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Dump Truck Operational Efficiency: A Case Study of the Don Mining and Processing Plant

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ABSTRACT

The paper considers the issues of the urgent problem of increasing the efficiency of the organization and planning of the maintenance system of mining dump trucks. The methods of analysis and synthesis of a priori information and statistical data of the enterprise show the need to improve the existing system for ensuring reliable operation of the dump truck fleet. Quantitative indicators are given that characterize the operational reliability of the park as the number of failures of the park as a whole, the main components and assemblies and the coefficient of technical readiness (CTR) of the park, analytical dependencies are obtained that approximate the dynamics of these indicators, depending on the duration of the studied service life. The obtained functional dependencies differ by type, with a significant discrepancy between planned and actual indicators, which in production conditions are eliminated by unscheduled operational measures of technical impact that reduce the overall efficiency of the maintenance and repair system of the fleet. The necessity of increasing the efficiency of the operating system at the stage of planning and organization of maintenance and repair is substantiated.

1. INTRODUCTION

In the national economic complex of the Republic of Kazakhstan, the metallurgical cluster is one of the top priorities in production. The metallurgical industry accounts for 21.2% of Kazakhstan's GDP and 43.5% of the manufacturing industry [1]. In Kazakhstan, the production of chromite ore is practically concentrated at the Khromtau deposit, in particular at the Don Mining and Processing Plant (DMPP).

DMPP, established in 1938 in Khromtau, ranks second globally in terms of proven reserves. The quality of the chrome ore extracted and processed at the plant is considered to be unparalleled in world practice. Most of the extracted ore from DMPP is supplied to ferroalloy plants in Aksu and Aktobe. DMPP consists of 27 structural divisions. According to official DMPP data, in 2022 the total volume of chromium ore production is 4,828 thousand tons [2]. The main production is concentrated in five key divisions, including the Molodezhnaya and 10th Anniversary of Independence of Kazakhstan mines, the Don mine, the ore processing and pelletizing plant, and crushing and processing plant No. 1. The production process at this enterprise is organized according to the classical scheme for mining enterprises and includes all regulated stages of the technological process for ore extraction and processing to produce marketable products, which are supplied to TNK Kazchrome ferroalloy plants located in Aktobe and Aksu.

Additional divisions ensure the stable operation of the enterprise, including transportation, repair, automation, and other auxiliary processes. The company also has additional divisions that ensure the stable operation of the enterprise in the tasks of transportation, repair, automation and other auxiliary processes.

Ore and waste rock transportation is one of the most labor-intensive processes in mining, accounting for 30–50% of operating costs [3].

Given this, optimizing transport processes and transport-technological systems at mining and processing plants is a key national economic challenge. The effective operation of a transport fleet depends on various organizational and technical factors set out in regulatory documents. An analysis of the available information has shown that the company has implemented a planned preventive maintenance and repair system for rolling stock. The efficiency of transport process management and vehicle utilization depends not only on the proper implementation of regulatory measures but also on the overall planning system and methodology for evaluating fleet operations. The research issues of this problem are covered in scientific and technical literature in sufficient detail [1, 2, 4-7].

Studies conducted by various authors draw attention to a number of problems related to the operation of dump trucks in the mining industry. One of the key aspects is the need to optimize the operational system to reduce the cost of transporting raw materials and increase the overall efficiency of the enterprise [8]. The introduction of modern technologies and automated monitoring systems can also contribute to more efficient management of dump trucks [9]. However, these studies have not fully solved the problems of optimizing the production process or provided a comprehensive assessment of heavy-duty vehicle performance. The rational operation of a transport fleet is assessed based on predefined criteria and indicators. However, existing methodologies do not fully account for various influencing factors, such as improvements in accounting methods and planning criteria.

The issue of this study is related to the need to solve some problems related to the operation of mining dump trucks at the DMPP These problems are mainly related to the planning and organization of maintenance of dump trucks and the choice of a rational criterion for evaluating their effectiveness.

Treiman and Kopanskaya [10] note that ore production indicators depend on mining and geological conditions. Poor selection or organization of an enterprise's transport systems can increase ore production losses by up to 6%, highlighting the need for proper mining technology optimization and improved transport efficiency.

Allahkarami et al. [11] point to the heterogeneity of factors and separate the factors affecting the reliability of vehicles into observable and unobservable factors, and propose the introduction of a mixed effects model that would help in the selection and development of maintenance programs and spare parts planning.

Zhetesova et al. [12] believe that operating costs associated with maintenance and repairs on quarry dump trucks increase due to design differences between vehicles and variations in working conditions, such as transportation distance and average road slope.

Murzagaliyev et al. [8] found that optimization of the dump truck operation system directly affects the economic efficiency of the enterprise, since the cost of transporting raw materials accounts for a significant share of total costs. However, this study does not provide a structural analysis of the dump truck maintenance and repair system, which may lead to the omission of important aspects of ensuring the durability and reliability of equipment.

The work of Ibraev emphasizes that problems in the technical condition of dump trucks can significantly slow down the mining process, increasing downtime and the total cost of production [4].

According to a study by Shteivand and Zykova [5], the safety system when working with dump trucks should be highly efficient, taking into account the specifics of the mining industry and the risks associated with transporting large volumes of material. The study did not consider aspects of transportation process optimization, which may compromise the effectiveness of the safety system in rapidly changing operational conditions.

Akhmedov et al.'s research [9] highlights that implementing modern technologies and automated monitoring systems can significantly enhance dump truck management efficiency and mitigate human-related risks. Human factors and staff training issues have not been sufficiently studied, which could hinder the successful implementation of automated systems.

