APPRAISAL RELIABILITY OF ELECTROMECHANICAL EQUIPMENT OF RAIL SERVICE CAR

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Resume

This study conducts an in-depth exploration into the principal factors that influence the reliability of specialized rail cars and auto-rail vehicles. It places a particular emphasis on key performance metrics including the average operational duration prior to failure, the proba¬bility of faultless operation, the rate of failure, and the gamma-percentage resource. Addition¬ally, the paper examines various methodologies for computing these metrics and quantitatively evaluating their respective values. It elucidates how specific units of electromechanical equip¬ment, which operate in conjunction with asynchronous motors and clutches, exhibit distribution patterns during failure that overlap between exponential and normal distributions. The study further presents a mathematical formula to approximate the reliability density of the distribution, a critical factor in recalibrating the metrics associated with specialized rail cars.

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1 Introduction

The work presented in this paper includes an in-depth exploration of the underlying reasons and specific nature of the damage that significantly compromises the operational effectiveness of the distinctive rolling stock compositions under the stewardship of the Joint-Stock Company, "Uzbekistan Railways". Comprehensive data analysis unveils that the majority of these adverse events (50%) are primarily due to mechanical breakdowns, followed by electrical dysfunction (31.8 %), and issues concerning the hydraulic machinery (18.2%) [1].

With these significant challenges at the forefront, it becomes an imperative requirement to conceptualize and implement an innovative approach to modernize the rail service cars during their overhaul stages. This initiative aims to substantially augment their technical diagnostics, thereby promoting overall operational efficiency. This particular research concentrates primarily on rail service cars, specifically the ADM-1 type, which comprise a significant portion of the fleet, with 145 units in operation under the umbrella of the "Uzbekistan Railways" Joint Stock Company [2].

The systematic maintenance of the requisite reliability standards of rail service cars and railway inspection vehicles, especially within the context of a market economy, hinges decisively on the strategic decisions made concerning their maintenance and repair (M&R). The reliability of the rail service cars is largely contingent upon the capability of its individual mechanical, electrical, and hydraulic components to sustain their initial technical characteristics during operational periods. This feature considerably impacts the overarching effectiveness of the railway transportation.

This overarching effect is quantitatively evaluated using the technical-economic efficiency metric, which encapsulates the performance spectrum of the rail service car functionalities. This includes the integral consideration of financial expenditure, labour contributions, and material costs. The troubleshooting process for the rail service car involves identifying potential failure points, tracking key performance indicators during operations, and appraising the technical processes that require the integration of complex mechanical, electrical, and hydraulic systems. This calls for a harmonized approach across the deployment location, aiming at maintaining both static and dynamic stability, which, in turn, ensures the seamless functionality of the primary contact network.

The novelty of this study is in obtaining the probability of distribution before the failure of the rail service car main equipment of, by superimposing exponential and normal Gaussian distribution laws. The results of this study could make it possible to adjust the indicators of separate and joint optimal frequency of the rail service car.

Reliability is the most important qualitative characteristics of the main equipment of the rail service car, as well as all the products of engineering facilities. According to [3], this is the property that the object must perform the specified functions, keeping in time the values of the established operational indicators within the specified limits corresponding to the specified modes and conditions of use, maintenance, repairs, storage and transportation. The reliability of the rail service car and equipment in detail is a complex property, including reliability, durability, maintainability and preservation [4].

2 Related works

The research conducted by numerous scientists has played a crucial role in shaping the contemporary designs of railway rolling stock. This body of work has largely addressed the significant challenges of assessing static and dynamic loads on rail carriages, with substantial contributions from researchers such as Anyakwo[5], Bogdevicius.[6], Bureika [7], Chao [8], EulitzKotte [9], Fan et al. [10], Kuznetsov et al. [11], Popp and Schiehlen [12], Sharma et al. [13], Sebesan and Baiasu [14]. Their theoretical insights, regulatory and technical solutions, as well as methods and algorithms for assessing the residual life of rail transport rolling stock, continue to be integral in the railway industry.

