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Evaluation of the reliability of a heavy diesel locomotive

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The article addresses the evaluation of the operational process of a heavy diesel locomotive type 15D/A, which was developed through the modernization of the TEM2 locomotive. The primary goal of the modernization was to improve technical and operational parameters while keeping investment costs low. The paper discusses the failure structure, causes of inefficiency and breakdowns, and calculates failure intensity parameters in relation to operational and transport performance. The determined indicators show relatively low failure rates for the analysed group of vehicles. Technical availability indicators – both operational and actual – were also evaluated. The research results demonstrate that the modernization reduced the locomotive's failure rate compared to other diesel traction vehicles, confirming the investment's rationale.

Key words: *heavy diesel locomotive, reliability, modernization, operational efficiency, maintenance*

1. Introduction

Contemporary challenges related to the sustainable development of railway transport are driving intensive modernization efforts of rolling stock, particularly locomotives. As the fleet ages, environmental requirements increase, and the need to improve energy efficiency grows, the modernization of existing vehicles becomes a key element of the railway sector's development strategy. In Poland, the average age of diesel locomotives exceeds 40 years, resulting in increased fuel consumption and the emission of harmful substances [4]. Similar issues are observed in other countries, where modernization not only involves the replacement of the drive system but also the implementation of modern control and energy management systems [6].

The modernization of locomotives aims not only to reduce operating costs but also to adapt vehicles to increasingly stringent emission standards. An example is the replacement of traditional two-stroke engines with modern power units, which allows for a significant reduction in fuel consumption and CO_2 emissions [4]. Additionally, the introduction of hybrid systems and the use of energy recovered during braking contribute to improved energy efficiency [3]. In the article [5], contemporary powertrain systems of rail vehicles were analyzed, including internal combustion engines, hybrid systems, and bi-mode propulsion systems. Attention was drawn to the increasing importance of energy storage, for example, through the use of ultracapacitors or fuel cells, which allows for an improvement in powertrain efficiency and adaptation to various operational conditions. For electric locomotives, optimizing traction systems, including the use of thyristor inverters and automatic control systems, is of key importance [9].

Another important aspect of modernization is improving reliability and operational safety. The introduction of online diagnostic systems and artificial intelligence algorithms enables early fault detection, which translates into reduced downtime and repair costs [14]. In the article [11], the use of thermal imaging for thermal analysis of the braking system and drivetrain of an electric locomotive under real operating conditions was presented. These studies enable the identification of potential operational issues and the assessment of the effectiveness of cooling and lubrication systems, which is crucial for ensuring the safety and reliability of rail vehicles.

Undoubtedly, an important aspect of the operation of internal combustion engines in locomotives is the wear of mechanical components, such as piston rings. The article [8] presents a study on the wear of modern sets of piston rings in a locomotive diesel engine. The analysis of the wear of these components is of key importance for evaluating engine durability and for planning maintenance and overhauls, which directly affect the reliability and operating costs of locomotives.

At the same time, rolling stock modernization must take into account the specifics of regional operating conditions, such as terrain configuration and infrastructure availability [1].

Due to the approaching deadline obliging the vehicle owner to perform P5-level repairs (major overhauls) to the SM48 series locomotives operated by them, taking into account the lack of planned changes in the vehicle components that could significantly increase the reliability of the traction means in question after the repair, and the financial factor related to the costs of carrying out such repair, it was planned to discontinue their operation.

The vehicles withdrawn from operation, taking into account the need to maintain a sufficient number of available locomotives in order to perform the planned operational work, had to be replaced with traction resources.

The lack of funds for the purchase of new rolling stock became a reason for developing a concept for the modernization of this series of locomotives, thanks to which the costs of obtaining vehicles with technical and operational parameters similar to those obtained by newly built vehicles amounted to approx. half of the value of brand new locomotives.

This modernization decision allowed the acquisition of about twice as many traction vehicles compared to purchasing new ones. This solution, considering earlier modernization decisions for other locomotive series, was well-received and helped maintain the operational fleet size.

2. Description of the analysed subject

The 15D/A locomotive is classified as a heavy diesel locomotive designed for freight train operations. Due to its layout of components typical for vehicles intended for shunting work – a single driver's cab and walkways on both sides of the engine compartment – the traction vehicle is suitable for heavy shunting work as well as for leading transfer and line trains. The traction characteristics also allow for double-traction operation.

