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Assessing the technical condition of mainline diesel locomotive power plants using modern diagnostic and automated monitoring technologies

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Abstract: The power units of mainline diesel locomotives are one of the primary technical systems ensuring the continuous and safe operation of railway transport. The operational reliability of these power units is directly linked to the timely assessment of their technical condition, the detection of malfunctions in their initial stages, and the scientifically-based organization of maintenance processes. Traditional, regulation-based maintenance methods often fail to fully reflect the actual technical condition of the aggregates, leading to increased operational costs, the occurrence of unscheduled failures, and a decrease in the operational readiness of locomotives. Therefore, integrating modern diagnostic tools and automated monitoring technologies into the maintenance system is one of the pressing scientific and practical tasks in the field of transport engineering. This study provides a comprehensive analysis of the capabilities of various methods for assessing the technical condition of mainline diesel locomotive power units, including vibration monitoring, thermographic inspection, physicochemical analysis of oil, monitoring of electrical parameters, and automated control systems based on intelligent sensors. The research methodology was based on systematic analysis, comparative evaluation of diagnostic parameters, monitoring of operational indicators, and assessment of maintenance efficiency. The diagnostic results showed that real-time monitoring of the power units' operating parameters enables the early detection of malfunctions, the prediction of their progression, and the optimization of maintenance intervals in accordance with operating conditions. The research findings confirmed that the application of modern diagnostic and automated monitoring technologies serves to enhance the operational reliability of mainline diesel locomotives, extend the service life of power unit components, reduce the number of unscheduled repairs, and optimize maintenance costs. Furthermore, it has been scientifically substantiated that implementing Condition-Based Maintenance (CBM) and Predictive Maintenance (PdM) principles significantly increases maintenance effectiveness and improves the operational availability coefficient of locomotives. The proposed integrated approach serves as a scientific and practical basis for increasing the accuracy of assessing the technical condition of mainline diesel locomotive power units, improving maintenance strategies, and widely implementing digital diagnostic systems in railway transport.

Keywords: mainline diesel locomotive, power units, technical condition, diagnostics, automated monitoring, vibration monitoring, thermography, smart sensors, SCADA, Condition-Based Maintenance, Predictive Maintenance, operational reliability, maintenance, railway transport

1. Introduction

Railway transport is one of the most vital components of the country's transport system, providing for the transportation of large volumes of cargo and passengers over long distances. The efficiency and safety of the transport process largely depend on the technical condition of the locomotive fleet, particularly the power plants of mainline diesel locomotives, which are the primary source of traction power and determine the locomotive's operational performance.

Under modern conditions of intensive railway transport use, the demands for reliability, cost-effectiveness, and environmental safety of locomotive power plants are increasing. Prolonged operation of equipment under variable loads, exposure to adverse operating factors, and the natural wear and tear of parts and assemblies lead to a deterioration in the technical condition of power units, a decrease in their efficiency, and a higher probability of failure. Failure to detect malfunctions in a timely manner can result in unscheduled repairs, rolling stock downtime, and significant economic losses.

Traditional maintenance and repair methods, based on scheduled overhaul intervals and periodic inspections, do not always allow for the timely detection of latent defects or an objective assessment of the equipment's actual condition. In this regard, the implementation of modern diagnostic and automation tools which ensure continuous monitoring of power plant operating parameters, prompt detection of deviations from standard indicators, and prediction of potential malfunctions is of particular relevance.

The development of digital technologies, microprocessor engineering, intelligent monitoring systems, and methods for processing large volumes of diagnostic data is opening up new opportunities for improving the locomotive maintenance system. The use of automated diagnostic complexes enables a shift from a system of scheduled preventive maintenance to maintenance based on actual technical condition, which in turn serves to increase

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equipment reliability, reduce operational costs, and ensure the rational use of resources.

Despite the existence of numerous studies on locomotive equipment diagnostics, the challenge of a comprehensive assessment of the technical condition of mainline diesel locomotive power plants using modern control and automation tools remains relevant and requires further scientific substantiation. The development of monitoring methods that improve diagnostic reliability and ensure the effective management of the technical condition of locomotives throughout their entire operational life is of particular importance.

