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Determination of the Risk of Failures of Locomotive Diesel Engines in Maintenance

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Abstract: This article presents a mathematical model of the risk of failures, depending on the operating parameters, of locomotive diesel engines. The purpose of this study is to determine the risk of failures of locomotive diesel engines in maintenance. The theory of probability and the theory of logic and reliability are used in this theoretical study. The innovations and main works are the first approaches to calculating the risk of failures of locomotive diesel engines by hourly fuel consumption, which, under operational conditions, allows for extending the life of locomotive diesel engines during maintenance. As a result, a maintenance process for 5D49 diesel engines is developed in a locomotive depot. When managing the maintenance processes of 5D49 diesel engines in the locomotive depot, it is determined that the optimal mileage is 45,000 km. The resource of 5D49 diesel engines in the locomotive depot increased by 2.4% in the management of the maintenance process compared to the existing maintenance system.

Keywords: maintenance; risk; locomotive diesel engines; management; reliability; probability of failure-free operation

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Citation: Baranovskyi, D.; Bulakh, M.; Michajłyszyn, A.; Myamlin, S.; Muradian, L. Determination of the Risk of Failures of Locomotive Diesel Engines in Maintenance. *Energies* **2023**, *16*, 4995. https://doi.org/10.3390/en16134995

Academic Editor: Constantine D. Rakopoulos

Received: 2 June 2023
Revised: 21 June 2023
Accepted: 25 June 2023
Published: 27 June 2023

1. Introduction

During the operation of locomotive diesel engines (LDEs), a natural aging process occurs, and the number of failures increases [1,2]. Eliminating the effects of a failure in operation is accompanied by significant costs. It is advisable to use some maintenance and repair processes to increase the reliability and durability of LDEs. Maintenance and repair processes consist of a set of targeted technical actions aimed at restoring the nominal values of LDE technical parameters. At the same time, resource can be restored and the probability of the failure-free operation of the LDE is increased [1,3,4].

The regulation of the maintenance and repair of LDEs, which work in various and changing environmental conditions, depending on the average operating time or the mileage, cannot and does not ensure the good condition of assemblies and mechanisms. As a result of this regulation, under harsh environmental conditions, LDE assemblies and mechanisms cannot be serviced and repaired in a timely manner. Therefore, LDEs operate under the conditions of the intensive wear of parts and work under the intensive contamination of the corresponding protective devices. Under normal operating conditions of LDEs, individual repair and maintenance activities are often performed prematurely. As a result, the working time of LDEs is wasted [5]. In practice, simple maintenance and repair technology refers to planned activities.

The period of the maintenance and repair of individual LDEs can be determined based on the probability of a failure-free operation [1,6]. It would be logical to assume that the maximum information on the change in the technical condition of individual LDEs will provide an opportunity to select the optimal combination and algorithm of technical actions in maintenance and repair systems.

Unfortunately, today, such maintenance and repair systems do not take into account the current technical resources of components and parts.

Many attempts have been made to address the issue of predicting resources and determining the timing of the maintenance and repair of engines, depending on the operational characteristics [4,6–9]. However, this issue has still not been resolved.

The use of diagnostic methods for certain parts, assemblies, or systems of LDEs [7,10–13] has been proposed for carrying out maintenance and repairs if there is any change in operational characteristics. However, the diagnostic information obtained about the technical condition of LDE to predict maintenance and repair timing is based on statistical information that is constantly changing. In addition, statistical information is collected for the specific operating conditions of LDEs.

The probability of a failure-free operation can be assessed by considering the risks that arise during the operation of an LDE [6,12,14–21]. If the risk of failures of an LDE is determined, then it is possible to build a maintenance system.

Let us present a short review of the literature on this research topic.

In [4,9], a method was presented to predict the durability of an engine based on measuring the wear of the elements of the piston–ring–cylinder system, and modeling was also performed. The disadvantage of this method is the need to know the nature and amount of wear in order to accurately forecast the engine's durability.

In the works of [7,22–24], it was shown that the most common method of determining the residual resource of engines, in practice, is the method of mathematical statistics and probability theory. The disadvantage of this method is that it can only be used to determine the residual engine resource of the fuel device.

In [13], the service life of the crankshaft bearings of the crankshaft of engines was determined based on the calculation of the hydromechanical characteristics. The disadvantage of the above study is the absence of a mathematical relationship between the resource of the engine crankshaft bearings and the hydromechanical characteristics, as well as the impossibility of applying the method to the entire engine.

In [19], an engine durability assessment algorithm was defined, which may allow optimizing the maintenance process and engine reliability. However, the authors used only statistical data and did not provide mathematical relationships to assess durability.

In many works, for example, those of [2,3,25–30], engine oil characteristics were used to estimate the service resource of car engines. Basically, these studies were intended to establish the timing of engine maintenance and indirectly allow the assessment or prediction of engine durability. The disadvantage of this approach is the need for constant access to the engine to take engine oil samples.

In [7], a simulation model of the repair and diagnostic complex was developed, which allows for the evaluation of the characteristics of its functioning. Such a model can only be applied to oilfield facilities. In [31], the basic principles of creating models of complex systems and a software implementation were presented. This study is applicable only to complex geographically distributed technical systems. In [32], semi-Markov availability models with discrete states were constructed. However, the application of this work is impossible.