Furthermore, dynamic strength and reliability calculation theories for mechanical systems on railway transport have been significantly advanced by Spiryagin. et al. [15], Sosnovsky and Scherbakov [16], Tretyakov [17-19], Vasilyev [20] and others. Today, over 25 organizations across Russia, Ukraine, Belarus, Kazakhstan, Latvia, Lithuania, Georgia, and Uzbekistan have taken practical strides to extend the lifespan of different rail vehicles types.

The reliability of specialized rail car is a field with extensive research. In terms of electromechanical equipment units, Zhou et al. [21] investigated the dynamics effect of wheel flats on the railway vehicle system. They found that the wheel flats exacerbate wheel-rail impact and locomotive component vibrations. Moreover, they identified that defects like wheel flats can be detected by analysing the frequency spectrum of current signals in a traction motor, providing insights for efficient monitoring and maintenance, which aligns with our focus on technical diagnostics.

In the realm of railway vehicle multi-body models, Bruni et al. [22] reviewed models for railway vehicle suspension components, discussing the required level of detail in view of the overall simulation model's accuracy. Their work underscores the need for precision in modelling components, which aligns with our approach of using a system analysis model for maintenance and repair. Similarly, Bruni et al. [23] emphasized the role of control and monitoring technologies in railway vehicle dynamics. Their findings underlined the need for comprehensive technical diagnostics in enhancing rail car reliability.

Evans and Berg [24] explored the challenges in the simulation of rail vehicle dynamics. They emphasized the importance of appropriate modelling choices for different applications and the increasing importance of validating simulation results, which this study takes into account. They also emphasized the role of simulation as an essential part of the design process for new vehicles and for investigating service problems with existing vehicles, thus validating our approach to calculate failure metrics through the system analysis.

Carlbom [25] discussed the combination of multibody and finite element models for the rail vehicle dynamics analysis, using the real track data as input. His work illustrates the importance of integrating different models to accurately assess vehicle behavior and validates our method of calculating overhaul life based on the failure probability indices.

Finally, Auciello et al. [26] proposed an innovative semi-analytic procedure for wheel-rail contact point detection, recognizing its substantial impact on the contact force direction and intensity. Their work highlights the significance of understanding the complex interplay between different rail car components, which resonates with our approach of studying overlapping failure distribution patterns in specialized rail cars.

Together, these studies demonstrate the rich, multifaceted understanding of the rail vehicle reliability and that it is an influencing factor. Building upon their insights, our research objective was to enhance the rail

Figure 1 *Photos of an ADM type rail service car*

car reliability through the strategic assessment and adjustment of the key operational metrics.

However, the contemporary literature still faces a gap in addressing the theory of oscillations and reliability of body frames, spring suspensions, and chassis of the rail service car. Those studies must also consider the optimization of dynamic characteristics and the rational design and modernization methodologies. The performance of the whole railway transport depends heavily on the adherence to the electric locomotives' movement schedule, with technical and economic indicators significantly influenced by the reliability of the rail service car mobile composition.

The reliability of rail service car is largely contingent on its electromechanical equipment, which must maintain optimal performance of designated functions, while preserving the operational indicator values within specified storage limits. Those limits correspond to the use, maintenance, and repair systems over time. The initial data to define reliability indicators are often statistical operation data from the functional units [27].

The object of this research of the rail service car is a self-propelled two-axle carriage. A load-bearing cabin is located on the front console. On the rear console there is a crane manipulator unit capable of mounting and dismantling contact network supports, loading and unloading various cargoes on railways. The mounting platform is located in the middle part of the rail service car. In addition, in the middle part under the frame of the rail service car there is a power plant that transmits power through hydraulic transmission to a three-phase generator.

The photographs of the object of study, taken by the authors during the survey of the rail service car operated by Uzbek Railways JSC, are shown in Figure 1.