The power units of mainline diesel locomotives are one of the primary technical systems ensuring the continuous and safe operation of railway transport. The technical condition of these units directly affects the locomotives' traction power, fuel consumption, operational reliability, and economic efficiency. Therefore, regularly monitoring the condition of power units, along with the early detection and prevention of malfunctions that occur during their operation, is one of the most critical tasks facing railway transport today.

In recent years, the widespread introduction of digital technologies, automated control systems, and modern diagnostic tools into railway transport has created new opportunities for improving methods of assessing the technical condition of locomotives. However, in practice, effective solutions for diagnosing mainline locomotive power units during operation, determining their residual service life, and organizing maintenance based on their actual technical condition have not yet been sufficiently developed.

There is a need to further develop scientific and methodological approaches for the comprehensive monitoring of the performance indicators of diesel-generator sets, fuel, lubrication, and cooling systems, as well as auxiliary electrical equipment, in order to identify latent defects and prevent emergency situations. In most cases, existing diagnostic tools are limited to monitoring only individual parameters and do not allow for a comprehensive assessment of the power unit's overall technical condition.

Improving the reliability of power units and enhancing maintenance and repair systems are among the key scientific directions in the fields of transport engineering and locomotive management. As a result of research in reliability theory, technical diagnostics, automated monitoring systems, and operational efficiency enhancement, significant scientific achievements have been made by both domestic and foreign scientists.

Scientific literature extensively covers the assessment of the technical condition of mainline diesel locomotive power units, the detection and prediction of malfunctions, maintenance optimization, and the implementation of automated diagnostic systems. At the same time, the rapid development of modern sensor technologies, microprocessor-based control devices, remote monitoring systems, and digital diagnostic complexes necessitates the further improvement of existing methods for monitoring power units.

An analysis of scientific sources shows that assessing the technical condition of mainline locomotive power units using modern diagnostic and automation tools, detecting malfunctions in their early stages, and increasing their reliability by implementing a condition-based maintenance system remain relevant issues. Research in this area is of great scientific and practical importance for increasing the operational efficiency of locomotives, reducing repair costs, ensuring the rational use of energy resources, and maintaining traffic safety in railway transport.

2. Research methodology

Structural Features of Modern Power Plants in Diesel Locomotives

Modern mainline diesel locomotives are high-tech transport vehicles in which power units serve as the primary source of traction. In recent decades, the design of these power units has undergone significant changes, driven by the need to increase fuel efficiency, reliability, and environmental safety, as well as to adapt to digital control and diagnostic technologies. Modern technical solutions are aimed not only at increasing locomotive power but also at providing the capability for continuous monitoring of the technical condition of key units during operation.

The core of the power units in most mainline diesel locomotives is a high-performance, supercharged internal combustion diesel engine. Unlike previous-generation engines, modern diesels are distinguished by their higher specific power, improved fuel efficiency, and reduced harmful emissions. Structurally, they are built with either a V-type or in-line cylinder arrangement and are equipped with a turbocharger, intercooling for the charge air, and electronic control systems for the fuel injection process.

One of the most important features of modern power units is the use of electronically controlled fuel systems. The use of electronic control units allows for the adjustment of injection timing, fuel delivery duration, and fuel rail pressure according to the engine's operating mode. This ensures more complete fuel combustion, reduces its specific consumption, and lowers the toxicity of exhaust gases. Furthermore, electronic systems enable automated monitoring of engine operating parameters and the recording of diagnostic data.

The turbocharging system is a crucial element in the design of modern power units. The turbocharger uses the energy from exhaust gases to increase the pressure of the air entering the engine cylinders. Increasing the air mass in the combustion chamber allows for greater fuel combustion efficiency and higher power output while maintaining the engine's relatively compact dimensions. Modern turbochargers are characterized by a high degree of automation and are equipped with instruments for monitoring temperature, pressure, and rotor speed [1-3].

In the design of modern power units, special attention is paid to the cooling system. During the operation of a diesel engine, a significant portion of the fuel's energy is converted into heat, which must be effectively dissipated to prevent components from overheating. Modern cooling systems include high-efficiency radiator sections, automatic thermoregulators, electric or hydrostatic fan drives, and digital temperature sensors. The use of automated control makes it possible to maintain the engine's optimal thermal regime, regardless of external climatic conditions and load levels.