Kontrobaeva and Salykov's work [13] raises an important question on optimization potential, which could ultimately enhance competitiveness in the raw materials market. This study did not analyze the possibility of introducing innovative technologies, which may lead to a loss of competitiveness in the long term.

Current dump truck operation practices at mining and processing plants rely on regulatory documents, equipment supplier recommendations, and established planning system provisions [14-17]. The established methodology for organizing the maintenance and routine repair system of vehicle fleets is implemented at the enterprise in question.

A preliminary analysis of literature and empirical data on this issue reveals discrepancies between planned and actual fleet performance indicators, primarily due to the rigid regulation of planning technology and maintenance system organization under actual operational conditions.

In practice, maintenance systems employ different approaches to implementing maintenance practices. For example, an analysis of international practices in vehicle maintenance planning and organization identifies two main approaches. The first, Preventive Maintenance, involves systematic pre-planned measures to prevent failures. The second, Unscheduled Maintenance, follows a reactive approach, where vehicles with failed components or parts are sent to a maintenance post if minor repairs can restore functionality without requiring full-scale repairs [18-22].

Research analysis shows various approaches to selecting criteria for evaluating the effectiveness of the maintenance and repair system of dump trucks [23-30]. At the same time, the most common indicator for evaluating the effectiveness of a fleet is the technical readiness coefficient (CTR), which must be adapted to specific conditions. Under DMPP conditions, this indicator serves as a criterion for assessing fleet performance. According to the enterprise's regulatory and accounting documentation, this indicator is defined based on the time spent on technological operations relative to operating hours. The definition of this indicator depends on the time spent on carrying out technological operations in the time interval, that is, in motorcycle operating hours.

Researchers in the studies [23-30] suggest considering the transport cycle as a stochastic model, taking into account the variability of the transport process and its estimated characteristics. Furthermore, the proposed mathematical models should include an analysis of vehicle arrivals under different operational conditions. This approach enables the use of models in studying technical objects during operation, as well as structuring arrival indices under the given conditions. It also highlights the importance of considering the influence of the fleet's age composition and its development on evaluation criteria. Sichko et al. suggest assessing vehicle technical readiness by balancing maintenance costs and operational efficiency. This section addresses the calculation of weighted average indicators of the optimal fleet readiness level, which must be accounted for during the planning stage and in the analysis of the obtained data [29].

Verevkin et al. [24] correlate downtime to organizational factors such as waiting for spare parts and claim that this can reduce the CTR by up to 5%. Sichko et al. [29] note the potential benefits of accounting for failures preemptively. It suggests the possibility of increasing the CTR of the fleet through the introduction of a preventive maintenance strategy. In the opinion of the authors of this article, this proposal deserves separate consideration.

Thus, this study aims to identify methods for improving the technical operation of mining dump trucks based on the study of indicators for evaluating the effectiveness of maintenance and repair planning, using DMPP as a case study.

2. MATERIALS AND METHODS

The DMPP, situated in western Kazakhstan, was selected as the research site. Geographical features, development scale, and adopted mining technology allow for identifying the maintenance and current repair system of quarry dump trucks as the research focus. In this study, data collection followed a structured approach. Initial data for each technical unit, obtained from on-board telemetry systems and diagnostic sensors, is recorded by the operator and transmitted to the control room. There, the data is analyzed to evaluate failures and determine appropriate maintenance and repair actions, with all information stored in an electronic database.

The initial unstructured data is systematized and grouped by failure categories for key components and assemblies. A comprehensive statistical dataset has been collected on dump truck technical condition, performance, downtime, and fuel consumption. The data obtained are grouped by technological feature into groups: engine, body, transmission, chassis, electrical equipment. Based on the collected data, an analysis of the planned, operational, and actual CTR of the fleet was conducted over the study period.

This approach enabled the identification of operational patterns and trends in dump truck performance, as well as the key factors affecting efficiency and correlations between various parameters.

The collected statistical data was analyzed using mathematical statistics, probability theory, correlation, and regression analysis methods. The study assumes that mining dump truck failures during operation at a fixed point in time follow a Poisson process, corresponding to the simplest failure model [31, 32].

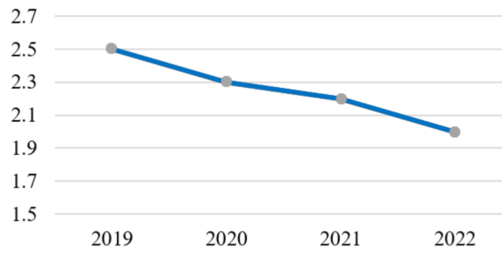

Figure 1. Changes in the frequency of vehicle downtime
Source: Inyiama and Oke [33]

The obtained data highlight the need to improve the methodology for recording and evaluating the existing maintenance and repair system at this enterprise. These measures have led to a reduction in repair time and downtime (Figure 1).

A maintenance cycle structure has been established for each vehicle model, defining the types and scope of maintenance work performed. Maintenance intervals for BELAZ-75309 vehicles are determined in accordance with the manufacturer's instructions, as shown in Table 1. Regular maintenance for these vehicles not only maintains their technical integrity but also ensures high reliability, safety, and economic efficiency during operation.

Table 1. Maintenance intervals for BELAZ-75309 vehicles

Maintenance 0	Maintenance 1	Maintenance 2	Maintenance 3	Seasonal Maintenance
100 engine hours	250 engine hours	500 engine hours	1000 engine hours	2 times a year

Source: RUPP "Belarusian Automobile Plant" [34]

Using the analytical method, a detailed study of the mining dump truck operational system was conducted, identifying the main stages of material processing as well as key components and technical nodes.

Using the functional method, key operational processes were identified, their impact on overall efficiency was assessed, and opportunities for optimizing each functional component were determined.