3 Methods

We conducted a collection and record procedure of the primary reliability information based on the guidelines stipulated in the documents "Procedure for conducting technical inspection" and "Checking the technical condition of the rail service car" [28]. Those procedures were carried out using the data from the "Mechanization Department" of the "Uzbekistan Railways". An assumption was made that the initial statistical information is objective, reliable, and selected [29] according to the sampling method provisions, ensuring sufficient volume for estimates with a given

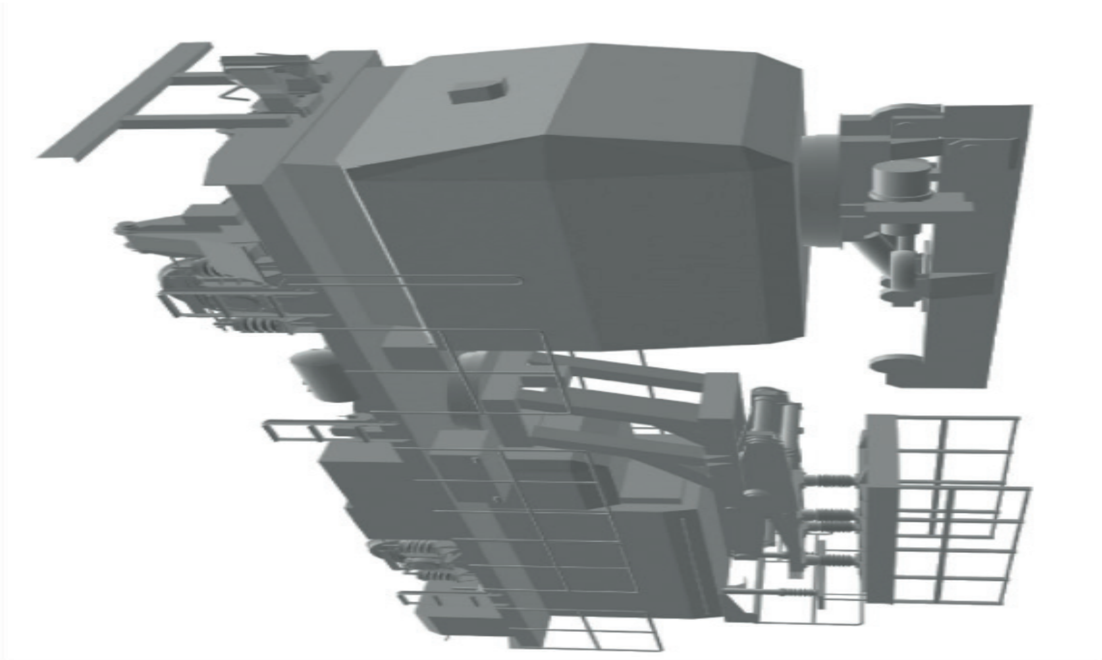

Figure 2 *The 3D model of the ADM type rail service car*

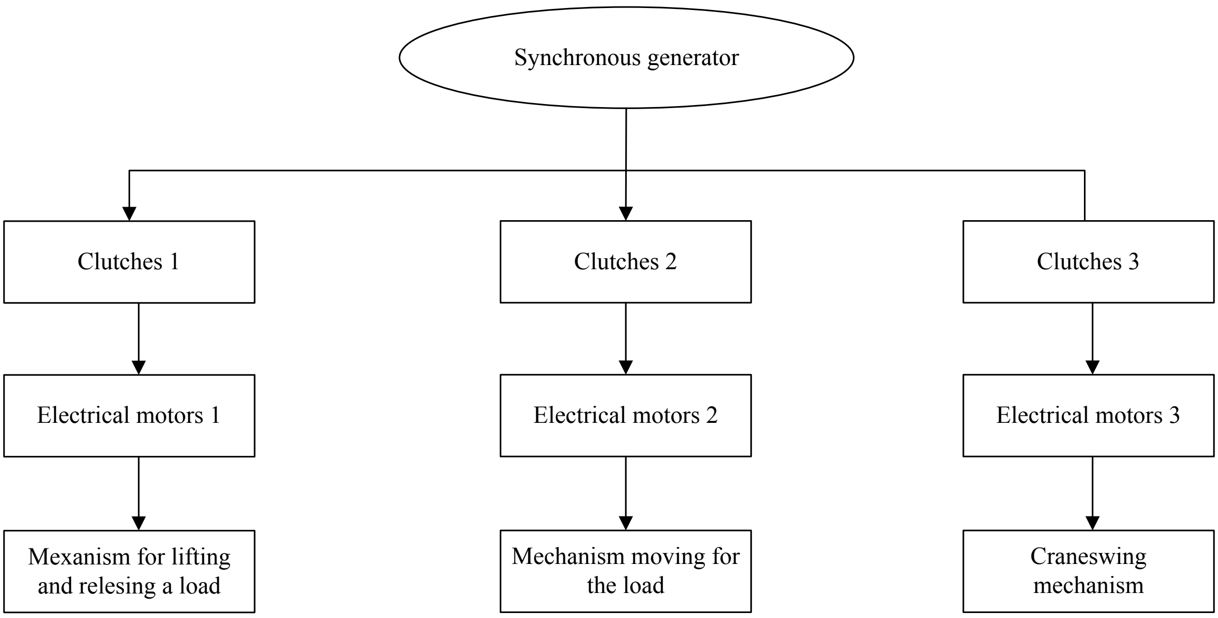

Figure 3 *A calculation scheme of the reliability of electrical equipment of the rail service car of the ADM type*

confidence level and accuracy. The analysis of statistical operation data for the rail service car types ADM from “Uzbekistan railways” JCS indicates that the technical condition of mechanical, hydraulic, and electrical equipment of the rail service car is a complex object, warranting a holistic consideration for assessing reliability indicators for each equipment type.

A 3D model of the rail service car is shown in Figure 2.

The reliability of electromechanical equipment significantly impacts the efficacy of the entire rail service car system. All the technical blocks of the electromechanical equipment (EE) consist of a synchronous three-phase current generator and three electric motors (EM1, EM2, EM3), each responsible for different mechanisms: lifting and lowering the load, load movement, and the crane swing. These are all connected to the synchronous generator via three clutches.