No less important is the lubrication system, which reduces friction between moving parts and protects surfaces from wear. Modern diesel locomotive engines use combined lubrication systems with forced oil circulation through fine-particle filters and heat exchangers. To increase operational reliability, pressure, temperature, and oil quality sensors are used, with their data transmitted to the locomotive's technical monitoring system.

Modern power units are characterized by the extensive use of electrical and electronic components. Locomotive equipment includes microprocessor control systems, digital controllers, intelligent sensors, and communication networks for data exchange. Such solutions enable functions like automatic power regulation, monitoring the technical condition of equipment, recording emergency events, and predicting the remaining service life of individual units.

A key design difference in modern power units is the direct integration of diagnostic tools into the equipment's structure. Whereas in the past, monitoring engine condition was primarily performed during scheduled inspections and repairs, modern locomotives are now being equipped with continuous monitoring systems. Parameters such as vibration, pressure, temperature, fuel consumption, lubricant quality, and exhaust gas composition are monitored. The data obtained is used to identify early signs of malfunctions and to prevent equipment failures.

One of the key directions in improving the design of power units is enhancing the environmental characteristics of diesel locomotives. To reduce harmful emissions, exhaust gas recirculation systems, catalytic converters, improved fuel injection control algorithms, and multi-stage turbocharging technologies are employed. The implementation of these solutions allows for compliance with modern international environmental standards while simultaneously increasing fuel efficiency [4-6].

Thus, the design of modern power units for mainline locomotives constitutes a complex system of interconnected mechanical, electrical, and electronic systems. Such units are characterized by a high level of automation, the use of electronic controls, the integration of technical diagnostic tools, and the application of technologies to increase fuel economy and environmental friendliness. The aforementioned design solutions create a foundation for implementing modern methods of monitoring the technical condition of equipment and for transitioning to a condition-based maintenance concept for locomotives, which is one of the main directions in the development of the locomotive industry.

3. Results and Discussion

Analysis of the Effectiveness of Modern Diagnostic Technologies in Assessing the Technical Condition of Diesel Locomotive Power Plants

The development of technical diagnostic tools for the power units of diesel locomotives is considered one of the primary ways to enhance the reliability of the locomotive fleet in both domestic and foreign practice. In recent years, particular attention has been given to creating automated monitoring systems that provide continuous oversight of the equipment's technical condition during operation.

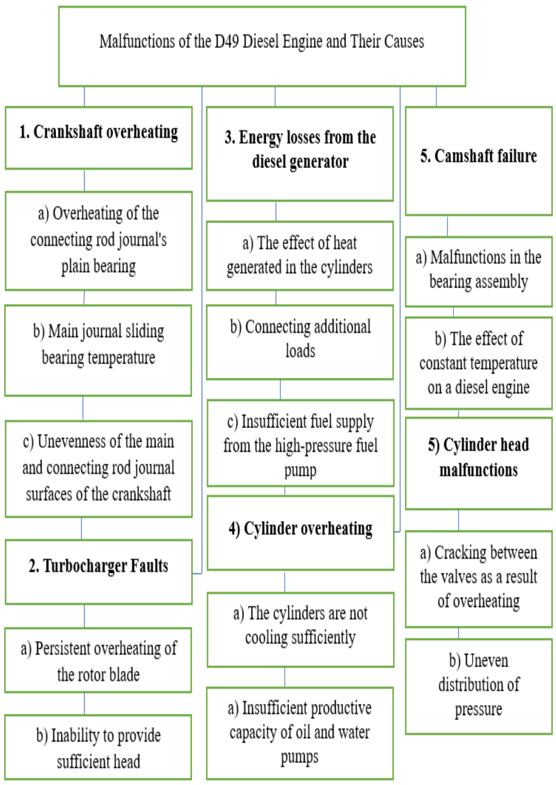
In CIS countries, comprehensive systems for monitoring diesel engine parameters are traditionally employed, which include measuring coolant temperature, oil pressure, crankshaft speed, and other operational parameters. Modern locomotives are being equipped with microprocessor-based control systems that enable the recording of malfunctions and the saving of equipment operational history for subsequent analysis.

Vibrational analysis and engine oil analysis methods have become particularly well-developed. Using spectral oil analysis makes it possible to detect the presence of wear products from engine components and to assess their degree of deterioration. This approach is widely used in diagnosing the cylinder-piston group, bearing assemblies, and elements of the valve train mechanism.