It is also known that machine learning systems have been used to predict engine life and repair times [5,13,20,33–45]. However, all of these methods are very voluminous.

Many attempts have been made to solve the problem of predicting resources and determining the timing of engine maintenance and repair, depending on operational characteristics [4,7,9]. However, this problem has still not been resolved.

It should also be noted that there is no approach for the construction of a maintenance system or for managing the maintenance processes of LDEs based on identifying the risk of failures.

In [1,6], studies of the durability of LDEs were given. In this case, the resource is determined based on the relative and hourly fuel consumption, and the prediction of the durability of LDEs is made by taking into account the probability of the failure-free operation.

The approaches given in [1,6] will be used in this work.

In [8,12,14–18,21,26,46–49], security systems on the basis of risks were constructed. These approaches will also be used in this work to determine the risk of failures of diesel engines to manage maintenance processes in a locomotive depot.

Considering, for example, maintenance and repair systems [50–53], it was found that hydraulic installations take into account certain operating parameters, which determine the probability of the failure-free operation.

In modern conditions, in many cases, the organization of the maintenance and repair processes of LDEs does not adequately correspond to the temporary and technological content, which leads to premature failures of LDEs. For the timely maintenance of LDEs in companies and organizations, an information base of indicators should be created. Such indicators can be the operational parameters of LDEs. Changing the operational parameters of LDEs in an automatic mode will signal the need to perform appropriate technical activities. The study presented in the work does not include a consideration of the load and speed regimes of LDEs.

The technical condition of LDEs affects operational parameters such as hourly fuel consumption, effective power, torque, etc. However, all operational parameters are quite difficult or almost impossible to take into account. Hourly fuel consumption can be taken as the main operational parameter as it is a weighted average. Hourly fuel consumption is not a momentary indicator. Changing the hourly fuel consumption of LDEs will directly indicate the technical condition and the need for maintenance. Therefore, this work assumes the use of hourly fuel consumption as the main indicator to determine the risk of failures of LDEs. The effective power and torque of LDEs are proportional to hourly fuel consumption. Therefore, the results of the effective power and torque of LDEs are not presented in this study.

The purpose of this study is to determine the risk of failures of locomotive diesel engines in maintenance.

To achieve the goal, it is necessary to build a functional diagram of the control system to manage LDEs' maintenance processes and to conduct theoretical and experimental studies to determine the risk of failures of LDEs during maintenance.

2. Materials and Methods

To manage the maintenance processes of LDEs, we apply the functional diagram of the control system (Figure 1).

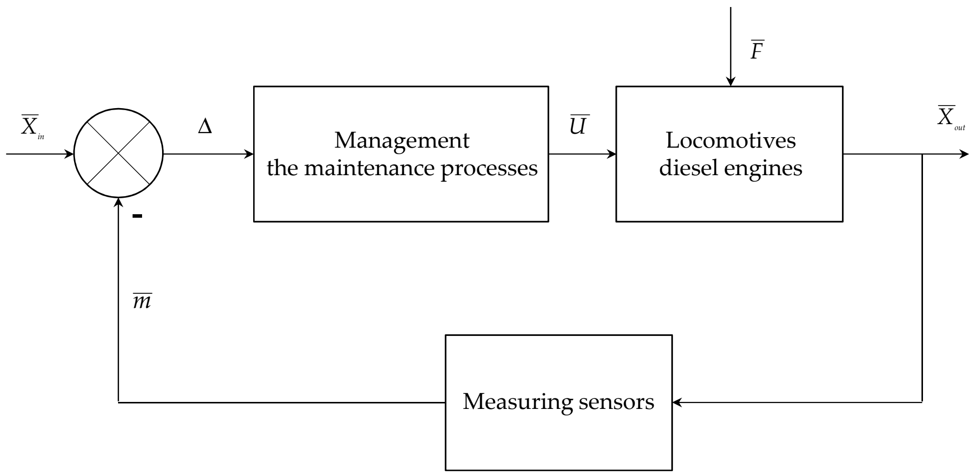

Figure 1. Functional diagram of the control system to manage the maintenance processes of LDEs.

In Figure 1, $\overline{X}_{in}$ represents input control parameters; $\overline{X}_{out}$ represents output parameters; $\overline{F}$ is the perturbation; $\overline{U}$ is the control signal; $\overline{m}$ represents the current values of the operational parameters of a diesel engine; Δ is the change of the operational parameters of a diesel engine.

To generate a control signal to manage the maintenance processes $\overline{U}$, information on the operational parameters of a diesel engine $\overline{m}$ is required.

Let us consider what operational parameters can be used in the management of LDE maintenance processes.

If the probability of the failure-free operation of LDEs during operation is a continuous function, it can be represented by the following graphic image (Figure 2) [1,6]. The area on the graph will determine the need of the maintenance processes of LDEs.