The power electric circuits of the rail service cars, type ADM are standardized. The 12 kW synchronous three-phase alternator is the electrical energy source. Each actuator is driven through electromagnetic clutches by the electric motors M1 for the load lifting and releasing mechanism (type ASVT-52), M2 for the load trolley moving mechanism (type 4AC100), M3 for the crane swing mechanism (type MKTF). These are

Table 1 *Summary table of reliability ratings for mechanical, electrical and hydraulic control equipment of the rail service car type ADM*

d	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
t_i, hour	61	79	80	81	92	94	101	104	111	123	132	140	142	202	213	217

Table 2 *Summary table of assessments of reliability indicators of mechanical, electrical and hydraulic equipment*

Types of equipment controls		Mechanical	Electrical	Hydraulic
		[*N, U, T*]	[*N, U, T*]	[*N, U, T*]
Observation plan	N	50	50	50
Estimates of the reliability indicators	d	12	14	16
Failure rate	λ_{av}; 1/h	$0.3661 \cdot 10^{-3}$	$0.370 \cdot 10^{-3}$	$0.444 \cdot 10^{-3}$
Lower confidence limit failure rate	λ_L; 1/h	$0.149 \cdot 10^{-3}$	$0.1575 \cdot 10^{-3}$	$0.169 \cdot 10^{-3}$
Upper confidence limit failure rate	λ_{av}; 1/h	$0.386 \cdot 10^{-3}$	$0.407 \cdot 10^{-3}$	$0.457 \cdot 10^{-3}$
Point estimate of mean time to failure	$\lambda_u H$; h	3266.9	2702.9	2252.2
Lower confidence limit of operating time	λ_L; h	2589.3	2457.0	5917.2
Upper confidence limit of operating time	$\lambda_u B$; h	6711.4	6349.2	2188.2
Probability of failure-free operation over the operating time	*P(t)*	0.54	0.69	0.41
Lower confidence limit of probability of failure-free operation	$P(t)_L$	0.74	284.7	0.401
Upper confidence limit of probability of failure-free operation	$P(t)_u$	0.74	284.7	0.713
Resource at γ = 90%	*T*; h	344.2	258.7	237.3
Lower bound of the confidence resource at γ = 90%	T_L; h	272.8	258.8	230.5
Upper confidence limit of probability of failure-free operation	T_u; h	707.1	668.9	623.4

N - number of items, d - number of failures

termed as electric executive units.