The design resulted from a comprehensive modernization of the TEM2 locomotive, retaining the frame, bogies, fuel tanks, and traction motors. The original Soviet-made diesel engine was replaced with a modern American-made propulsion unit compliant with UIC 624 Annex A (Stage IIIa) emission requirements. The rated power of the TEM2 locomotive is 882 kW (1200 HP), while the modernized 15D/A locomotive has nearly double the power – 1550 kW (2107 HP). As a result, the original shunting characteristics were replaced by those of a line freight locomotive, while retaining the functionality of a shunting locomotive.

The locomotive consists of 11 main components arranged in such a way as to ensure proper weight distribution of wheelset pressures on the track. These components meet current national and EU standards. Access for maintenance personnel complies with the maintainability requirements of the vehicle, thanks to which inspection and repair activities can be performed in a shorter time, compared to the original, non-modernized version of the vehicle.

Figure 1 shows the location of the main components of the 15D/A locomotive, and Table 1 provides their descriptions.

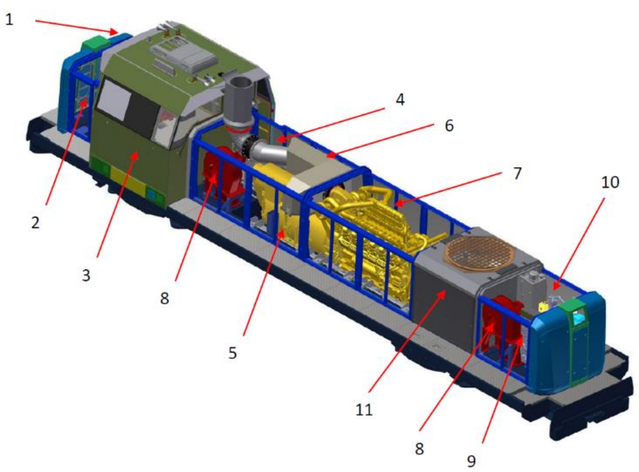

Fig. 1. Location of the main components of the 15D/A locomotive

Table 1. Main components of the 15D/A locomotive

No.	Component
1	Battery compartment
2	Electrical compartment – medium and high-voltage cabinets
3	Driver's cab
4	Main rectifiers of the locomotive
5	Main generator and auxiliary generator
6	Exhaust silencer
7	Diesel engine
8	Traction motor fans
9	Pneumatic panel
10	Compressor unit
11	Cooling unit

Table 2 presents the basic technical and operational characteristics of the analysed locomotives.

Table 2. Basic technical and operational characteristics of the 15D/A loco

Parameter	Value
Manufacturer	ŁTZ, BMZ, NEWAG (modernization)
Type	15D/A
Purpose	Shunting, freight train operations
Gauge	UIC 505-1
Axle arrangement	Co'Co'
Total length	16,970 mm
Maximum width	3084 mm
Maximum height from railhead	4553 mm
Distance between extreme axles	12,800 mm
Tare weight	110,000 kg ±3%
Service weight	116,000 kg ±3%
Fuel capacity	5400 kg (6000 dm^3)
Cooling system fluid volume	680 dm^3
Sand capacity	800 kg
Control multiplicity	Control of two locomotives from one cab
Locomotive control	Microprocessor controller
Transmission type	Electric
Brake system	Knorr-Bremse
Chassis type	Bogie
Connection to bogie	Pivot pin and spherical supports
Distance between pivot pins	8,600 mm
Number of bogies	2
Number of traction motors	6
Number of driving axles	6
Coupling type	Screw coupling

3. Analysis of recorded failures

Failure data were collected over a two-year period for a group of more than a dozen locomotives, based on operational logs and maintenance reports documenting the service and repair processes. These documents include:

- The railway vehicle logbook
- The periodic inspection logbook for traction vehicles
- The current repair logbook for traction vehicles.

These records contain detailed information such as:

- Series and vehicle number
- Date of failure identification
- Cause of failure
- Duration of maintenance tasks
- Type of work (maintenance level)
- Work description
- Labor intensity of repairs
- Diagnostic parameter values before and after repairs
- Quantity and value of materials and spare parts used
- Repair technology.

3.1. Recorded failures

The failure structure of the analyzed group of 15D/A locomotives is shown in Fig. 2. Table 3 explains the work order code fragments used in the chart labels (Fig. 2).

The fault coding system uses digits separated by dots. Each subsequent section of the code corresponds to the subsequent levels of decomposition of the system into subsystems. The method of the cited coding system assumes the division of the locomotive into units, subassemblies and elements, which to some extent corresponds to the classification of the coding method of the position-group method described in [2]. Table 3 presents the highest level of decomposition of the system into units.