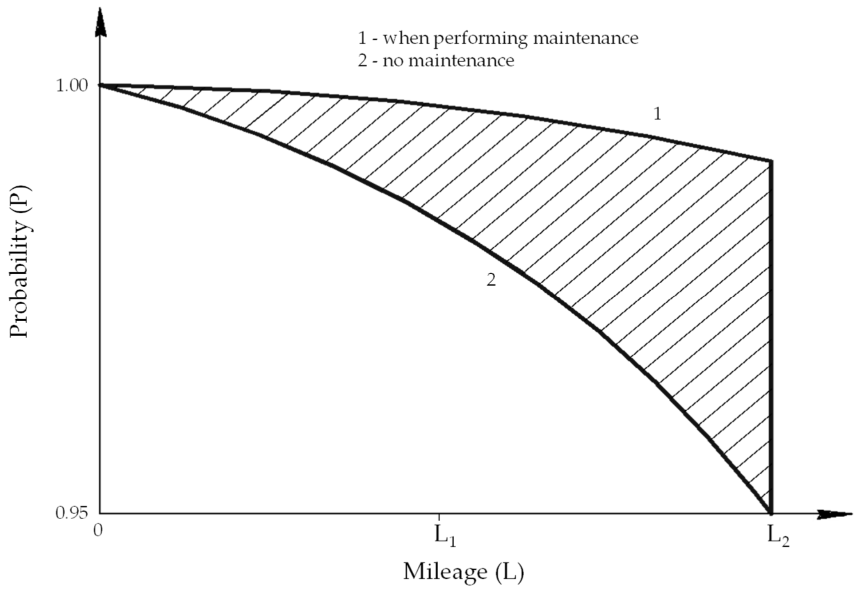

Figure 2. Probability of a failure-free operation of an LDE during operation, depending on the mileage [1,6].

In Figure 2, L_2 represents the mileage at which LDE maintenance should be performed. Therefore, L_2 mileage for each LDE is a different value. L_1 mileage is preventive maintenance. Accordingly, L_1 mileage for each LDE is a different value.

With a limit value of the probability of a failure-free operation of an LDE, the maintenance time can be determined. The area shown in Figure 2 shows the possibility of increasing the probability of a failure-free operation of an LDE almost to the initial value when carrying out maintenance or technical interventions. This increases the reliability and durability of LDEs and reduces the risk of failures during operation.

To determine the maintenance period, which is located in the shaded area (Figure 3), it is necessary to have information about the technical condition of LDEs.

The impact of maintenance and repair on the probability of the failure-free operation of LDEs during operation is presented in Figure 3.

Figure 3 shows a graphical interpretation of a decrease in the probability of the failure-free operation of LDE when it is time to perform maintenance and repair operations. The figure shows points 1, 3, 5, 7, 9, and 11. The restoration points for the probability of the failure-free operation of an LDE during maintenance include 2, 4, 6, 8, 10. The restoration of the probability of the failure-free operation of an LDE during repair is given as point 12. Such a picture is possible provided that the maintenance and repair will be carried out in full and will be performed well. The change in the probability of the failure-free operation of LDEs clearly shows the importance of the maintenance and repair systems for reliability and the possibility of reducing the risk of failures.

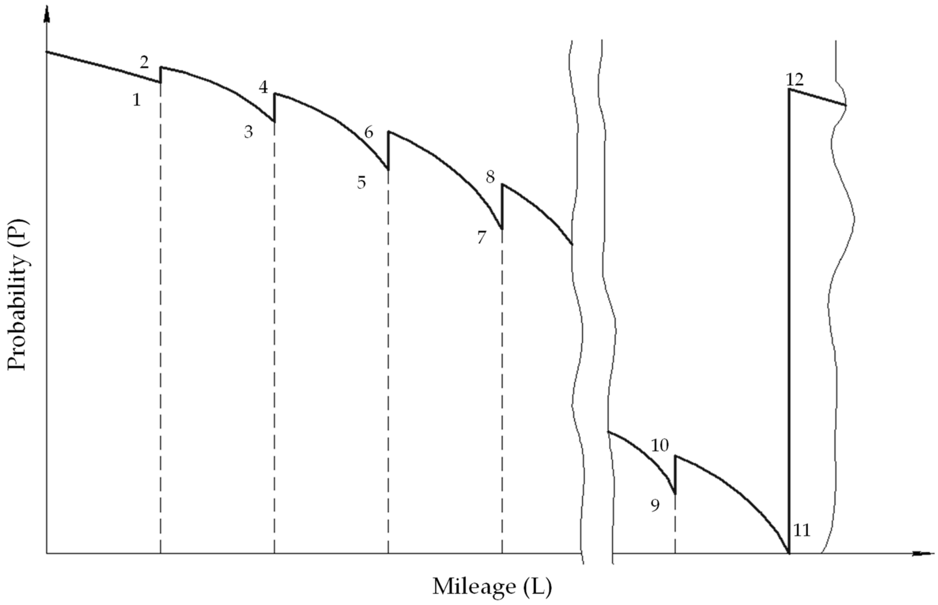

Figure 3. Probability of a failure-free operation of an LDE depending on the mileage during maintenance and repair operations.

When the limiting condition is reached (for example, at maintenance (point 1)) and when technical actions are performed in full, the probability of the failure-free operation of LDEs increases, as shown with point 2.

In the case of non-maintenance or a low-quality performance of work, the possibility of the failure-free operation of LDEs in operation is reduced, for example, from point 1 to point 3, 5, etc.

The dependence, shown in Figure 3, indicates the need for maintenance and repair in order to restore the probability of the failure-free operation of LDEs. Maintenance and repair systems provide a slow decrease in the probability of the failure-free operation of LDEs and, accordingly, slow down the occurrence of the limit condition of the engine systems.

