additionally characterizes the reduction in the duration of work by the amount of time spent on scheduled maintenance of the tractor.

The coefficient of technical use depends on three indicators of reliability: reliability, maintainability, and durability. It increases with a clearer organization of repair and maintenance, with an aggregate method of repair, when carrying out maintenance outside the period of field work or outside working hours, with sufficient availability of materials and spare parts.

Thanks to this, we obtained the opportunity, using a specific example of the fuel system of tractors when operating on biodiesel fuel, to implement one of the fundamental principles for improving the reliability of technical systems, the essence of which is to identify and eliminate malfunctions of subsystem elements that limit the operational reliability of the fuel system in operation on failure and reduced time for troubleshooting.

The description of the functioning of the systems is given in the form of a state graph. The mathematical model of the functioning of the system is a system of ordinary differential

equations. The system of linear differential equations with constant coefficients was solved analytically for a limited number of elements at a fixed value of failure and recovery rates [43]. To establish the nodes limiting the reliability of the fuel system, using statistical data, dependencies of the failure probabilities for their main elements were obtained.

As a result of the experimental studies, it was found that the use of biodiesel fuel in the operation of mobile agricultural machinery adversely affects the reliability of its functional systems. Biodiesel fuel is more aggressive toward fuel system construction materials than mineral diesel fuel.

It was determined that among the possible failure probabilities of fuel system elements, the main role belongs to the high pressure fuel pump and seals (0.047–0.066). Plunger pairs are the limiting reliability factor in a high pressure fuel pump and are particularly affected by the mode of operation (dynamic or static). In the static mode, the surface layer of the metal is saturated with hydrogen, followed by its destruction. The appearance of free hydrogen on the surface of materials, which promotes the formation of oxide films and the penetration of hydrogen into the surface layers of the metal, leads to hydrogen wear [47]. Leveling this negative activity is possible by reducing the amount of methanol in biodiesel and replacing some structural materials with biofuels that are inert to the environment. To reduce the negative impact of this process, it is necessary to reduce the total downtime of equipment.

To increase the service life of fuel systems, it is necessary to replace the sealing materials for engine fuel systems made of natural or synthetic rubber with fluoroplastics. This will increase the reliability of the engine as a whole by 3–4 times [44,45].

In addition, the booster pump, nozzles, and valves were distinguished by rather high failure probabilities (0.032–0.052). To reduce the wear dynamics, it is necessary to provide for the possibility of additional flushing of the engine with mineral fuel during its long stops. For injectors, one way to increase reliability is to increase the diameter of the injector nozzles.

The calculated parameters determine the complex indicators of the reliability model, the coefficient of availability and technical use, the values of which were in the range of 0.66–0.71 and 0.36–0.4, respectively.

The experimentally obtained values of reliability indicators indicated that the use of biodiesel fuel leads to a decrease in smoke, a decrease in oxides of solid particles, and an increase in CO₂ and NO_x. At the same time, the complex of total emissions of NO_x and particulate matter for mineral fuel is higher than for biodiesel fuel [49,50].

After the replacement of structural materials, the probability of failures decreases. In general, the probability of fuel system failures decreased by more than 32%. This increases the resource of the fuel system, and hence the engine and the tractor as a whole.

5. Conclusions

As a result of the research carried out, for the first time, a reliability model of engine fuel systems operating on biofuel based on the Markov process was developed. The model takes into account the probabilistic indicators and is designed to assess the reliability of complex mechanisms. Using the obtained dependences of the analytical model, it is possible to reliably assess the degree of influence of biodiesel fuel on the reliability of the diesel fuel system and the performance of the machine-tractor unit. The resulting model allows for complex comparisons of the effectiveness of various ways to improve the reliability of engines running on biodiesel fuel.