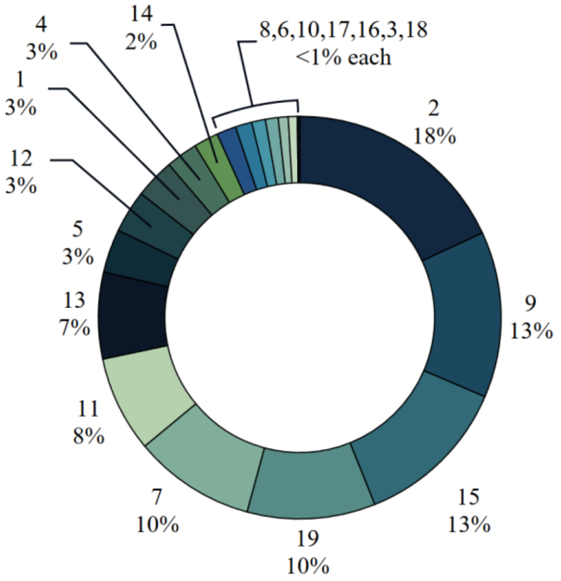

Fig. 2. Failure structure of the analysed locomotive group

Table 3. Explanation of work order code fragments

Code	Component	Code	Component
1	Others	10	Radiotelephone
2	Pneumatic system	11	Electric machines
3	Suspension	12	Batteries
4	Brake mechanical part	13	Lighting
5	Wheelsets	14	Diesel engine
6	Brake pneumatic part	15	Cooling system
7	Coupling and pneumatic couplers	16	Lubrication system
		17	Fuel system
8	Sandboxes	18	Turbocharger
9	Electrical equipment	19	Driver's cab

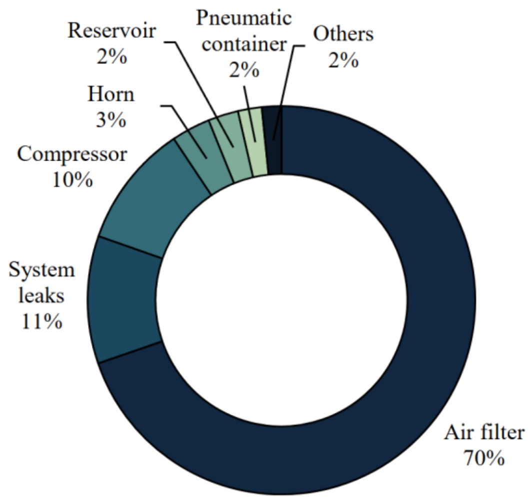

Fig. 3. Failure structure of the pneumatic system

The most common causes of failures in the analyzed group of 15D/A locomotives include:
- Pneumatic system failures – 18%
- Electrical equipment failures – 13%
- Cooling system failures – 13%
- Driver's cab component failures – 10%.

Failures in these components account for nearly half of all recorded inefficiencies.

Figure 3 shows the failure structure of the pneumatic system – the most unreliable component of the analyzed locomotive group.

The most common causes of pneumatic system failures are:
- Air filter failures – 70%
- System leaks – 11%
- Air compressor failures – 10%.

The most unreliable component in the pneumatic system is the air filters, accounting for approximately 14% of all recorded failures. In most cases, the issue is caused by membrane clogging, which disrupts airflow. The membrane must be cleared using compressed air, and if this is ineffective, the component must be replaced.

About 11% of pneumatic system failures result from leaks, primarily at joints and pneumatic valves.

One in ten pneumatic system failures is related to compressor unit damage, often due to oil shortages, clogged filters, or leaks affecting the component's performance.

Figure 4 shows the failure structure of the electrical equipment in the analyzed locomotive group. The main causes of electrical equipment failures are:
- Contactor failures – 31%
- Engine controller failures – 22%
- CAN bus and software issues – 11%
- GPS system failures – 8%.