Carrying out engine repairs (point 11) allows restoring the probability of the failure-free operation almost to its original technical condition (point 12). Figure 3 shows the interpretation of the repair processes (points 11 and 12), taking into account the recovery factor of an LDE.

The mathematical expression of the probability of the failure-free operation of LDEs before repair (point 11), taking into account the performance of maintenance and with a discrete distribution, will have the following form:

$$P_r = (P_{sv} - \Delta P \cdot L) \cdot RF, \tag{1}$$

where P_{sv} is the established value of the probability of the failure-free operation of LDEs at the beginning of operation; ΔP is the decrease in the probability of the failure-free operation of LDEs per 10,000 km of mileage; L is the mileage of an LDE; RF is the recovery factor after repair.

The recovery factor in Formula (1) will be the value after repair of an LDE. During maintenance of an LDE, RF has no effect on the probability of the failure-free operation.

In this case, the condition of carrying out LDE repair must be observed as

$$P_r \geq P_{bv},$$

where P_{sv} is the boundary value of the probability of the failure-free operation of LDEs to establish the time of repair.

A timely maintenance schedule increases the probability of downtime and the durability of LDEs. Operational parameters are indicators of changes in the technical condition of LDEs. The indicator can be evaluated based on the determination of the risk of failures of LDEs.

The technical condition of LDEs affects operational parameters such as hourly fuel consumption, effective power, torque, etc. In this work, hourly fuel consumption ($\overline{m}$) is taken as an indicator of the operational parameters of LDEs.

Experimental dependence of hourly fuel consumption of 5D49 diesel engines on the probability of failure-free operation is shown Figure 4.

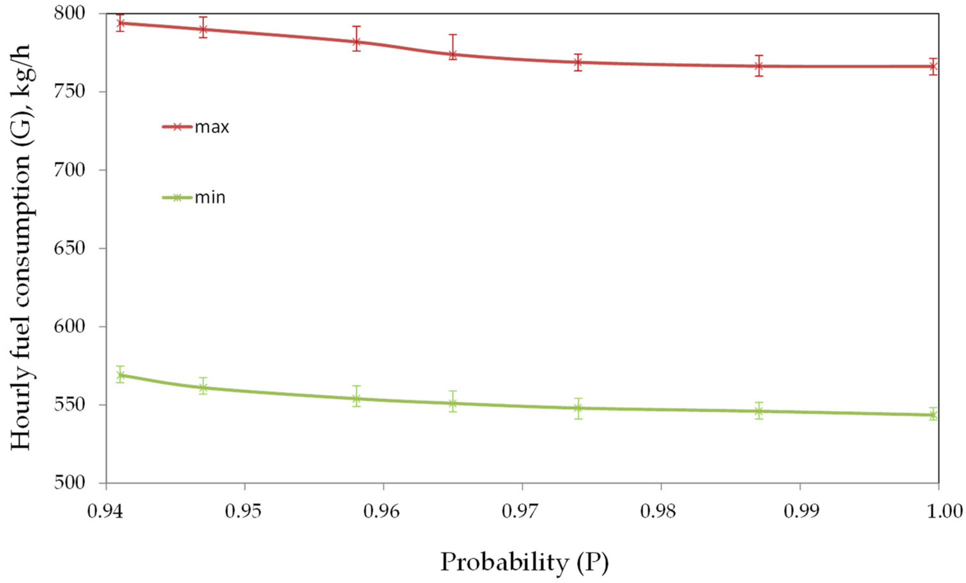

Figure 4. Experimental dependence of hourly fuel consumption of 5D49 diesel engines on the probability of failure-free operation.

Using the experimental data (Figure 4), the dependence of hourly fuel consumption on the probability of the failure-free operation of LDEs is shown in Figure 5.

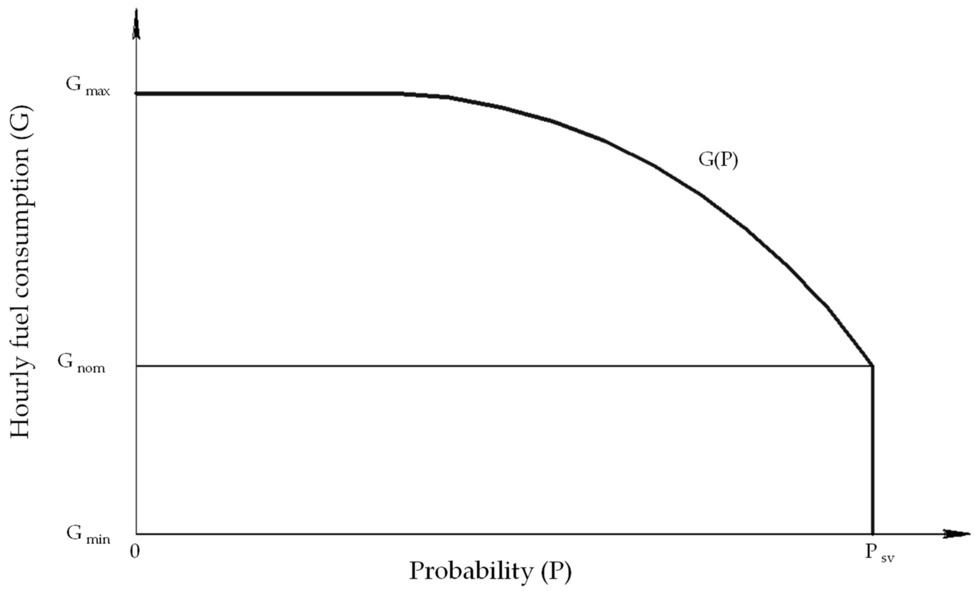

Figure 5. Dependence of hourly fuel consumption on the probability of the failure-free operation of LDEs.