According to the developed model, experimental studies were carried out to determine the complex reliability indicators. The availability factor of the fuel system when operating on biodiesel fuel without the replacement of structural materials was 0.66, while with the replacement of 0.71, and the coefficient of technical utilization without replacement of materials was 0.36, and with the replacement of 0.4. At the same time, the time for performing technological operations for the maintenance and repair of fuel equipment decreased by 10–25%. Since the availability factor is a complex indicator in assessing the

reliability of functional systems, it is obvious that one of the ways to improve it can be to replace the structural materials of the diesel fuel system with a biodiesel fuel inert to the aggressive environment, which is based on carboxylic acids.

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References

1. Čedík, J.; Pexa, M.; Mader, D.; Pražan, R. Combustion characteristics of compression ignition engine operating on rapeseed oil-diesel fuel blends. *Agron. Res.* **2019**, *17*, 957–973.
2. De, T.; Sikder, J.; Narayanan, C.M. Biodiesel synthesis using immobilised lipase enzyme in semi-fluidised bed bioreactors—Bioreactor design and performance analysis. *Environ. Prog. Sustain. Energy* **2017**, *36*, 1537–1545. [\[CrossRef\]](#)
3. Martin, S.S.; Chebak, A.; El Ouafi, A.; Mabrouki, M. Modeling and Simulation of Hybrid Power System Integrating Wind, Solar, Biodiesel Energies and Storage Battery. In Proceedings of the 2016 International Renewable and Sustainable Energy Conference (IRSEC), Marrakech, Morocco, 14–17 November 2016; pp. 457–463. [\[CrossRef\]](#)
4. Janardhana, K.; Sridhar, S.; Dixit, C.K.; Deivakani, M.; Tamilselvi, S.; Kaladgi, A.R.; Afzal, A.; Baig, M.A.A. ANFIS modeling of biodiesels' physical and engine characteristics: A review. *Heat Transf.* **2021**, *50*, 8052–8079. [\[CrossRef\]](#)
5. Oke, E.O.; Adeyi, O.; Okolo, B.I.; Ude, C.J.; Adeyi, J.A.; Salam, K.K.; Nwokie, U.; Nzeribe, I. Heterogeneously catalyzed biodiesel production from Azadirachta indica oil: Predictive modelling with uncertainty quantification, experimental optimization and techno-economic analysis. *Bioresour. Technol.* **2021**, *332*, 125141. [\[CrossRef\]](#)
6. Georgogianni, K.G.; Kontominas, M.G.; Pomonis, P.J.; Avlonitis, D.; Gergis, V. Conventional and in situ transesterification of sunflower seed oil for the production of biodiesel. *Fuel Process. Technol.* **2008**, *89*, 503–509. [\[CrossRef\]](#)
7. Kovalenko, N.; Hutsol, T.; Labenko, O.; Glowacki, S.; Sorokin, D. Ecological and Economical Substitution of Production of Hydrogen. In *ENVIRONMENT. TECHNOLOGIES. RESOURCES. Proceedings of the International Scientific and Practical Conference*; Rezekne Academy of Technologies: Rezekne, Latvia, 2021; Volume 1, pp. 127–131. [\[CrossRef\]](#)
8. Kovalenko, N.; Kovalenko, V.; Hutsol, T.; Ievstafieva, Y.; Polishchuk, A. Economic Efficiency and Internal Competitive Advantages of Grain Production in The Central Region of Ukraine. *Agric. Eng.* **2021**, *25*, 51–62. [\[CrossRef\]](#)
9. Kukharets, S.; Hutsol, T.; Glowacki, S.; Sukmaniuk, O.; Rozkosz, A.; Tkach, O. Concept of Biohydrogen Production by Agricultural Enterprises. *Agric. Eng.* **2021**, *25*, 63–72. [\[CrossRef\]](#)
10. Mohapatra, A.K.; Senapati, A.K.; Jha, G.; Sharma, K.; Kumar, P. Preheating of sunflower blended biodiesel for the improvement of performance characteristics of a DI diesel engine under various loads. *Int. J. Eng. Adv. Technol.* **2019**, *8*, 921–926. [\[CrossRef\]](#)
11. Singh, P.; Goel, V.; Chauhan, S.R. Effects of dual biofuel approach for total elimination of diesel on injection system by reciprocating friction monitor. *Proc. Inst. Mech. Eng. Part J J. Eng. Tribol.* **2018**, *232*, 1068–1076. [\[CrossRef\]](#)
12. Singh, P.; Chauhan, S.R. Influence of temperature on tribological performance of dual biofuel. *Fuel* **2017**, *207*, 751–762. [\[CrossRef\]](#)
13. Tziourtzioumis, D.; Demetriades, L.; Zogou, O.; Stamatelos, A.M. Experimental investigation of the effect of a B70 biodiesel blend on a common-rail passenger car diesel engine. *Proc. Inst. Mech. Eng. Part D J. Automob. Eng.* **2009**, *223*, 685–701. [\[CrossRef\]](#)
14. Ahmed, S.A.; Zhou, S.; Zhu, Y.; Feng, Y.; Malik, A.; Huang, Y. Numerical and comparative study of butanol and ethanol diesel blends in a turbocharged compression ignition diesel engine 2019. *Int. Agric. Eng. J.* **2009**, *28*, 19–32.
15. Lin, B.-F.; Huang, J.-H.; Huang, D.-Y. Experimental study of the effects of vegetable oil methyl ester on DI diesel engine performance characteristics and pollutant emissions. *Fuel* **2009**, *88*, 1779–1785. [\[CrossRef\]](#)
16. Tryhuba, A.; Hutsol, T.; Tryhuba, I.; Pokotyńska, N.; Kovalenko, N.; Tabor, S.; Kwasniewski, D. Risk Assessment of Investments in Projects of Production of Raw Materials for Bioethanol. *Processes* **2021**, *9*, 12. [\[CrossRef\]](#)
17. Yildiz, I.; Caliskan, H.; Mori, K. Energy, exergy and environmental assessments of biodiesel and diesel fuels for an internal combustion engine using silicon carbide particulate filter. *J. Therm. Anal. Calorim.* **2021**, *145*, 739–750. [\[CrossRef\]](#)
18. Tryhuba, A.; Bashynsky, O.; Hutsol, T.; Rozkosz, A.; Prokopova, O. Parameters of the Energy Supply System of Agricultural Enterprises with Using Wind Power Installations. In Proceedings of the 6th International Conference—Renewable Energy Sources (ICoRES 2019), Krynica, Poland, 12–14 June 2019; Volume 154, p. 06001. [\[CrossRef\]](#)