From a reliability perspective, this electric circuit system operates so that a failure in one unit leads to a failure of the entire rail service car, but does not impact the reliability of other executive unit blocks. This structure is known as a system with serially connected elements in reliability theory (Figure 3).

Hence, the structural reliability of the object in question over time t can be expressed as [2]:

$$P(t) = P_{EE}(t) \cdot P_{CSM}(t) \cdot P_{MML}(t) P_{CS}(t), \tag{1}$$

where:
$P_{EE}(t)$ represents the failure-free operation probability of the synchronous electric generator, an hour (h).
$P_{CSM}(t)$ is electromagnetic clutch of the load lifting and releasing motor, h.
$P_{MML}(t)$ is load moving motor, h.
$P_{CS}(t)$ is crane rotation motor within a specified tolerance, h. [30].
Expressing *P(t)* in terms of failure rate allows to rewrite Equation (1) as:

$$P(t) = \exp\left[-\sum_{i=1}^{u} \int_0^t \lambda_i(x) dx\right]. \tag{2}$$

A total of 145 rail service cars units, with unified power electrical circuits, were observed over three years to determine the failure rate of electromechanical equipment. The observation included types of ADM rail service cars. The total number of devices observed was $N = 40$. After the failure, the devices were not replaced. Observations were conducted until the run $L = 100 \cdot 10$ km, within which $d = 10$ items of electromechanical equipment failed, with operational times t_i = 8.3; 40.4; 40.6; 45.4; 47.7; 53; 69.1; 100.3; 161.9; 168.5 hThe law of probability distribution for failure for the rail service car is known to be exponential. In the railway transport, the reliability of the rail service car is commonly assessed by mileage, i.e., the distance an object travels while in working condition [31].

For the rail service car, a plan, (N, U, T_o), is recommended, where N represents the number of items under observation, U indicates plans where failed items were not replaced, and T_o estimates the duration of observations or, in general, the established mileage after which the rail service cars functionality is restored. A summary of results of the rail service cars basic equipment scores, based on many years of observations, is presented in Tables 1 and 2.

$$\begin{matrix} \sum t_{m.hour} = 1198 \cdot \sum t_{e.hour} = \\ = 1536 \cdot \sum t_{hyd.hour} = 1466 \end{matrix}. \tag{3}$$

Table 3 *The probability of failure-free operation of rail service cars and operating time hours*

Mileage in hours	200	500	1000	2000	2500	3000	4000
P(l)	0.93	0.85	0.72	0.52	0.44	0.37	0.27