According to Figure 5, the average value of the risk of failures of LDEs by hourly fuel consumption, depending on the probability of the failure-free operation, has the following form:

$$R_G = \frac{1}{G_{nom}} \left(\int_{G_{nom}}^{G_{\max}} \int_{0}^{P_{sv}} G(P) dGdP + \int_{G_{\min}}^{G_{nom}} \int_{0}^{P_{sv}} dGdP \right), \quad (2)$$

where $G(P)$ is a function of hourly fuel consumption on the probability of the failure-free operation of LDEs; $G_{\max}$ and $G_{\min}$ are maximum and minimum hourly fuel consumption; G_{nom} is hourly fuel consumption of LDE during the nominal mode.

For the dependence of hourly fuel consumption on the probability of the failure-free operation of LDEs (Figure 5), the risk zones are presented in Figure 6.

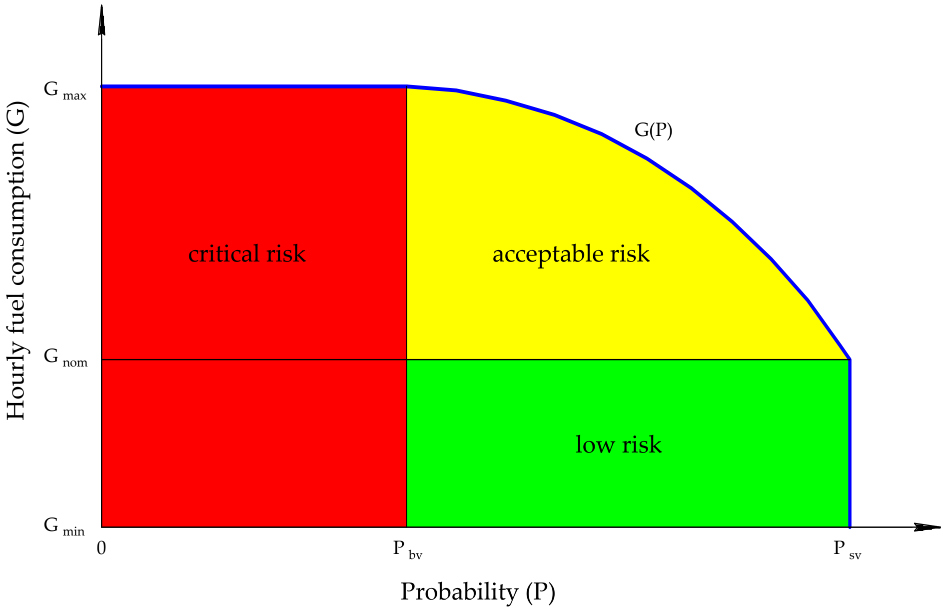

Figure 6. Risk zones for the dependence of hourly fuel consumption on the probability of the failure-free operation of LDEs.

Figure 6 shows the risk areas marked in green, yellow, and red. Green indicates a low-risk area. The area of acceptable risk is indicated in yellow. The critical-risk area is marked in red. The same designation for the risk zones will be used in other figures.

According to the designated areas in Figure 6, it is proposed to assess the risk of failures of LDEs for the indicator of hourly fuel consumption using the following expressions:

- Low risk:

$$R_G^l = \frac{1}{G_{nom}} \int_{P_{bv}}^{P_{sv}} \int_{G_{\min}}^{G_{nom}} dGdP. \quad (3)$$

- Acceptable risk:

$$R_G^a = \frac{1}{G_{nom}} \int_{P_{bv}}^{P_{sv}} \int_{G_{nom}}^{G_{\max}} G(P) dGdP. \quad (4)$$

- Critical risk:

$$R_G^c = \frac{1}{G_{nom}} \int_0^{P_{bv}} \int_{G_{\min}}^{G_{\max}} G(P) dG dP. \tag{5}$$

If the value of P_{bv} is equal to P_r, on the basis of expression (1), we can write:

- Low risk:

$$R_G^l = \frac{1}{G_{nom}} (G_{nom} - G_{\min}) \cdot \Delta P \cdot L. \tag{6}$$

- Acceptable risk:

$$R_G^a = \frac{1}{G_{nom}} (G_{\max} - G_{nom}) \int_0^{\Delta P \cdot L} G(P) dP. \tag{7}$$

- Critical risk:

$$R_G^c = \frac{1}{G_{nom}} (G_{\max} - G_{\min}) \int_{\Delta P \cdot L}^{P_{sv}} G(P) dP. \tag{8}$$

Based on the above mathematical models, a comprehensive assessment of the risk of failures can be performed using the risk indicator of hourly fuel consumption of LDEs.

3. Results

The methodological results of the study on determining the risk of failures of LDEs allow us to proceed to the presentation of the results of theoretical and experimental studies. At the same time, the theoretical and experimental studies were carried out to determine the risk of failures of 5D49 diesel engines.