19. Marczak-Grzesik, M.; Budzyń, S.; Tora, B.; Szufa, S.; Kogut, K.; Burmistrz, P. Low-Cost Organic Adsorbents for Elemental Mercury Removal from Lignite Flue Gas. *Energies* **2021**, *14*, 2174. [\[CrossRef\]](#)
20. Ganesan, R.; Manigandan, S.; Shanmugam, S.; Chandramohan, V.P.; Sindhu, R.; Kim, S.H.; Brindhadevi, K.; Pugazhendhi, A. A detailed scrutinize on panorama of catalysts in biodiesel synthesis. *Sci. Total Environ.* **2021**, *777*, 145683. [\[CrossRef\]](#)
21. De Faria, D.R.G.; de Medeiros, J.L.; Araújo, O.D.Q.F. Screening biorefinery pathways to biodiesel, green-diesel and propylene-glycol: A hierarchical sustainability assessment of process. *J. Environ. Manag.* **2021**, *300*, 113772. [\[CrossRef\]](#)
22. Milojević, S.; Džunić, D.; Marić, D.; Mitrović, S.; Pešić, R. Tribological assessment of aluminum cylinder material for piston compressors in trucks and buses brake systems. *Int. J. Engine Res.* **2021**, *22*, 2267–2280.
23. Senthil Kumar, A.P.; Yuvaraj, S.; Thomas Renald, C.J.; Janaki, S.; Sadesh, K. A review of the performance and emission characteristics of a stationary diesel engine fueled by schleicheraleosa oil methyl ester (Some), blends of neem biodiesel, Rice bran biodiesel, palm and palm Kernel oil, Jatropha oil. *Int. J. Mech. Prod. Eng. Res. Dev.* **2019**, *9*, 857–861.
24. Molina, G.J.; Morrison, J.; Carapia, C.; Soloiu, V. A study on viscosity and lubricity effects of n-butanol and its mixtures in oil. In Proceedings of the STLE 2019—74th Annual Meeting and Exhibition of the Society of Tribologists and Lubrication Engineers, Nashville, TN, USA, 19–23 May 2019; pp. 105–109.
25. Silva, J.R.; Carvalho Filho, M.G.A.; Brasilino, T.C.; Bicudo, I.M.G.; Santos, A.G.; Souza Candeia, R.A. Influence of soybean biodiesel content on basic properties of biodiesel-diesel blends. *Fuel* **2009**, *88*, 738–743. [\[CrossRef\]](#)
26. Janakiraman, S.; Lakshmanan, T.; Chandran, V.; Subramani, L. Comparative behavior of various nano additives in a DIESEL engine powered by novel Garcinia gummi-gutta biodiesel. *J. Clean. Prod.* **2020**, *245*, 118940. [\[CrossRef\]](#)
27. Caligiuri, C.; Renzi, M.; Bietresato, M.; Baratieri, M. Experimental investigation on the effects of bioethanol addition in diesel-biodiesel blends on emissions and performances of a micro-cogeneration system. *Energy Convers. Manag.* **2019**, *185*, 55–65. [\[CrossRef\]](#)
28. Zare, A.; Stevanovic, S.; Jafari, M.; Verma, P.; Babaie, M.; Yang, L.; Brown, R.J.; Bodisco, T.A. Analysis of cold-start NO₂ and NO_x emissions, and the NO₂/NO_x ratio in a diesel engine powered with different diesel-biodiesel blends. *Environ. Pollut.* **2021**, *290*, 118052. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Kurczyński, D. Effect of the rme biodiesel on the diesel engine fuel consumption and emission. *Commun. Sci. Lett. Univ. Zilina* **2021**, *23*, B308–B316. [\[CrossRef\]](#)
30. Hönig, V. Specifications of wear of oils in two-fuel systems. *Manuf. Technol.* **2018**, *18*, 567–571. [\[CrossRef\]](#)