Through the synthesis of obtained data, comprehensive strategies and recommendations were developed to optimize the dump truck operational system at the mining and processing plant.

The integration of various scientific methods ensured a comprehensive approach to the study, enhancing research reliability and the applicability of results under real mining and processing conditions.

3. RESULTS

Currently, the mining industry plays a key role in supplying raw materials to various industries [35]. Within this critical sector, evaluating and optimizing the dump truck operation system are essential to ensuring production efficiency and sustainability. In this context, the DMPP serves as a focal point for analysis and evaluation.

Assessing bulk cargo transportation efficiency, considering road condition constraints, is a key aspect of logistics planning and vehicle operation. This need is justified by several factors. Assessing load capacity and cargo utilization factors is crucial for transportation cost-effectiveness. Maximizing vehicle cargo capacity optimizes routes, reduces trips, lowers costs, and boosts productivity. Taking into account road conditions in the assessment of transportation parameters makes it possible to comply with legislation and ensure traffic safety.

The DMPP dump truck operation system plays a central role in mineral mining and processing. Evaluating this system is a necessary step to detect issues, develop effective strategies, and maintain a balance between productivity, safety, and cost-effectiveness. One of the important aspects of the assessment is the analysis of the technical condition of dump trucks. Mining and processing plants regularly analyze failure types and frequency, including their causes and consequences. Regulations for spare parts control have been implemented, workflow mapping has been introduced to optimize labor resource use during repairs, and incentive measures have been established to reduce transport downtime.

This research enhances machine durability and reduces downtime (Figure 2), which is crucial for continuous mining operations. In this regard, the authors assessed planned and actual indicators to evaluate the adopted vehicle maintenance system in compliance with regulatory requirements. Figure 2 presents research data on the distribution of technical work types over the reporting year.

These data show the time allocated to scheduled maintenance and unplanned routine repairs required for troubleshooting key components and assemblies of heavy-duty vehicles: namely, downtime due to a malfunction of the chassis – 2070.78 hours, bodywork – 1977.22 hours, electrical equipment – 969.41 hours, internal combustion engine – 495 hours, transmission – 234.94 hours. Meanwhile, the time allocated to scheduled maintenance is 715.36 hours. Based on the obtained data, a Pareto chart was constructed to illustrate each system component's cumulative impact on total downtime. The obtained experimental data allow for quantifying failure distribution among key mining dump truck components in total downtime duration. According to the obtained data, there is a considerable disparity in downtime, with repair-related delays significantly exceeding the total time allocated to fleet maintenance and repairs. Routine maintenance accounts for 11.03% of total downtime, whereas troubleshooting-related delays constitute 89.97%. This highlights the need to implement measures to minimize downtime through improved maintenance and diagnostics.

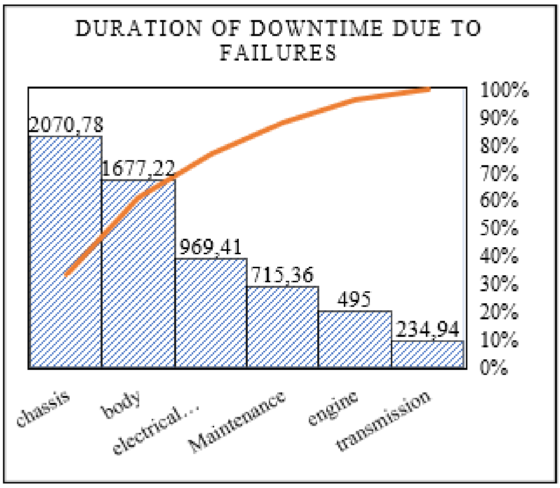

Figure 2. Duration of downtime due to failures

Another significant finding is the weak correlation between the number of failures in the presented groups and the time required for their resolution. In the system of maintenance and repair of heavy-duty vehicles adopted at this enterprise, there is a significant prevalence of technical impacts (routine repairs) on the components and assemblies of the chassis, bodywork and electrical equipment. This suggests the need for further analysis of this aspect when developing a methodology for heavy-duty dump truck fleet planning.

An analysis of the statistical technical condition of dump trucks revealed several key trends and the main causes of failures (Figure 3). The gradual wear of key components is a key factor impacting overall equipment performance, while the increasing frequency of failures in electronic control and monitoring systems is a growing concern, as it can cause malfunctions and reduce operational efficiency [36]. Problems with the wear of the braking mechanisms have also been identified, which poses a serious safety risk and requires immediate intervention. A certain emphasis was placed on the causes of failures related to insufficient regular maintenance and untimely replacement of worn parts. According to the presented data, Figure 3 shows the total number of failures in key dump truck components, based on a systematic analysis of component failure data, highlighting the need for a strict maintenance schedule to prevent major malfunctions and ensure equipment durability.

An analysis of the obtained data (Figure 3) led to an important practical conclusion regarding the substantial impact of unplanned maintenance compared to the regulated time allocated for fleet upkeep. As per DMPP's annual plan, the total number of maintenance operations is 67, accounting for 21.6% of all technical interventions. Considering the aforementioned data, the actual time and cost of maintenance and repair may deviate significantly from planned indicators due to varying troubleshooting complexity across different vehicle groups. Furthermore, a comparison of reported and actual enterprise data has shown that this results in discrepancies between planned and actual maintenance system performance indicators for the heavy-duty dump truck fleet.