For expressions (6)–(8), the risk of failures of 5D49 diesel engines are given depending on the mileage by hourly fuel consumption (Figure 7). In this case, the function $G(P)$ is treated as a linear function.

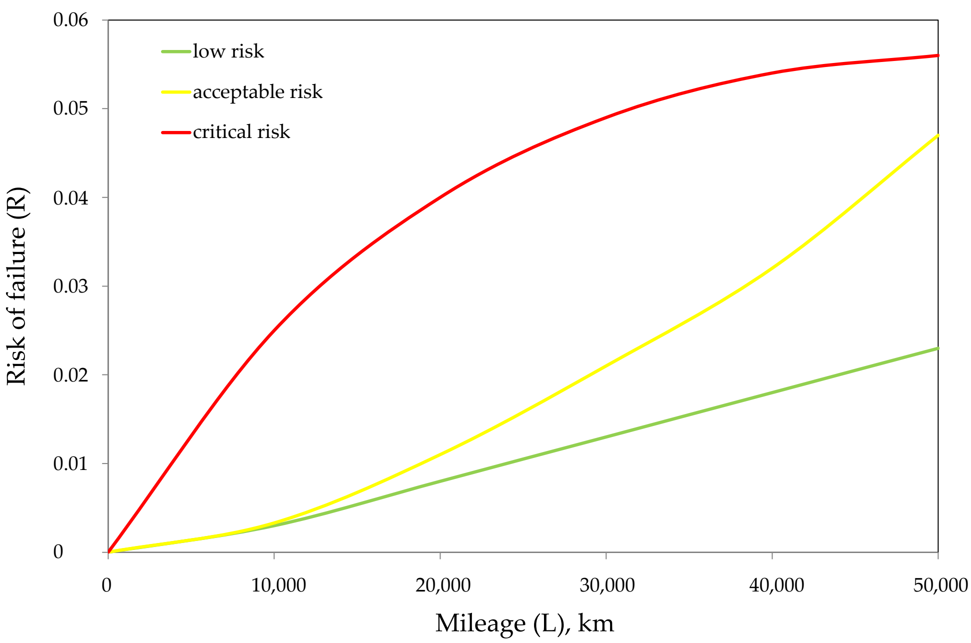

Figure 7. Dependence of the risk of failures of 5D49 diesel engines on the mileage by hourly fuel consumption.

The theoretical study (Figure 7) confirms the methodological result. So, the critical risk of 5D49 diesel engines at 50,000 km is 0.056, the acceptable risk is 0.047, and the low risk is 0.021.

When conducting the experimental study, the hourly fuel consumption of 5D49 diesel engines was monitored using the on-board system of a locomotive. An example of data from the on-board system of a locomotive is shown in Figure 8.

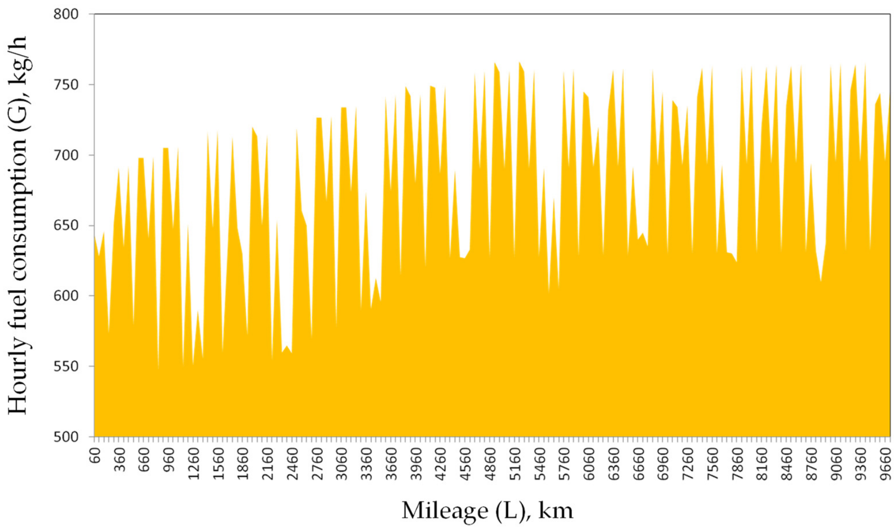

Figure 8. Hourly fuel consumption of 5D49 diesel engines depending on the mileage of a locomotive.

Furthermore, from the obtained data, hourly fuel consumption, $G_{\max}$ and $G_{\min}$, has been determined. Further, in accordance with the methodological assumptions, the risk of failures of LDEs is calculated.

For eight tested 5D49 diesel engines in a locomotive depot (Ukraine), depending on hourly fuel consumption, the experimental results of the risk of failures are shown in Figure 9. Based on the measured values of hourly fuel consumption, it is necessary to calculate the risk of failures of LDEs similarly to expressions (6)–(8). In this case, changes in the technical condition of LDEs have been represented by a continuous value. Hourly fuel consumption of 5D49 diesel engines during the nominal mode is G_{nom} = 620.4 kg/h.