31. Mosarof, M.H.; Kalam, M.A.; Masjuki, H.H.; Alabdulkareem, A.; Habibullah, M.; Arslan, A.; Monirul, I.M. Assessment of friction and wear characteristics of Calophyllum inophyllum and palm biodiesel. *Ind. Crops Prod.* **2016**, *83*, 470–483. [\[CrossRef\]](#)
32. Nagy, A.L.; Knaup, J.; Zsoldos, I. A friction and wear study of laboratory aged engine oil in the presence of diesel fuel and oxymethylene ether. *Tribol. Mater. Surf. Interfaces* **2019**, *13*, 20–30. [\[CrossRef\]](#)
33. Peng, D.-X. Room temperature tribological performance of biodiesel (soybean oil). *Ind. Lubr. Tribol.* **2016**, *68*, 617–623. [\[CrossRef\]](#)
34. Reddy, M.S.; Sharma, N.; Agarwal, A.K. Effect of straight vegetable oil blends and biodiesel blends on wear of mechanical fuel injection equipment of a constant speed diesel engine. *Renew. Energy* **2016**, *99*, 1008–1018. [\[CrossRef\]](#)
35. Singh, P.; Goel, V.; Chauhan, S.R. Impact of dual biofuel approach on engine oil dilution in CI engines. *Fuel* **2017**, *207*, 680–689. [\[CrossRef\]](#)
36. Kiktev, N.; Lendiel, T.; Vasilenkov, V.; Kapralyuk, O.; Hutsol, T.; Glowacki, S.; Kuboń, M.; Kowalczyk, Z. Automated Microclimate Regulation in Agricultural Facilities Using the Air Curtain System. *Sensors* **2021**, *21*, 8182. [\[CrossRef\]](#)
37. Dzieniszewski, G.; Kuboń, M.; Pristavka, M.; Findura, P. Operating Parameters and Environmental Indicators of Diesel Engines Fed with Crop-Based Fuels. *Agric. Eng.* **2021**, *25*, 13–28. [\[CrossRef\]](#)
38. Borek, K.; Romaniuk, W.; Roman, K.; Roman, M.; Kuboń, M. The Analysis of a Prototype Installation for Biogas Production from Chosen Agricultural Substrates. *Energies* **2021**, *14*, 2132. [\[CrossRef\]](#)
39. Khokhlov, A.; Golubev, V.; Khokhlov, A.; Marin, D.; Golubev, S. Decreasing the wear of precision pairs of fuel injection equipment in diesel engines. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2019; Volume 403, p. 012101.
40. Sudan, R.D.M.; Nanthagopal, K. Tribological aspects of biofuels—A review. *Fuel* **2019**, *258*, 116066. [\[CrossRef\]](#)
41. Rocabrano-Valdés, C.I.; González-Rodríguez, J.G.; Díaz-Blanco, Y.; Juantorena, A.U.; Muñoz-Ledo, J.A.; El-Hamzaoui, Y.; Hernández, J.A. Corrosion rate prediction for metals in biodiesel using artificial neural networks. *Renew. Energy* **2019**, *140*, 592–601. [\[CrossRef\]](#)
42. Jain, N.L.; Soni, S.L.; Poonia, M.P.; Sharma, D.; Srivastava, A.K.; Jain, H. A durability study of a compression ignition engine operating with Thumba (*Citrullus colocynthis*) vegetable oil. *Environ. Sci. Pollut. Res.* **2019**, *26*, 8992–9004. [\[CrossRef\]](#)
43. Xiao, H.; Zou, H.; Liu, S.; Li, C. An investigation of the friction and wear behavior of soybean biodiesel. *Tribol. Int.* **2019**, *131*, 377–385. [\[CrossRef\]](#)
44. Tucki, K.; Mruk, R.; Orynych, O.; Wasiak, A.; Świć, A. Thermodynamic fundamentals for fuel production management. *Sustainability* **2019**, *11*, 4449. [\[CrossRef\]](#)
45. Holubek, M.; Pexa, M.; Pavlu, J.; Cedík, J.; Vesela, K.; Kuchar, P. Analysis of the influence of fuel on oil charge and engine wear. *Manuf. Technol.* **2019**, *19*, 64–70. [\[CrossRef\]](#)