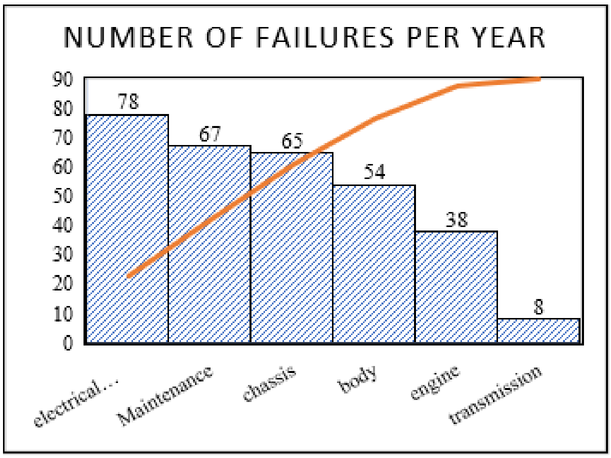

Figure 3. Number of planned and unplanned interventions to eliminate failures

This conclusion is confirmed by the data presented in the graph. According to Figures 1 and 2, downtime duration due to chassis, body, and electrical equipment failures exceeds the regulated limits by factors of 2.89, 2.34, and 1.35, respectively:

$$\frac{L_{ch}}{L_{mnt}} = \frac{2070.78}{715.36} = 0.89 \quad (1)$$

$$\frac{L_{body}}{L_{mnt}} = \frac{1677.22}{715.36} = 2.34 \quad (2)$$

$$\frac{L_{ee}}{L_{mnt}} = \frac{969.41}{715.36} = 1.35 \quad (3)$$

where,

L_{mnt} – labor intensity of troubleshooting work.

L_{ch} – labor intensity of work to eliminate chassis faults, people × hours.

L_{body} – labor intensity of work to eliminate malfunctions of the body, people × hours.

L_{ee} – labor intensity of troubleshooting workelectrical equipment, person × hours.

These data indicate the need for better organization and optimization of technological operations to enhance the productivity of scheduled maintenance and routine repairs. This fact is also confirmed by differences in the values of the planned and actual CTR. At the enterprise, this issue is mitigated through unplanned operational processes. This, in fact, indicates weak organization and planning within the entire maintenance and repair system.

One of the key problems of mining and processing plants is equipment downtime due to failures and malfunctions [37]. At the same time, the structured planning and organization system for maintenance and repairs aims to ensure transport reliability and efficiency. Therefore, to reduce repair time and costs while extending operational time and service intervals, it is necessary to develop a set of organizational and technical measures.

The CTR of the dump truck fleet is an important indicator, indicating equipment availability and operational efficiency (Figure 4). This indicator is influenced by multiple factors affecting dump truck condition and performance. Regular maintenance and timely repairs help sustain high efficiency and extend the service life of equipment.

A key metric of fleet operational efficiency is the CTR, defined as the ratio of operational time to the total time vehicles spend on shift [38, 39]:

$$k_{tr} = \frac{T_O}{T_T} \tag{4}$$

where,

T_O – operational time, calculated as total time minus downtime due to maintenance and repairs (hours).

T_T – total time, hours.

In this paper, the authors followed the following procedure for determining the CTR value.

Maintenance operating time was calculated by summing the shift duration of each transport unit (dump trucks), obtained from on-board computers and recorded in the database. With technological breaks (refueling, lunch, etc.) included, this totals 744 hours per month.

To maintain a high CTR, a monitoring and diagnostic system is essential, as it enables the rapid identification of malfunctions and the implementation of corrective actions.

The authors analyzed the monthly dynamics of the CTR for the fleet of this enterprise throughout the calendar year, based on transport shop reports, as shown in Figure 4. Additionally, the average CTR values for the business plan, operational plan, and actual performance were considered as key parameters.

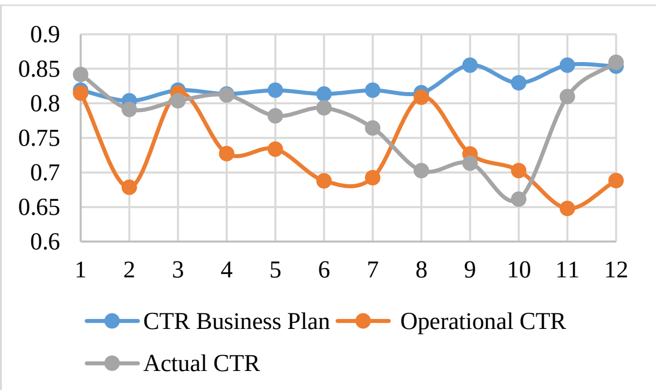

Figure 4. Dynamics of changes in the CTR of the dump truck fleet

The analysis of the obtained data reveals the following insights. The planned fleet CTR values remain stable within the range of 0.80–0.85. Meanwhile, the operational CTR values fluctuate between 0.65 and 0.85, exhibiting characteristic peaks at different times of the year. The actual fleet CTR values tend to decrease relative to the planned values, remaining within the range of 0.67–0.85.

The observed discrepancies in CTR values can be attributed to the specifics of the methodology for scheduling and performing maintenance interventions, where standard time intervals for defect elimination operations are strictly regulated, yet actual performance deviates significantly from the planned values. Efforts to mitigate these deviations at the enterprise necessitate periodic unplanned interventions to address failures.