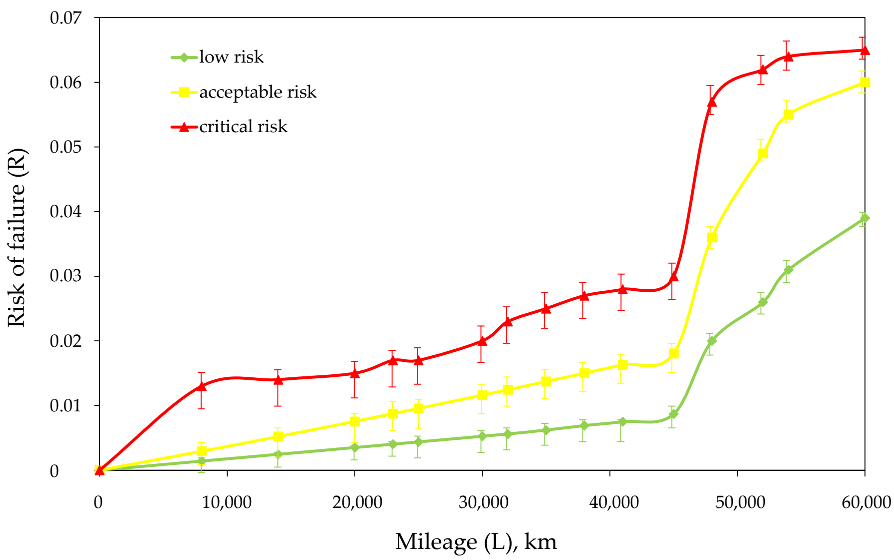

Figure 9. Experimental results of the risk of failures of 5D49 diesel engines in a locomotive depot on the mileage.

The theoretical results (Figure 7) and the experimental results (Figure 9) of the risk of failures of 5D49 diesel engines in terms of hourly fuel consumption are similar in nature. However, the critical risk for theoretical and experimental results on a mileage of up to 50,000 km differs by 6.7%. Despite such a big difference, the approach to determining the risk of failures of LDEs is adequate as it takes into account the change in the technical condition of the engine systems. For the rest of the LDEs' mileages, the difference in critical risk did not exceed 12.5%.

In order to compare the theoretical and experimental results, statistical treatment was carried out. The correlation coefficient and the square of the Pearson correlation coefficient have been determined. An F test has been performed according to the Fisher criterion. The results are presented in Table 1.

Table 1. Results of mathematical and statistical elaboration of theoretical and experimental results.

Risk	Correlation Coefficient	Pearson Squared Correlation Coefficient	F-Test
Low	0.8529	0.7274	0.9723
Acceptable	0.9404	0.8844	0.7377
Critical	0.7588	0.5758	0.8295

The obtained results indicate an acceptable convergence of the results of the theoretical and experimental research. It can be concluded that the results of the theoretical and experimental research are adequate. $\overline{X}_{in}$ = 30,000 km has been taken as the input parameter to manage the maintenance process. Under the impact on the maintenance system, $\overline{F}$ = 1000 km, as a result of the maintenance process management, the output parameter $\overline{X}_{out}$ = 45,000 km has been obtained. The load and speed modes of 5D49 diesel engines must remain without overloads. Short-term overloads of 5D49 diesel engines cannot be longer than 22 s.

According to the risk of failure expressions (6)–(8), Figure 10 shows the maintenance system and the risk of failures of 5D49 diesel engines.

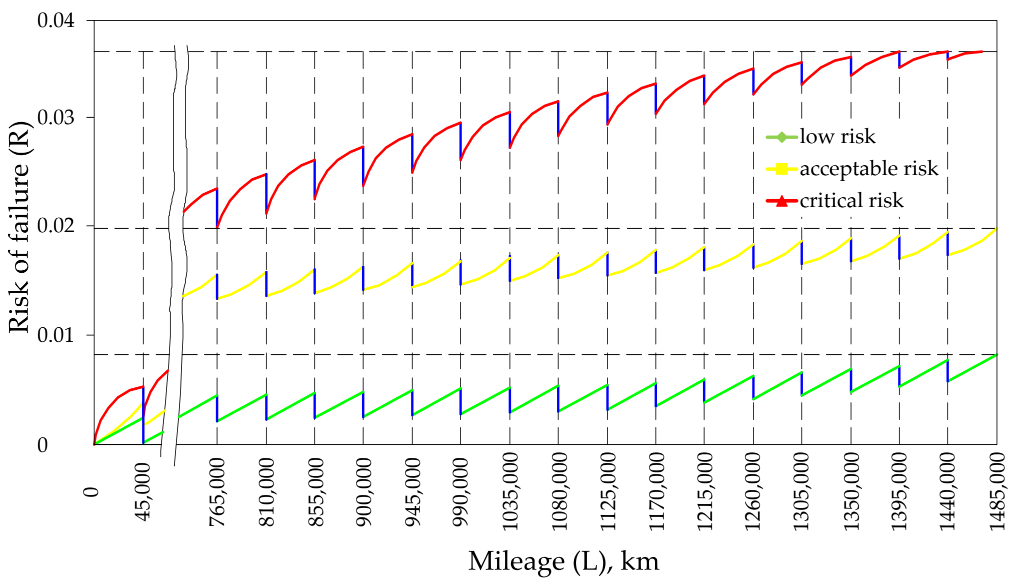

Figure 10. Theoretical maintenance system and the risk of failures of 5D49 diesel engines depending on the mileage.