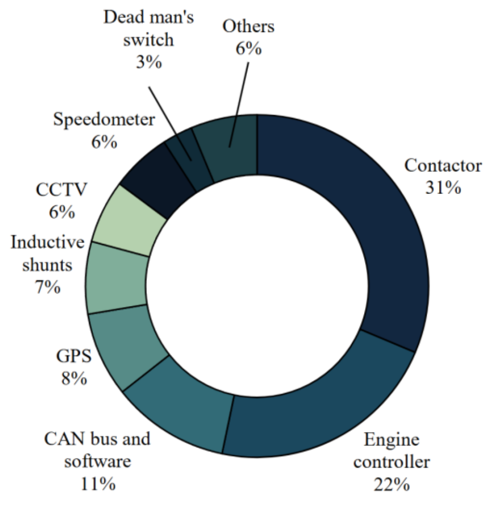

Fig. 4. Failure structure of the electrical equipment

Approximately one-third of failures are caused by contactor damage, primarily line contactors, excitation contactors, shunting contactors, and traction motor contactors. These failures are mainly due to power supply issues and errors.

Every fifth failure of electrical equipment results from damage to the combustion engine controller, which results in the inability to start it.

About 11% of failures are related to errors in the software of the traction vehicle's on-board computer and damage to the CAN bus. As a result, there is a loss of connection and a lack of communication between important components of the locomotive, preventing its proper use.

In 8% of cases, electrical equipment failures occur as a result of incorrect operation of the GPS device. This has an impact on the difficult work of the department responsible for planning vehicle maintenance – due to the lack of possibility of obtaining actual data on the number of hours of operation of the combustion engine until its next inspection, and the dispatch, because the positioning of the locomotive can be predicted only on the basis of processed information from the train timetable sent by the IT systems of the railway infrastructure manager. The GPS positioning system, using a fuel probe, also allows for monitoring the fuel tank filling level and any accelerated volume or mass losses.

3.2. In-service failures

Among the registered damages causing the unsuitability of a traction vehicle considered as a technical object, it is necessary to distinguish those occurring during train operation, light running, or shunting work were distinguished and resulted in the need to replace it with a replacement vehicle or to call another traction vehicle to pull the damaged traction means from the railway line – a section of the line between two signalling posts – to the nearest station for repair or sending it to a workshop.

In order to facilitate the classification and analysis of information relating to faults, damage codes are used that uniquely identify the damaged component (subassembly).

Failures can be categorized by their cause, such as damage to a component (subassembly). The causes include unfavourable weather conditions, improper vehicle operation by the traction team, use of improper material or material with improper properties, contamination or improper fuel composition, and improperly performed repairs by the maintenance department or guarantor.

Figure 5 shows the structure of recorded failures.

The most failure-prone components include electrical circuit devices and apparatuses, accounting for 30% of all failures, the internal combustion engine, responsible for 17% of all failures, and elements of the vehicle's pneumatic system, constituting 9% of total failures. A significant proportion of incidents involve locomotive breakdowns without the identification of a specific faulty component, representing 21% of all reported failures. This may result from specific operational conditions at the time, temporary malfunction of a component or subsystem that later returned to normal operation without showing signs of damage, or improper handling by the train crew, which, while not causing physical damage, temporarily impedes proper vehicle operation.

Based on statistical data concerning operational and transport activity, it is possible to determine the failure rate parameter [12] – an index associated with maintainability, characterizing the reliability of the analyzed locomotive group. In the given case, this parameter defines the number of failures requiring the deployment of a replacement vehicle or the towing of the damaged locomotive off the railway track, in relation to operational output expressed in vehicle-kilometers and gross ton-kilometers performed by the given vehicle population.

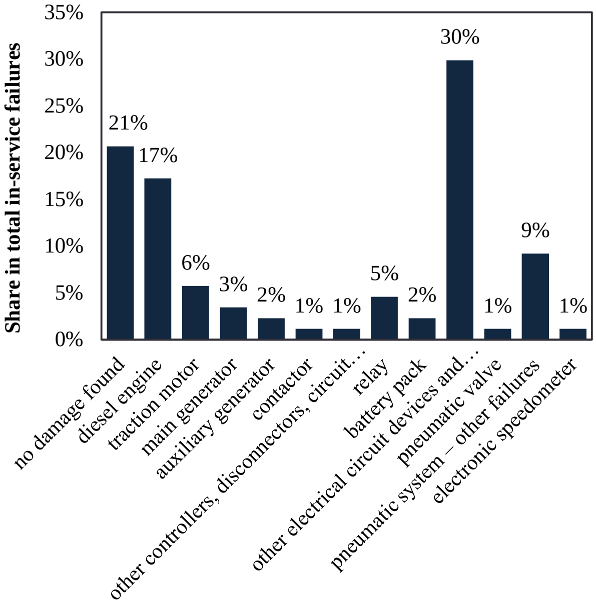

Fig. 5. In-service failure structure of the analysed locomotive group

The failure rate for operational performance is given by (1):

$$z_l = \frac{N(l)}{N_O \cdot l} = 25.06 \left[\frac{\text{failures}}{\text{million vehicle}-\text{km}}\right] \quad (1)$$

where: $N(l)$ – number of failures during operational work l, N_O – population size, l – operational work.