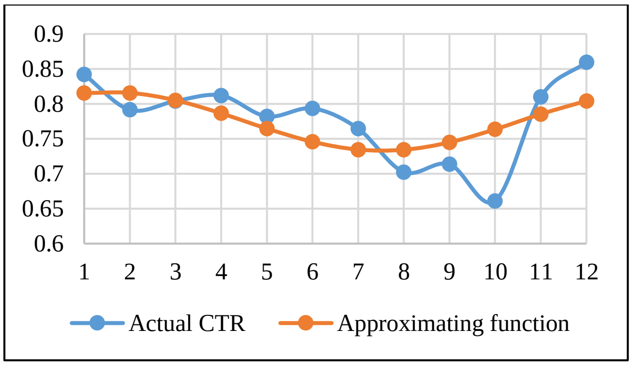

Figure 5. Actual CTR of the dump truck fleet of Don MPP

Such periodic adjustments to the work program undermine the stability of the transport equipment maintenance system. Another important consideration is that the fleet CTR value is calculated as the average across all transport units. In practice, individual transport units may remain idle for extended periods due to unforeseen organizational factors not accounted for in planning, since they are subject to strict supplier regulations. Therefore, it is necessary to review the methodology for maintaining transport equipment operability, which should comply with regulatory requirements while allowing technological process owners to adjust the required operations register.

For a deeper analysis of the data, a detailed examination of these dependencies was performed, establishing correlations between the studied parameters using classical probability theory and mathematical statistics. Regression equations approximating the functional relationships were derived, and their adequacy to the studied data was validated.

Figure 5 presents a graphical representation of actual CTR values for the dump truck fleet (row 1), along with the theoretical model (row 2).

As previously noted, the dynamics of actual CTR value changes over a calendar year exhibit periodicity, closely resembling cyclical processes that can be described using trigonometric functions.

The approximation was performed following the algorithm presented in the study [40], with the approximating function chosen in the following form:

$$y = A \cdot \cos(B \cdot x + C) + D \tag{5}$$

where,

A is the oscillation amplitude.

B is the indicator of the function period.

C is the phase shift (displacement along the horizontal axis).

D is the upward or downward displacement (average value of the function).

Parameter Selection

Period:

The function should have a period of $T=12$ months. Since the cosine function has a period of $2\pi/B$, we determine B as follows:

$$B = \frac{2 \cdot \pi}{12} = \frac{\pi}{6} \approx 0.5236 \quad (6)$$

Amplitude:

The amplitude A determines the spread of function values. Data analysis indicates that the maximum value is approximately 0.7452, while the minimum is about 0.6612. Thus, the amplitude is calculated as:

$$A = \frac{0.7452 - 0.6612}{2} \approx 0.042 \quad (7)$$

Average value:

The average value of the function can be estimated as the mean of all the data points:

$$D = \frac{0.842 + 0.7915 + ... + 0.8596}{12} \approx 0.775 \quad (8)$$

Phase shift:

Phase shift: The phase shift C is chosen to align the function's maxima and minima with the observed data, with C ≈ -0.799, ensuring proper positioning along the horizontal axis.

Final formula:

As a result of statistical processing, including correlation and regression analysis, the approximating function modeling the studied process was obtained as follows:

$$y = 0.042 \cdot \cos(0.5236 \cdot x - 0.799) + 0.775 \quad (9)$$

where,

y is the dependent variable, representing the actual CTR value.

x is the current argument value (in radians).

0.775 is the average CTR value over the studied period.

0.042 is the oscillation amplitude.

0.5236 is the oscillation frequency.

0.799 is the phase shift.

The main results of the regression analysis, based on n = 12 observations, include a correlation coefficient of R = 0.6718, a standard error of Δ = 0.0241, and an analysis of variance using the F-test ($F_{calc} = 8.22 > F_{table} = 6.7$) at a significance level of 0.05. These results demonstrate that the obtained relationship adequately describes the studied process and can be accepted as a model for characterizing the dynamics of CTR changes under production conditions.

An analysis of the model based on actual CTR data reveals the inherent instability of this indicator, which, in turn, disrupts the regularity of the transportation process. However, ensuring the stability of this parameter is essential in production conditions. In our view, the most effective solution is to optimize the organization of the entire operational system, particularly in terms of technical management, including the planning of maintenance and repairs.

A graphical representation of CTR dynamics for the dump truck fleet, based on the company's reporting data, is shown in Figure 6.

The approximating CTR function according to the business plan of the enterprise for the dump truck fleet is obtained in the form of a linear relationship:

$$y = 0.003936 \cdot x + 0.800771 \quad (10)$$

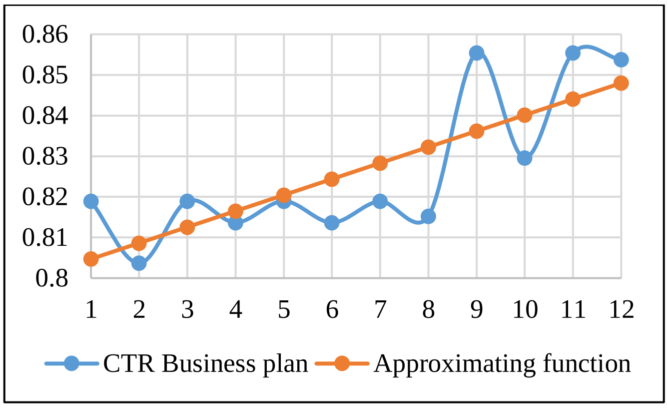

Figure 6. CTR business plan for DMPP dump truck fleet

With regression statistics and variance analysis indicators, including a correlation coefficient of R= 0.781501, a standard error of Δ = 0.0118, and an F-test result of $F = 15 > F_{table} = 3.88$, the approximating function sufficiently describes the planned CTR dynamics over the studied time period.

The data on the dynamics of CTR dependence for the dump truck fleet, presented in Figure 6, illustrate the irregular implementation of planned technical measures aimed at maintaining the fleet in working condition. This irregularity arises from the practical application of a planned preventive maintenance and repair system, which is primarily influenced by the varying regulated time intervals for different brands and types of transport equipment.

This factor should be taken into account when developing a methodology for organizing and planning maintenance and repair systems for a transport fleet under real production conditions. Consequently, to balance the workload of process equipment, it is essential to identify ways to distribute the workload more evenly across the transport workshop sections responsible for maintenance and repairs.