In the theoretical maintenance system, the risk of failures of the 5D49 diesel engines according to the indicator of hourly fuel consumption (Figure 10) for the mileage of 1,485,000 km are as follows: low risk is 0.00825, acceptable risk is 0.0198, and critical risk is 0.036.

The maintenance system and the risk of failures of 5D49 diesel engines have been experimentally tested. The maximum risk of failures for four LDEs according to the hourly fuel consumption did not exceed 0.04 in the range of 1,460,000–1,500,000 km. This risk value corresponded to the need to repair four LDEs.

The theoretical values of the resources of LDEs (Figure 10) differ from the experimental results by 15–30,000 km. The theoretical values of the low and acceptable risk of failures of LDEs differ from the experimental results since the hourly fuel consumption in operation differs from the theoretical calculations.

The presented results of the theoretical and experimental studies confirm the methodological premises for determining the risk of failures of LDEs.

4. Discussion

Since the operational parameters of LDEs affect their technical condition and it is rather difficult or almost impossible to take into account all operational parameters, hourly fuel consumption has been taken as the main operational parameter in this work. Hourly fuel consumption is not a momentary indicator, and the value of hourly fuel consumption is a weighted average. A change in an LDE's hourly fuel consumption indicates the need for maintenance. Therefore, in this work, it was proposed to use hourly fuel consumption as a main indicator for determining the risk of failures of LDEs.

Based on the proposed functional diagram of the control system to manage the maintenance processes of LDEs (Figure 1), in this work, a mathematical model has been proposed to determine the risk of failures of LDEs by hourly fuel consumption. This mathematical model allows you to determine the time required to manage the maintenance processes of diesel engines. The practical results correlate with the theoretical dependencies and confirm the effectiveness of the proposed approaches to determining the risk of failures of LDEs by hourly fuel consumption.

The reviewed scientific works did not determine the risk of failures of LDEs on the basis of hourly fuel consumption during operation. Thus, the contribution of this study lies in the fact that it proposes, for the first time, approaches for determining the risk of failures of LDEs according to hourly fuel consumption during maintenance. The theoretical dependence of the risk of failures of 5D49 diesel engines on the mileage by hourly fuel consumption (Figure 7) and the experimental results (Figure 9) for the mileage of 45,000 km correspond. It should be noted that between the dependencies there is a practical convergence of the theoretical and practical results for the low and acceptable risks. The experimental results of critical risk (Figure 9), starting from the mileage of 8000 km, increase to 0.013 and continue to increase. The theoretical dependence of critical risk (Figure 7) is a smooth increase and may result from the assumed linear dependence, which, in practice, has a different course. Nevertheless, this algorithm for determining the risk of failures of LDEs by hourly fuel consumption depending on the mileage can be used in practice to determine the timing of maintenance and repair.

Managing the maintenance processes of 5D49 diesel engines has a technical impact on the mileage of 45,000 km. The repair of 5D49 diesel engines should be carried out at the mileage of 1,485,000 km according to hourly fuel consumption, which corresponds to the value of the risk of failures—0.036.

The resource of 5D49 diesel engines in the locomotive depot increased by 2.4% in the resulting management of the maintenance processes compared to the existing maintenance processes.

5. Conclusions

This article presents the results of a theoretical and experimental study to determine the risk of failures of LDEs during maintenance.

The technical condition of LDEs affects the operational parameters, and it is rather difficult or almost impossible to take into account all operational parameters. In this work, hourly fuel consumption has been taken as the main operational parameter since the value of hourly fuel consumption of LDEs is a weighted average value. The change in the hourly fuel consumption of LDEs has an impact on the maintenance system.

Theoretical research allowed us to obtain a mathematical model of the risk of failures of LDEs based on hourly fuel consumption. The experimental results confirmed the desirability of applying theoretical premises.

The novelty of this work is the first proposed method for determining the risk of failures of LDEs according to hourly fuel consumption. Based on this approach, under operating conditions, it is possible to extend the service life of LDEs during maintenance.

As a result of determining the risk of failures of the 5D49 diesel engine, it was found that the optimal maintenance mileage is 45,000 km. At the same time, the service life of the overhaul increases by 2.4%. The potential cost savings associated with the use of the proposed method for determining the risk of failures of 5D49 diesel engines according to hourly fuel consumption in order to manage the maintenance processes of diesel engines can amount to 2.4–5% of the operating costs.

From the standpoint of the scientific–theoretical component of the obtained results of determining the risk of failures of LDEs during maintenance, the results are useful. These results can be useful for organizing maintenance operations. Using a mathematical model of the risk of failures of LDEs based on hourly fuel consumption for organizing maintenance operations, it is possible to construct a maintenance system for LDEs of other groups. At the same time, it is necessary to conduct experimental studies of hourly fuel consumption on existing engines in order to determine the mileage at which maintenance should be carried out.

In the future, it is planned to consider the impact of additional operational and technical parameters of LDEs on the probability of failure-free operation.

Author Contributions: Conceptualization, D.B., S.M. and L.M.; methodology, D.B., M.B. and S.M.; software, M.B. and A.M.; validation, D.B., S.M., M.B. and A.M.; formal analysis, D.B.; investigation, D.B., S.M., M.B. and L.M.; writing—original draft preparation, D.B. and M.B.; writing—review and editing, D.B., S.M., M.B. and L.M.; visualization, M.B. and A.M.; supervision, D.B.; project administration, D.B. 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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