International practices are characterized by a broader use of digital technologies and remote monitoring systems. Major railway companies are implementing intelligent platforms that provide real-time transmission of diagnostic data to specialized data processing centers. This allows for centralized monitoring of the technical condition of the locomotive fleet and a prompt response to any issues that arise [7-8].

The application of big data, cloud computing, and artificial intelligence technologies is a promising field. Analysis of the collected operational data enables the creation of mathematical models for equipment wear and the forecasting of potential failures. As a result, the accuracy of diagnostics and the efficiency of planning repair work increase significantly.

A comparative analysis of local and international experience shows that the most effective solutions are comprehensive diagnostic systems that integrate automated monitoring of equipment's technical condition, intelligent data analysis, and forecasting tools. The further development of these technologies involves integrating digital platforms for locomotive life cycle management and implementing the digital twin concept for the power unit (Fig. 1).



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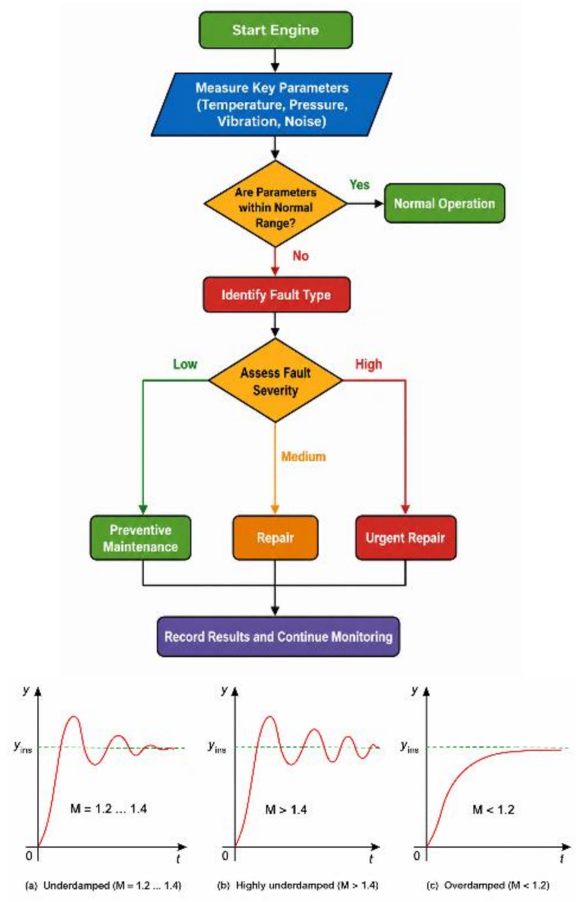

Fig. 1. Key factors affecting the operational characteristics and performance of internal combustion engines

Analysis of Modern Approaches to Assessing the Technical Condition of Locomotive Equipment

Assessing the technical condition of locomotive equipment is a vital component of the system for ensuring railway transport reliability. Traditional inspection methods were primarily based on conducting scheduled inspections and repairs at specified time intervals or distances traveled. However, the development of diagnostic technologies has revealed the limitations of this approach, as the actual technical condition of individual components can differ significantly from standard benchmarks.

Modern methods for assessing technical condition are based on the principle of continuously monitoring equipment performance parameters. Such systems are fundamentally comprised of digital sensors, microprocessor-based devices for information processing, and specialized software suites for data analysis. The use of these technologies allows for monitoring the equipment's technical condition directly during operation, without taking the locomotive out of service.

Modern methods for assessing technical condition are based on the principles of continuous monitoring of equipment performance parameters. The foundation of such systems consists of digital sensors, microprocessor-based devices for information processing, and specialized software suites for data analysis. The use of these technologies allows for the monitoring of the equipment's technical condition directly during operation, without taking the locomotive out of service.

One of the most common methods is parametric diagnostics, which is based on analyzing changes in the equipment's operating parameters. Temperature, pressure, rotational speed, fuel consumption, vibration characteristics, and other indicators are monitored. Deviations from their standard values may signal an emerging malfunction.

Vibrodiagnostic methods, which enable the detection of defects in bearing assemblies, imbalances in rotating parts, shaft misalignments, and other mechanical damage in their early stages of development, have become widespread. The high sensitivity of this method makes it possible to predict equipment failure long before any external signs of a malfunction appear.