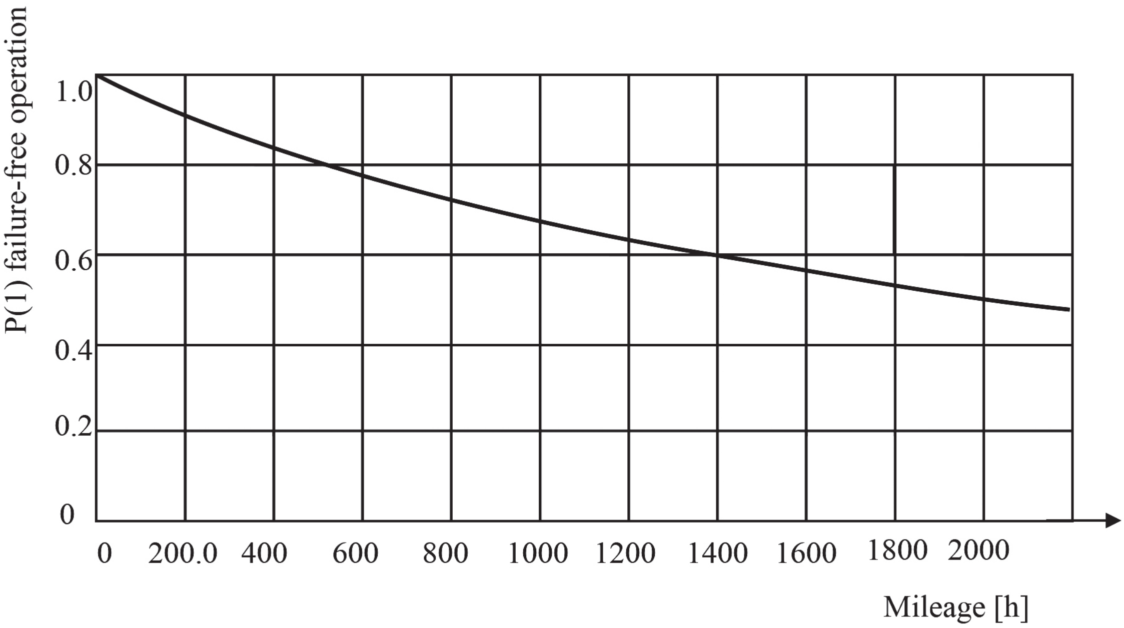

Figure 4 *Graph of the probability of failure-free operation of the rail service car with an exponential distribution law*

4 Results and discussion

The dignity plan (N, U, T_o) allows for a shorter observation period since there is no need to wait until the failure of all objects is reached. Using this monitoring plan, it is possible to assess the following indicators of the main equipment of rail service car: the average time to failure of the items, the probability of trouble-free operation at various runs of the rail service car, the lower and upper failure rates and the percentage resource of the main equipment of rail service car.

As a result, this plan can be efficiently used in practice to assess reliability indicators, given the large number of rail service cars 144 units for "Uzbekistan railways" JSC.

In the data given in Table 2, the following notation applies:

- T_o - is the mean time to failure,
- $P(l)$ - is the probability of failure-free operation at $l = 400 \cdot 10^3 km$,
- $\lambda(l)$ - is the intensity of the failure,
- $\gamma = 90\%$ - denotes the gamma percent resource.

For the selected plan, the average intensity of refusal was calculated as:

$$\hat{\lambda} = \frac{d}{\sum_{i=1}^{d} + (N-d) \cdot T_0} = \\ = \frac{10}{[739.2 + (40 - 10)] \cdot 10^3 km} = 60 \cdot 10^{-6} \frac{1}{km}. \quad (4)$$

For the calculated $\hat{\lambda}$, the two-sided confidence limits were defined, with a confidence level $\beta = 0.9$.

The lower limit:

$$\lambda_L = \frac{\hat{\lambda} N \chi^2{}_{\frac{1-\beta}{2}}, 2d}{d\left(2N - d + \frac{1}{2}\chi^2 \frac{1-\beta}{2}, 2d\right)} = \\ = \frac{2.60 \cdot 10^{-6} \cdot 40 \cdot \chi^2_{1\frac{1-0.9}{2}, 2 \cdot 10}}{10 \cdot \left(2 \cdot 40 - 10 + \frac{1}{2}\chi^2_{1\frac{1-0.9}{2}, 2 \cdot 10}\right)} = \\ = 0.115 \cdot 10^{-6} \frac{1}{km} \quad (5)$$

The upper limit:

$$\lambda_u = \frac{\hat{\lambda} N \chi^2{}_{\frac{1+\beta}{2}, 2d}}{d\left(2N - d + \frac{1}{2}\chi^2{}_{\frac{1+\beta}{2}, 2d}\right)} = \\ = \frac{2.60 \cdot 10^{-6} \cdot 40 \cdot \chi^2{}_{\frac{1+\beta}{2}}, 2d}{10 \cdot \left(2 \cdot 40 - 10 + \frac{1}{2}\chi^2_{2\frac{1+0.9}{2}}, 2d\right)} = \\ = 3.599 \cdot 10^{-6} \frac{1}{km}. \quad (6)$$

Values for $\chi^2_{1\frac{1-0.9}{2}, 2 \cdot 10}$ and $\chi^2_{2\frac{1+0.9}{2}, 2d}$.

We note that $x_1^2 < x_2^2$, therefore, the significance of the chosen law does not contradict the experimental data. The calculated values λ_u and λ_L are covered with a probability of 0.9; the true values of the parameter λ.