46. Dharma, S.; Sebayang, A.H.; Silitonga, A.S.; Sebayang, R.; Sarjianto; Ginting, B.; Damanik, N.; Ramlan, Y.P.; Alif, H.H. Corrosion behaviours of mild steel in biodiesel-diesel fuel blend. In Proceedings of the 2018 International Conference on Applied Science and Technology (iCAST), Manado, Indonesia, 26–27 October 2018; Volume 8751635, pp. 10–15.
47. Nagy, A.L.; Knaup, J.; Zsoldos, I.A.L.; Knaup, J.; Zsoldos, I.; Knaup, J. A review on the effect of alternative fuels on the friction and wear of internal combustion engines. In *Vehicle and Automotive Engineering; Lecture Notes in Mechanical Engineering*; Springer: Cham, Switzerland, 2018; pp. 42–55.
48. Sinha, S.; Agarwal, A.K. Experimental investigation of the effect of biodiesel utilization on lubricating oil degradation and wear of a transportation cid engine. *J. Eng. Gas Turbines Power* **2010**, *132*, 042801. [[CrossRef](#)]
49. Shamun, S.; Belgiorno, G.; Blasio, G.D. *Engine Parameters Assessment for Alcohols Fuels Application in Compression Ignition Engines*; Springer: Singapore, 2020; Volume 8, pp. 125–139. [[CrossRef](#)]
50. Niculescu, R.; Clenci, A.; Iorga-Siman, V. Review on the Use of Diesel–Biodiesel–Alcohol Blends in Compression Ignition Engines. *Energies* **2019**, *12*, 1194. [[CrossRef](#)]