The use of intelligent diagnostic systems based on artificial intelligence and machine learning technologies is a promising direction. Such systems can analyze large volumes of operational data, identify hidden patterns in parameter changes, and predict the remaining service life of the equipment. Implementing the concept of predictive maintenance significantly increases the reliability of the locomotive fleet and reduces maintenance costs.

Modern approaches envision a transition from a system of scheduled preventive maintenance to maintenance based on actual technical condition. This concept relies on an objective assessment of the equipment's real-time state and allows for repair work to be carried out only when there is a confirmed need.

The power units of mainline diesel locomotives operate under complex and constantly changing conditions, which directly affects their technical condition. Sharp temperature changes, humidity, dust, and aggressive environmental factors, as well as the vibrations and shock loads that occur when the locomotive travels over uneven sections of track, reduce the operational reliability of the power unit's components. Furthermore, high traction loads, frequent changes in engine operating modes, prolonged operation at maximum power, and repeated starts and stops lead to the accelerated wear of the diesel-generator set's assemblies.

Under the influence of these factors, defects of varying severity can appear in the components of the cylinder-piston group, the fuel apparatus, the turbocharger, and the cooling and lubrication systems. These malfunctions lead to a decrease in the power output of the power units, an increase in fuel consumption, and a decline in environmental performance, while also negatively affecting the overall operational reliability of the locomotive. Therefore, continuous monitoring of the power units' technical condition using modern diagnostic and automated monitoring tools is an essential requirement for ensuring their efficient and safe operation [9-10].

Power units are operated in various climatic and operational conditions, which significantly affects their performance, reliability, and technical condition. When assessing the impact of environmental factors on the operation of power units, the intensity of solar radiation, atmospheric air temperature and relative humidity, the amount of precipitation, atmospheric pressure levels, and the presence of dust, abrasive particles, and other pollutants in the air are taken into account.

High temperatures adversely affect the thermal performance of the diesel engine, generator, and auxiliary systems, which increases the load on the cooling system and can shorten the service life of the units. In low-temperature

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conditions, the physicochemical properties of the fuel change, the efficiency of the lubrication system decreases, and starting the engine becomes more difficult. High air humidity can degrade the insulating properties of electrical equipment and accelerate corrosion processes.

The presence of dust and other mechanical particles in the atmosphere leads to the rapid wear of air filters, turbochargers, and cylinder-piston group components. Furthermore, in mountainous regions, the decrease in atmospheric pressure reduces the amount of air entering the engine cylinders, which negatively impacts the efficiency of the combustion process and the power output of the power unit.

Therefore, when operating the power units of mainline diesel locomotives, it is crucial to consider the influence of climatic factors and to monitor their technical condition using modern diagnostic and automated monitoring systems. This allows for the detection of malfunctions at an early stage, increases the reliability of the equipment, and reduces operational costs.

Mathematical evaluation of the reliability of internal combustion engines

The reliability of internal combustion engines (ICEs), which serve as the primary power units for mainline locomotives, is a key factor in determining the efficiency and safety of the transportation process. Under conditions of intensive locomotive use, the failure of individual engine components leads to a decrease in power, an increase in fuel consumption, a deterioration of environmental performance, and the need for unscheduled repairs. Therefore, to objectively assess the technical condition of these power units, it is essential to employ mathematical reliability analysis methods that allow for a quantitative assessment of the probability of uninterrupted equipment operation and the forecasting of its residual life.

Engine reliability is defined as the ability of the engine to maintain the values of its parameters, which characterize the performance of its specified functions, within established limits for a given period, provided that the conditions for operation, maintenance, and repair are met. A quantitative assessment of reliability is based on the statistical analysis of failures and the use of probabilistic models.

The main indicator is the probability of the engine operating without failure for a specified time (t):

$$P(t) = N(t) \times N_0$$

where N_0 is the initial number of engines under observation, and N(t) is the number of engines that have remained operational by time (t).

The probability of failure is determined by the following expression:

$$Q(t) = 1 - P(t)$$

To analyze the operational reliability of diesel locomotive engines, the failure rate is a widely used indicator that expresses the probability of a failure occurring per unit of time:

$$\lambda(t) = f(t) \times P(t)$$

where f (t) is the probability density of the time to failure.