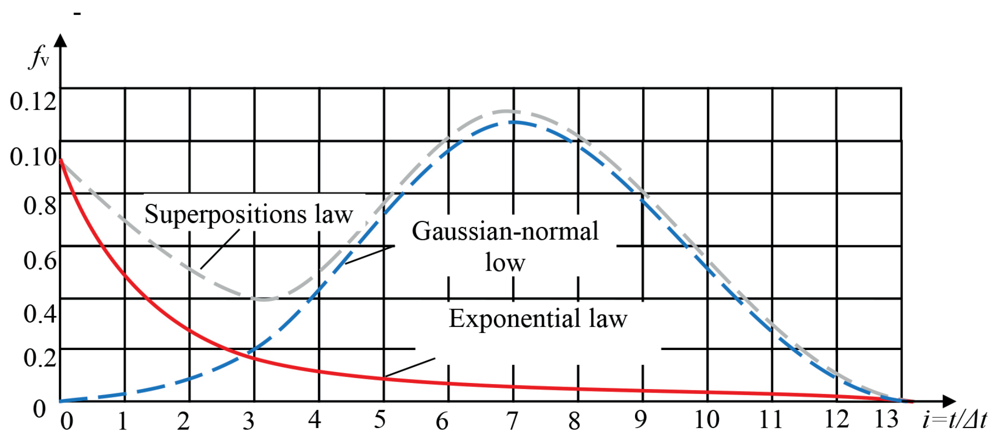

Figure 5 *Overlay of exponential and normal Gaussian laws of distribution of the rail service car time to failure Δt = 1000 km (The colours in this picture have no semantic characters)*

The point estimate of the mean time to failure is:

$$\hat{L} = \frac{1}{\lambda} = \frac{1}{2.60 \cdot 10^{-6}} = 384.61 \cdot 10^3 \, km \,. \quad (7)$$

The lower and upper confidence limits of the mean time to failure are:

$$L_{av.H} = \frac{1}{\lambda_L} = \frac{1}{3.599 \cdot 10^{-6}} = 0.277 \cdot 10^6 \, km;$$
$$L_{av.B} = \frac{1}{\lambda_u} = \frac{1}{0.115 \cdot 10^{-6}} = 8.695 \cdot 10^6 \, km. \quad (8)$$

Probability of the trouble-free operation, for a mileage l = *400 x 10*[3] km, is:

$$P(l) = e^{-\hat{\lambda} l} = e^{-2.60 \cdot 10^{-6}} \cdot 400 \cdot 10^3 = 0.361 \,. \quad (9)$$

The probability of failure-free operation is provided in Table 3.

It's worth noting that the probabilities of no-failure operation for runs of *50 x 10*[3], *100 x 10*[3], *200 x 10*[3], *300 x 10*[3], and *400 x 10*[3] km are respectively 0.878, 0.771, 0.594, 0.45, and 0.361 (refer to Figure 4).

Based on the Table 3, we built a Figure 4.

The two-sided confidence limits for P(l) are determined by the calculated values of λ_u and λ_L as:

$$P(l) = e^{-\hat{\lambda}_L l} = e^{-0.115 \cdot 10^{-6} \cdot 400} = 0.9999 \,, \quad (10)$$

$$P(l)_u = e^{-\hat{\lambda}_u l} = e^{-3.599 \cdot 10^{-6} \cdot 400} = 0.99985 \,. \quad (11)$$

The 90 %-gamma percentage resource (γ = *90%*) is determined as:

$$L_{\gamma L} = \frac{1}{\lambda_L}(-\ln 0.9) = \frac{1}{3.599 \cdot 10^{-6}}(-\ln 0.9) = $$
$$= 29.27 \cdot 10^3 \, km, \quad (12)$$

$$L_{\gamma u} = \frac{1}{\lambda_u} = \frac{1}{0.115 \cdot 10^{-6}}(-\ln 0.9) = $$
$$= 915.6 \cdot 10^3 \, km. \quad (13)$$

The ADM type of the rail service cars share a characteristic feature that their failures can be caused by more than one simultaneously acting causes. For example, three-phase actuator motors can fail under the influence of their rotor, causing the phenomenon of eccentricity, wear of internal and external bearing rings, wear of electrical insulation of motors under the influence of heating and overvoltage. Depending on which of the processes develops more intensively, failure of one or joint action of other types occurs. Thus, the total probability of distribution of duration of operation up to the failure of the electromechanical equipment having a clutch, and working on different kinds of loading is a mix, a superposition of several distributions.