The failure rate for transport performance is given by (2):

$$z_m = \frac{N(m)}{N_O \cdot m} = 2.73 \left[\frac{\text{failures}}{\text{100 million gross ton}-\text{km}}\right], \quad (2)$$

where: $N(m)$ – number of failures during transport work m, m – transport work, other markings – as above.

Appropriate processing of the collected operational data made it possible to determine the failure rate parameter for other types of diesel traction vehicles in relation to operational performance – see Fig. 6, and transport performance – see Fig. 7.

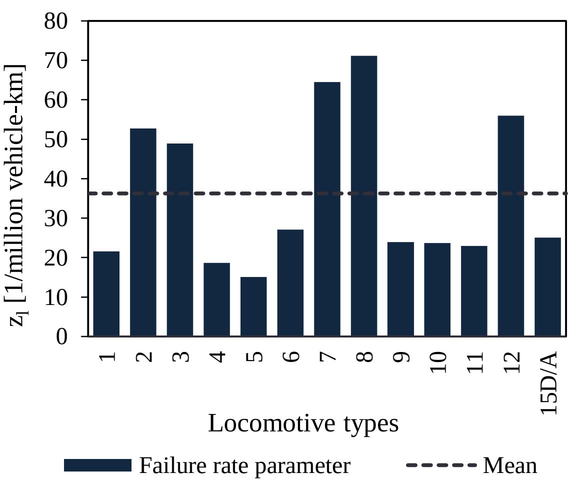

Fig. 6. Failure rate parameter in relation to operational performance

Data for the remaining vehicles, as with the analysed locomotives, were collected over the same two-year operational period. The dashed lines in the graphs indicate the average indicator values for all types of locomotives. The remaining locomotives are diesel-powered, comprising both line-haul (freight) and shunting types, with several units (more than a dozen in each group) included in the analysis.

The failure rate parameter related to operational performance, calculated for the studied group of traction vehicles, amounts to 25.06. This value represents approximately 69% of the average value of the parameters determined for other types of diesel locomotives. Such a value indicates a relatively low failure rate for the 15D/A vehicle population, consistent with modernization expectations and assumptions.

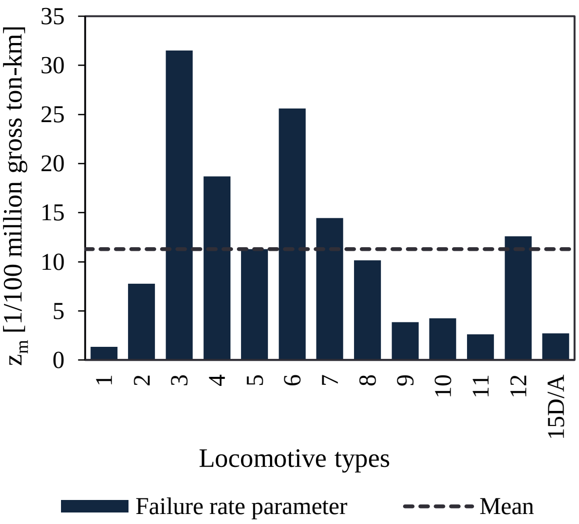

Fig. 7. Failure rate parameter in relation to transport performance

The failure rate intensity parameter relative to transport performance, calculated for the analyzed population of traction vehicles, amounts to 2.73, which constitutes approximately 24% of the average value of the parameters determined for other types of diesel traction locomotives. These low values of failure rate intensity indicators support the conclusion that this type of locomotive is characterized by low unreliability.

3.3. Availability

Availability is defined as the ability of a given system to remain in a state that allows it to perform its required functions under specified conditions, at a specified time or within a given time interval, assuming the required external resources are provided [13]. Availability depends not only on maintenance-related unserviceability but also on the probability of unserviceability that prevents the system from fulfilling its assigned functions (known as the effect of unavailability) [10].

The availability index is understood as the probability that the traction vehicle is in an operational state at time t. Therefore, the technical availability index must satisfy eq. (3):

$$A(t) = 1 - F(t) + \int_0^t [1 - F(t - \tau)]\, h(\tau) d\tau \qquad (3)$$

where: $h(t)$ – renewal density function: $h(t) = \frac{H(t)}{dt}$.