Within the operational framework of the transport workshop at Don MPP, an integral component of the planned utilization system for the material and technical base is the operational planning of individual technological processes. At specific stages of the production cycle, this approach allows for adjustments to the operational performance of the transport fleet. Based on this, the authors of this study conducted an analysis of transport workshop data on the dynamics of CTR changes for the dump truck fleet, the results of which are presented below in Figure 7.

The analysis of the presented dependence reveals significant variations in the operational CTR of the fleet. The approximating function for this dependence is given by the following expression:

$$y = 0.085 \cdot \cos(\frac{\pi}{6} \cdot x) + 0.7248 \quad (11)$$

Similar to the trigonometric function of the actual CTR Eq. (9), the components of this formula are defined as follows:

y is the dependent variable, representing the operational CTR.
x is the current value of the argument.
0.7248 is the average CTR value for the studied period.
0.085 is the amplitude of fluctuations.

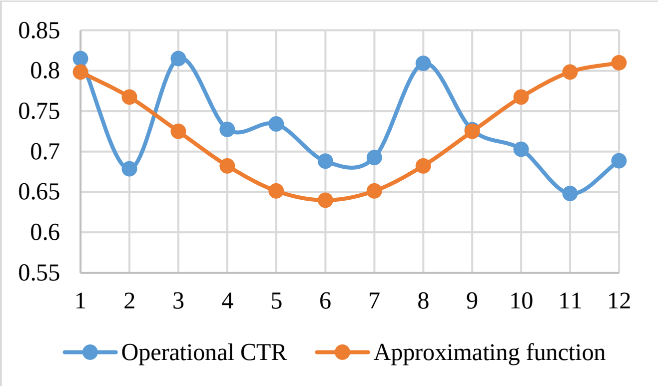

Figure 7. Operational CTR of the DMPP dump truck fleet

From a practical perspective, operational planning of maintenance and repair plays a crucial role in the overall system of fleet management, serving as a key tool for regulating unforeseen, i.e., unplanned, technical interventions. In this context, operational planning is intended to align the actual CTR value of the fleet with the targets specified in the business plan. These adjustments cannot be fully anticipated at the initial stage of developing the fleet's maintenance and repair system, as regulatory provisions do not include a dedicated methodology for organization and planning. This is primarily due to the fact that such regulations are based on strictly defined supplier actions and do not account for the possibility of preemptive preventive measures.

The analysis of CTR dependencies—actual, operational, and planned—approximated by Eqs. (9)-(11), respectively, demonstrates substantial deviations of actual and operational CTR values from the planned targets. These deviations should be considered when planning appropriate technical interventions for the company's transport fleet. This issue is directly linked to optimizing the methodology for planning the maintenance and repair system and selecting a rational criterion for evaluating its effectiveness. Evidently, the evaluation criterion should be formulated as an analytical model of the objective function, incorporating the influence of the most significant indicators or parameters affecting the efficiency of transport operations.

With regard to the performance of vehicles, the analytical model can take into account factors such as load capacity, driving speed, loading and unloading time, and route efficiency. The productivity equation may include time and fuel costs, as well as the efficiency of using a cargo unit depending on transportation conditions. Such models can be represented as a system of equations describing the interrelationships between various parameters and their impact on the overall fleet performance [35, 41].

In cargo transportation cost modeling, analytical equations can take into account factors such as fuel costs, vehicle wear and tear, and maintenance expenses. The cost equation may include parameters reflecting the efficiency of load capacity and cargo space utilization. These dependencies can be modeled using a system of equations, where the coefficients and exponents of the variables express their impact on total transportation costs.

According to the results of the study, it is necessary to consider the cyclical nature of maintenance processes at the initial planning stage, the excessive role of operational planning, and the discrepancy between the share of repair work and the expected levels defined by regulatory standards for technical interventions on the object of work. These factors are among the key elements affecting the efficiency of transport equipment operation.

Analytical models characterizing the dynamics of CTR changes depending on the work schedule provide a clear understanding of the complexity of practical modeling under the existing methodology for planning and organizing maintenance and repair in production conditions. They also indicate the need for improving optimization strategies for this system.

As for the mathematical method, to solve this problem, the hierarchy analysis method can be used, allowing consideration of the hierarchical structure of criteria and subcriteria. Additionally, the weighted summed estimates method accounts for weighting coefficients for each criterion, depending on their significance in a specific environment. These multi-criteria analysis methods provide mathematical tools for objectively assessing the impact of various factors and making informed decisions under diverse external conditions.

Comprehensive measures are proposed to optimize the operational system of mining dump trucks at DMPP. First and foremost, it is recommended to upgrade the fleet by introducing more powerful and modern dump truck models, as well as by implementing innovative technologies, including automated monitoring and control systems. Optimizing maintenance processes is another key aspect. Developing flexible maintenance schedules and implementing fault prevention systems will help ensure the timely detection and elimination of issues.

A performance management system is also becoming increasingly important. Establishing key performance indicators (KPIs) and utilizing monitoring data will facilitate the identification and resolution of bottlenecks in operations. Additionally, a cost management system, which includes regular analysis of transport operating costs and the development of a maintenance budget, will help reduce overall expenditures. Coordination with suppliers and service centers, along with ensuring compliance with regulations and standards, will contribute to the efficient operation of vehicles.

Implementing these optimization measures will not only enhance the efficiency of the mining dump truck operation system but also improve safety and adaptability to changing operational conditions.

The next step is to develop a mathematical model that determines the weighting coefficients for each criterion, reflecting their relative importance in a multi-criteria assessment. The methodology for evaluating the efficiency of heavy-duty dump trucks during transportation, which considers individual performance indicators, follows a systematic approach for a more detailed and accurate assessment of key operational aspects.