When the failure rate is constant, the degradation process can be described by the exponential distribution law:

$$P(t) = e^{\lambda(t)}$$

This model is considered optimal for the normal operating period of the engine, which occurs after the break-in process is complete and before the onset of accelerated wear of the cylinder-piston group components, fuel system, and valve train mechanism.

Mean time to failure is defined as the mathematical expectation of the continuous operating time:

$$T_{av} = 1/\lambda$$

It is advisable to apply a structural-functional approach to complex technical systems, including the diesel-generator units of mainline locomotives.

The power plant under consideration may include the following functional subsystems: the cylinder-piston group, lubrication system, cooling system, fuel system, turbocharger, and electronic control system. The failure of any of these subsystems can limit the engine's operational capability, which justifies the need to use a series reliability model.

Modern diagnostic tools enable a transition from traditional statistical reliability assessment to the parametric forecasting of technical condition. In this context, the objects of analysis are diagnostic parameters such as combustion pressure, exhaust gas temperature, fuel consumption, oil pressure, vibration characteristics, and the toxicity indicators of exhaust gases.

The technical condition coefficient can be used to assess the level of technical degradation:

$$K_{ts} = X_t \times X_n$$

where X_t is the current value of the parameter being controlled, and X_n is its nominal value.

Using automated monitoring systems and intelligent diagnostic complexes enables the continuous collection of operational data and the real-time calculation of current reliability indicators. Based on the results obtained, it is possible to forecast the engine's residual life and schedule maintenance based on its actual condition.

Thus, the mathematical assessment of the reliability of mainline locomotive internal combustion engines relies on probabilistic-statistical methods, failure intensity models, and diagnostic criteria for technical condition. The combined application of reliability theory methods with modern diagnostic and automation tools ensures a more accurate assessment of the condition of power units and helps reduce operational costs while maintaining the required level of traffic safety [11].

Methods for Assessing the Technical Condition of Mainline Diesel Locomotive Power Plants

Assessing the technical condition of the power plants of mainline diesel locomotives is crucial for ensuring reliable locomotive operation, preventing malfunctions, and increasing the effectiveness of maintenance. During the technical assessment process, the current operational capability of units and systems is determined, along with their degree of wear and remaining service life. In modern practice, several methods are used to assess the technical condition of power plants (Fig. 2.).

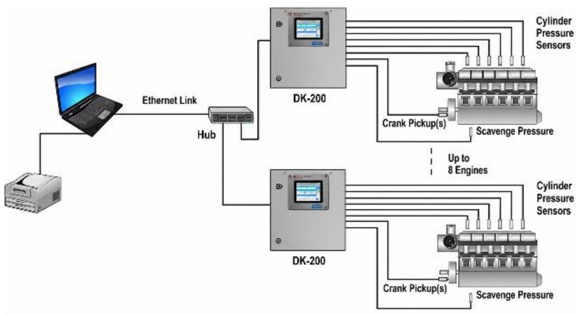

Fig. 2. Assessing the technical condition of the power plants of mainline diesel locomotives

Assessing the technical condition of the power units of mainline locomotives is a critical stage in the operational process, serving to ensure their reliable performance, prevent malfunctions, and extend their service life. The technical condition assessment process is divided into traditional and modern diagnostic methods, depending on the techniques used and the level of monitoring.

Under modern operating conditions, diagnostic methods are increasingly being used to assess the technical condition of power units. These methods are based on the direct measurement and analysis of changes occurring in the equipment's operation.

Diagnostic assessment methods include:

- vibration diagnostics;
- thermal diagnostics (analysis of temperature fields);
- acoustic diagnostics;
- oil condition analysis.

For example, vibration diagnostics can detect the wear of bearings, shafts, and rotating parts at an early stage. Thermal diagnostics, in turn, enables the identification of malfunctions in the cooling system and combustion process.

Assessing the technical condition of power units based on diagnostics offers the following advantages:

- the ability to detect malfunctions early;
- a reduction in the number of unscheduled repairs;
- optimization of maintenance costs;
- an increase in the operational reliability of the locomotives.

Furthermore, based on diagnostic results, maintenance can be transitioned to a condition-based principle, which is an important direction for modern railway transport.