In practice, equation (3) is not applicable due to the fact that the very concept of the technical availability coefficient is understood as a stationary value that the function A(t) tends to approach with increasing time [7] – equation (4):

$$A = \frac{T_0}{T_0 + U_0} \qquad (4)$$

where: T_0 – mean time the locomotive remains in an operational (serviceable) state, U_0 – mean time the locomotive remains in an unserviceable state.

According to [2], the technical availability index is synonymous with the term "availability" and is classified as a fundamental reliability characteristic of renewable systems, taking into account the failure rate and maintainability of the vehicle.

The analysed group of vehicles undergoes both corrective repairs and preventive maintenance. Consequently, two types of technical availability have been distinguished: operational availability and actual availability.

Operational availability (A_o) is calculated by considering the time the traction vehicle remains in an unserviceable state due to a failure.

Actual availability (A_r) is calculated by considering both the time the traction vehicle is unserviceable due to a failure and the time it is undergoing preventive maintenance as specified in the Maintenance System Documentation.

To assess the technical availability of the analysed group of locomotives over a specific time interval (0, t), the operational availability A_o should be calculated using eq. (5):

$$A_O = \frac{\sum_{i=1}^{N} TZ_i}{\sum_{i=1}^{N} TZ_i + \sum_{i=1}^{N} TN_i} = 0.8609 \qquad (5)$$

where: TZ_i – time the locomotive (i) remains in a serviceable state, TN_i – time the locomotive (i) remains in an unserviceable state, N – population size.

The actual availability A_R can be determined using equation (6):

$$A_R = \frac{\sum_{i=1}^{N} TZ_i}{\sum_{i=1}^{N} TZ_i + \sum_{i=1}^{N} TN_i + \sum_{i=1}^{N} TO_i} = 0.7784 \qquad (6)$$

where: TO_i – time the locomotive (i) remains in an unserviceable state due to preventive maintenance, other symbols – as previously defined.

Considering the short, two-year service period of the analysed group of traction vehicles, the relatively low values of the indicators may be attributed to the initial phase of vehicle operation – the so-called run-in period.

4. Conclusions

The modernization of the TEM2 locomotive to the 15D/A version has resulted in the acquisition of vehicles with favourable operational characteristics, including nearly a twofold increase in power output, while maintaining reasonable investment costs – approximately 50% of the price of new locomotives.

The most common causes of vehicle failureability include failure of the pneumatic system (especially air filters), electrical equipment, cooling and cab driver components. It is therefore essential to review the range and capability of preventive maintenance tasks for the mentioned components.

The failure rate intensity parameter for the analysed vehicle population, in relation to operational performance, is 25.06 failures per million vehicle-kilometers, and in relation to transport performance, 2.73 failures per 100 million gross ton-kilometers. These values indicate a lower failure rate compared to other types of diesel locomotives – 69% and 24% of the average values for these parameters, respectively.

The operation and actual technical availability indicator values are below expectation for the modernized units because of the initial phase of operation – so-called running-in period. Monitoring and viewing the indicators at subsequent operation years is recommended..

The conducted analysis validates the justifications of modernization decisions as an excellent method of extending the lifespan of rolling stock and improving its operability with a low budget..

The results of the research can serve as a basis for developing the best maintenance and modernization strategies for other similar vehicles.

Upon completion of the criterion in view of calendar time to perform preventive activities at the P4 level, the entire inter-repair time could need to be thoroughly analyzed for reliability along with the test described above. The analysis would also need to include other RAMS parameters (reliability, availability, susceptibility and maintenance and safety) so as to have the entire view of how the entire system operates. Use of such a method allows one to make an overall estimation of the technical condition and life of modernized locomotives. Further developing the examination of traditional indicators, one can identify patterns and trends of failure modes, estimate the efficiency of the selected maintenance strategy, and define the reliability growth or degradation in time.

It may be a solution for providing support in the decision-making process regarding the continuation, modification or abandonment of some practices that are functioning within the maintenance system. In addition, using the RAMS indicators within the system evaluation allows for the identification of the most likely failing parts within the locomotive. This then enables the scheduling of design or operation-based action that aims to eliminate weak links, increase system reliability and extend the inter-repair cycles. Implementation of such a method not only allows for the achievement of high values of technical availability indicators that give the opportunity to ensure continuity of operations, but also facilitates the optimization of costs and affects the estimation of the effectiveness of investments in rolling stock modernization.

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