At the first stage, the primary criteria affecting transportation efficiency are identified, including load capacity, cargo volume, fuel consumption, and road surface wear. These main criteria are then broken down into subcriteria, enabling a more detailed analysis.

An essential part of the methodology is the assignment of weighting coefficients, where each criterion and subcriterion is assigned a weight based on its significance. The next stage involves defining measurement methods, where specifications and criteria for each indicator are established. This includes selecting data collection methods, such as using sensors to measure fuel consumption or conducting visual inspections to assess road surface wear.

The final stage involves documenting the methodology, providing a detailed description of each criterion, subcriterion, weighting coefficient, and measurement method. This ensures transparency, reliability, and repeatability in the evaluation process. This approach enables the development of a systematic tool for a comprehensive assessment of heavy-duty dump truck efficiency, taking into account individual performance indicators and ensuring a more precise analysis and effective management of transport processes.

4. DISCUSSION

One of the key aspects of this study is accounting for the specific conditions of the DMPP. Regional factors such as the geological characteristics of deposits, climatic conditions, and local economic factors can significantly impact the efficiency of dump truck operations.

Assessing the technical condition of vehicles is crucial to ensuring their reliable operation. This approach helps prevent potential failures and optimize maintenance processes.

An important outcome of the study is the identification of factors affecting the reliability of vehicle operation in the mining industry. An analysis of several studies on this issue has established that ensuring the reliable operation of the transport fleet depends on a combination of various factors identified in previous research.

Gryaznov and Antropova [42] suggest taking into account the balance of interests in fleet maintenance and establishing contractual relationships between specialized service companies and individual enterprises. They also indicate that the optimal CTR for assessing the profitability of the maintenance and repair system is 0.75–0.85. However, according to the results of this study, the CTR value ranges between 0.66–0.85. Moreover, the actual CTR follows different dependency patterns, highlighting the need to refine the methodology for estimating these values. Significant fluctuations in CTR further lead to non-compliance with planned maintenance and repair schedules.

Zinovieva and Smirnova [43] propose a methodology for calculating the reliability of mining equipment based on CTR. In their view, the introduction of predictive maintenance can increase fleet CTR by 12%, while the installation of diagnostic sensors for components and mechanisms, in addition to the existing monitoring system, can reduce failures by 15%. The findings of this study align with these conclusions, emphasizing the necessity of incorporating additional corrective measures into the existing methodology for planning maintenance and repair activities. Such adjustments should be based on thorough analysis and statistical data to account for the most probable failures. These measures can enhance the efficiency of the maintenance and repair system by reducing the share of unplanned technical interventions.

Ergashev et al. [44] argue that failure prevention is achieved solely through technological operations, as maintenance planning is not feasible due to the probabilistic nature of failures. However, in practice, such an approach is not sufficiently effective, as a linear relationship between the condition of transport equipment and service life exists only for corrosion and fatigue wear. Furthermore, excessive disassembly of mechanisms during repairs shortens the interval until the next repair by 15–30%. These findings are consistent with this study, which indicates that the downtime of major dump truck components at DMPP significantly exceeds the standard repair time. This fact underscores the necessity of adapting the manufacturer's regulated standards to real production conditions. Such an adaptation would help reduce the frequency of operational technical interventions required to maintain fleet operability.

Minimizing the share of operational technical interventions remains a key area for further research.

Researchers Allahkarami et al. [11] noted that it is impossible to account for all unobservable factors in reliability assessments, which ultimately leads to bias in reliability estimates. According to the authors of this study, one such factor is the limitation in predicting planned maintenance and servicing of the dump truck fleet. This limitation arises from strict adherence to supplier regulations without considering real operational conditions and the presence of unobservable factors.

This issue highlights the necessity of a more detailed analysis of comprehensive performance assessment indicators, particularly by balancing an object's time in various operational states [45]. This conclusion aligns with the findings of this study, which indicate that although the planning and organization of maintenance and repair systems for dump trucks comply with regulated requirements and standards, discrepancies exist between planned and actual performance data (e.g., CTR). In response, under real production conditions, the company implements operational measures to maintain its fleet in working condition.

A comparison between standard maintenance and repair time and actual execution time reveals that the use of modern forecasting techniques based on probabilistic methods can significantly improve the accuracy and efficiency of maintenance [14, 15, 46, 47]. These methods play a crucial role in enhancing maintenance strategies. The mathematical models describing CTR variations in the DMPP fleet of heavy-duty dump trucks, developed in this study, build upon previous models. They complement existing research and further reinforce the need for an innovative approach to fleet operation, covering organization, planning, control, and maintenance method adjustments.

Overall, evaluating the mining dump truck operation system at DMPP is a crucial step toward ensuring the sustainability and efficiency of mining operations in this region. The findings of this study provide a basis for implementing improvements and developing management strategies aimed at achieving optimal performance in the modern mining industry.

The analysis conducted by the authors highlights the necessity of considering the uneven distribution of component and assembly failures when planning and organizing maintenance efforts to ensure fleet operability.

Leonida's study found that 10 hours of downtime for mining transport equipment corresponds to a 2–5% decrease in productivity [48]. Based on this finding, the volume of unplanned downtime for heavy-duty dump trucks due to failures at DMPP can lead to significant reductions in labor efficiency and overall productivity. Consequently, the conclusions of this study emphasize the importance of minimizing unplanned downtime, making it a critical issue for further research.