Although traditional methods for assessing the technical condition of mainline locomotive power units are effective to a certain extent, their capabilities are limited under modern operating conditions. The use of parametric and diagnostic assessment methods makes it possible to determine the actual condition of power units, predict malfunctions, and extend the service life of locomotives. This, in turn, lays the groundwork for scientifically substantiating the importance of modern diagnostic and automation tools in the following sections.

The efficient operation of mainline diesel locomotive power units in modern conditions requires continuous and precise monitoring of their technical condition. Traditional periodic inspections do not allow for the timely detection of latent malfunctions occurring in power units. For this reason, modern diagnostic tools are currently being widely implemented in the assessment of power units.

Modern diagnostic tools allow for real-time monitoring of power unit operation, measurement of key operational parameters, and their analysis. With these tools, the assessment of the technical condition is carried out based on precise measurements rather than subjective judgment.

Diagnostic systems typically consist of the following components:

- sensors and measuring elements;
- signal processing modules;
- data acquisition and storage units;
- analysis and visualization software.

Temperature and pressure are the most critical diagnostic parameters when assessing the technical condition of power units. With modern temperature sensors, the following are continuously monitored:

- cylinder head and block temperature;
- coolant temperature;
- exhaust gas temperature.

Pressure sensors, in turn, allow for the assessment of the fuel and oil supply systems' condition. A deviation of these indicators from their nominal values indicates the onset of malfunctions in the power units.

Vibration diagnostics is one of the most effective methods for detecting mechanical wear and malfunctions in power units. With modern vibration sensors, the following can be identified at an early stage:

- the condition of bearings;
- imbalance of rotating parts;
- defects in shafts and mechanisms.

Through the spectral analysis of vibration signals, the root causes of malfunctions are identified and their stage of development is assessed.

Oil condition is a crucial source of information when assessing the technical condition of power units. In modern diagnostic systems, the following are monitored using special sensors:

- oil temperature;
- contamination level;
- the amount of metal particles.

Oil analysis directly reveals the wear processes occurring in the internal components of the diesel engine.

In the efficient operation of mainline locomotive power units, automated monitoring and control systems (AMCS) play a crucial role alongside diagnostic tools. These systems enable the real-time observation, analysis, and, where necessary, implementation of automatic control decisions for power units.

The primary tasks of automated monitoring systems are as follows:

- continuous monitoring of power unit operating parameters;
- detection of deviations from standard values;
- predicting the probability of malfunctions occurring;
- prompt transmission of information to the locomotive engineer and the dispatch center.

Such systems reduce the impact of the human factor and increase the reliability of the operational process [12-13].

4. Conclusion

During this research, the maintenance technology for the D49 diesel engine's lubrication system was comprehensively analyzed, and its impact on operational reliability was evaluated. The results revealed that the lubrication system is crucial for the engine's stable operation, the effective lubrication of friction parts, normal heat dissipation, and extending the service life of the main units. The research confirmed that a deterioration in the technical condition of lubrication system elements, a decrease in oil quality, contamination of filter elements, and a deviation of oil pressure from standard values negatively affect the engine's operational performance, leading to accelerated component wear and an increased risk of unscheduled failures.

The research findings indicated that organizing the maintenance process based on diagnostic data, rather than solely on regulations, is more effective. Regular monitoring of oil pressure, oil temperature, the physicochemical properties of the oil, and filtration efficiency allows for the detection of malfunctions in their early stages of development. This serves to facilitate timely preventive maintenance, increase the reliability of units, and reduce operational costs.

It has been shown that automated monitoring systems enable continuous tracking of the primary operational parameters of diesel engines and allow for the rapid detection of deviations from standard operating modes. The use of digital sensors and microprocessor-based systems helps to increase the accuracy of measurements and the reliability of diagnostic conclusions.

An analysis of the capabilities of intelligent systems has revealed that employing artificial intelligence and machine learning technologies opens up prospects for transitioning to proactive (predictive) maintenance of locomotive equipment. The creation of digital twins for power units and the application of remote monitoring technologies are of particular relevance.

Analysis of existing diagnostic systems confirms their high efficiency in ensuring the operational reliability of locomotives. At the same time, further improvement of diagnostic tools should be aimed at increasing the accuracy of failure prediction, reducing implementation costs, and expanding the capabilities for automated analysis of operational data.

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