The statistical data on duration of operation up to failure of electromechanical equipment of separate units of the rail service car, especially asynchronous motors, working together with a clutch, suggest an overlay of the exponential law and the normal Gaussian law. Figure 5 presents the distribution of distance travelled by the rail service car of the ADM type before failure, confirming the presence of two superposition's.

This superposition can be described by the formula for density distribution:

$$f(l) = K_1 f_1(l) + K_2 f_2(l) \,, \quad (14)$$

where K_1*=0.2* and K_2*=0.8* represent the share of failures distributed exponentially (Exponential law Curve 1 red color) and normally (Gaussian Curve 2 blue color) respectively, as depicted in Figure 4. In the same figure, (Superpositions low Curve 3 grey) represents the total superimposed laws distribution: $f_1(l)$; $f_2(l)$ respectively denote the distribution densities under exponential and normal conditions.

$$f_1(l) = \frac{1}{L_{av.1}} \cdot \exp f_1(l) = \left(-\frac{l}{L_{av.1}}\right) = $$
$$= \frac{1}{384.61 \cdot 10^3} \cdot \exp\left(-\frac{400 \cdot 10^3}{384.61 \cdot 10^3}\right) = \,, \quad (15)$$
$$= 0.918 \cdot 10^{-3} \frac{1}{km}$$

$$f_2(l) = \frac{1}{2\pi\delta} \cdot \exp\left[-\frac{(l - l_{av.2})^2}{2\delta^2}\right] = \\ = \frac{1}{2 \cdot 3.14 \cdot 0.15} \cdot \exp\left[-\frac{(400-277)^2}{2 \cdot 0.15^3}\right] = \\ = 0.021 \cdot 10^{-3} \frac{1}{km}, \quad (16)$$

where $\delta = 0.15$ - tis the relative error of the mean value, selected according to the recommended values [3]. We can find the total distribution density by substituting Equations (15) and (16) into Equation (14), resulting in

$$f(l) = 0.2 \cdot 10^{-3} \frac{1}{km}.$$

5 Conclusions

A comprehensive analysis of statistical data, concerning the operation of the ADM type Joint-Stock Company rail service cars, particularly focusing on their power electromechanical equipment, elucidates that the operational state of mechanical, hydraulic, and electrical equipment exhibits complex interdependencies. These dynamically interconnected entities operate across various modes, which underscores the need for a systematic exploration of the quantitative reliability indicators that bear a significant influence on their effective utilization.

The observation plan denoted as $[N, U, L_0]$ facilitates the ascertainment of essential indicators and provides an estimate of the following parameters: L_{av}, denoting the mean time to failure; $P(l)$, representing the probability of failure-free operating time across different runs; $\lambda(l)$, indicating the lower and upper boundaries of failure rates, and the gamma percent resource when γ is equivalent to *9 0%*.

By applying the test and basing the analysis on the numerical values at specific levels of significance, authors can affirm that the selected law does not contravene the experimental data. The total probability distribution, concerning the failures of electromechanical equipment tends to align with a superposition of both exponential and normal Gaussian laws. The calculation of these distribution densities is of the utmost importance for determining and adjusting the crucial reliability indicators during both the design and operation phases of the rail service car.

By factoring parameters of the main units in the operating mode, the model installation site, the average costs associated with current repairs, and the expenditure incurred during the emergency recovery operations, a mathematical model has been formulated. This model aids in determining the optimal maintenance intervals utilizing uncertain Lagrange multipliers.

The practical implications of this mathematical model extend to the design process and the investigation of fundamental reliability characteristics of the main units. For instance, this model can be effectively applied to assembly platforms of the rail service cars at “Uzbekistan Railways” JSC. This exemplifies the practical application of these models in assessing and enhancing the reliability of rail service car in real exploitation operational scenarios.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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