Researcher Park determined that the development of applications for recording ore mining data and compiling daily dump truck operation reports is a crucial step in the digitalization and optimization of mining processes. These applications can significantly enhance the efficiency of mining transport management by providing accurate and real-time data. They allow for continuous tracking of ore production volumes, dump truck performance, and fuel consumption, enabling operational feedback that is essential for real-time decision-making and production process planning.

The daily reports generated by these applications contribute to transparent and systematic documentation, simplifying internal accounting while also providing data for performance analysis, trend identification, and potential optimization areas [49].

As noted by Alamdari et al. [50], machine learning methods for predicting the fuel consumption of mining dump trucks represent an innovative approach that optimizes operating costs and enhances efficiency in mining operations. Machine learning enables the creation of models specifically adapted to the unique characteristics of each dump truck, considering its technical condition and operational features. This approach allows for more precise and individualized forecasts, ultimately contributing to reduced fuel consumption and optimized transportation budgets.

A study by Botyan et al. [51] highlights that during the operation of mining dump trucks, the highest proportion of sudden failures occurs in specific groups of components (e.g., suspension elements). This issue poses a challenge for both suppliers and the MPP operations service, as it often necessitates unplanned and costly emergency interventions, affecting the timing and quality of maintenance and repair planning. To address this issue, the authors propose refining the methodology for determining the optimal inter-repair period.

Carman and Zainuri [52] recommend developing maintenance schedules for mining dump trucks that consider component and assembly operating times, thereby minimizing operating costs. Their studies, along with the research of Ishkov et al. [53], emphasize the need to adjust maintenance and repair schedules for quarry dump trucks based on their actual operating conditions.

The study by Pryalukhin et al. [54] suggests transitioning from scheduled repairs to a system based on actual equipment lifespan. They also propose a mathematical model for calculating the reliability of electrical components integrated into dump truck monitoring systems to optimize maintenance schedules and develop more flexible service plans for their components.

According to the authors of this study, the regulatory standards set by mining dump truck suppliers act as a constraint on the development of a flexible preventive maintenance and repair system. In the methodology section of this work, the authors describe the participation of the dispatch service in collecting and compiling statistical data on failures and malfunctions, forming an electronic database of initial information.

In this regard, future research proposes the full automation of mining dump truck operations and the reduction of failure rates, as a means to centralize the maintenance and monitoring process [55].

One of the key challenges affecting the technical condition of the fleet is the enterprise's dependence on the availability of original spare parts. In this regard, standard technical and economic regulations and the contractual system with manufacturers create difficulties in quickly addressing malfunctions and failures.

In the study by Baikin et al. [56], it is proposed to address this issue using elements of reliability theory, specifically by determining the expected operating time until failure. This approach would allow for a more accurate estimation of the probability of component and assembly failures and enable the incorporation of this data into the planning of regulatory enterprise documents. Naturally, this would require enhancing the methodology for maintenance and transportation planning, which will be the focus of future research.

Potential errors in failure and downtime records may influence the accuracy of calculated indicators. The use of data from the enterprise's operational service could introduce errors in the studied indicators due to the limited size of the dataset. However, in this study, the authors relied on statistical materials from the enterprise's planning and economic department, mitigating this issue.

Another potential limitation concerns the consideration of current regulations governing maintenance and repair procedures for dump trucks. The authors suggest that this constraint can be addressed in the future by improving the planning system for maintenance and repair.

This research is based on materials from DMPP in Khromtau, the leading enterprise in the mining sector of the Republic of Kazakhstan. The production processes and technologies implemented at DMPP are among the most representative for other mining and processing plants.

In the DMPP context, where resource supply is of strategic importance, evaluating the dump truck operation system is a critical step toward enhancing the competitiveness and sustainability of production. The implementation of this research's findings could serve as a key element in the company's strategic management, ensuring its preparedness to address the challenges of the modern mining industry.

5. CONCLUSIONS

This paper presents an assessment of the standard system used to ensure the operability of mining dump trucks at a mining and processing plant. The study highlights that transportation operations at the plant play a critical role in the production process and have a significant impact on the overall functioning of the enterprise's production cycle.

Mining and processing enterprises have adopted a planned preventive maintenance and repair system for their transport fleets. However, an analysis of scientific and technical sources as well as practical production experience reveals discrepancies between planned and actual fleet performance indicators. This finding underscores the need to explore new approaches for increasing maintenance efficiency.

Using a specific example, this paper demonstrates that unscheduled operational interventions account for 89.97% of the total time spent on maintenance and repair operations for vehicle systems and components.

To model the dynamics of changes in the CTR of the fleet over the study period, approximating functions have been proposed (Eqs. (9)-(11)). An analysis of the CTR models for actual, operational, and planned values shows significant deviations in actual and operational CTRs compared to planned indicators. These fluctuations should be taken into account when planning maintenance operations.

It has been established that operational planning is used to stabilize actual CTR values, aligning them with business plan targets at the planning level. When developing an annual maintenance and repair plan, it is recommended to adjust technological operation schedules based on historical failure data, predicting the most likely component failures over time.

The findings emphasize the need for an improved methodological approach to maintenance planning and organization. This requires the development of an analytical model for the target function, which takes into account the most significant factors influencing the planned and predictive maintenance system.

The paper also reviews alternative approaches to planning and organizing maintenance and repair for mining dump trucks, as well as methods for improving performance evaluation criteria. However, these approaches differ in methodological focus and provide only a partial perspective on the problem. Therefore, this study is unique in that it specifically addresses enhancing fleet operability, taking into account the risks associated with component and system failures identified in the research.

At the same time, the findings can be integrated with other studies, potentially leading to a higher overall efficiency in transport operations.

Thus, the study confirms that optimizing the mining dump truck operation system at DMPP is a promising step toward enhancing productivity and ensuring the sustainability of mining operations.

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