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RESEARCH

Methods and applications of digital monitoring for mine haul road assessment

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Abstract Transportation of rock mass is the main cost factor in open-pit mining, covering both the maintenance of mine haul roads and the operation of dump trucks. The high importance of optimizing the operation of mine transport is confirmed by the leading share of its costs in the total cost of mineral extraction. A relevant area of optimization is the development and implementation of digital technologies for processing data on the state of mine haul roads. The solution to these issues should be based on the results of research and development work on collecting and processing information on the operational and technical condition of dump trucks and mine roads. This study simultaneously tests three different modern digital monitoring methods, such as: unmanned aerial vehicle (UAV); vital information management system (VIMS) and GNSS-based data acquisition system (Racelogic VBOX), which allow experimental measurements of mine dump truck operating parameters both within the framework of special single experiments and in term of long-term monitoring measurements. The article presents data from experimental measurements to establish the condition of two sections of mine haul roads at the Vostochny open pit mine, Ekibastuz coal deposit. The study assessed the impact of mine road defects on the operating parameters of 130-ton dump trucks of the CAT 785 from Caterpillar, including recording the range of loads on the metal structures of dump trucks during their movement from road defects that exceed the regulated values of the manufacturers. Recommendations are presented to improve the efficiency of operation of mine haul roads.

Keywords Mine haul roads · Digital monitoring · Experimental measurements · Testing · Technical condition assessment

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1 Analysis of publications

Currently, scientists and researchers are trying to find the best combination of several methods of digital monitoring of the state of mine haul roads, which can use the advantages of different methods. The development of mine motor transport is associated with an intensive growth in the unit capacity and cost of machines, their dimensions and weight, which dictates the need to determine the optimal parameters of its operation. Since it is impossible to evaluate the efficiency of motor transport without considering its dependence on such indicators as the durability of

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metal structures of dump trucks, fuel consumption, tire life, volumes of current and major repairs of the road surface and others, then taking into account these circumstances, an analysis of the results of previous studies was performed, on which the proposed work is based.

In previous studies, the authors argue that improving the condition of mine roads can have a positive impact on mine transport operations, such as increased productivity, safety, increased tire life, and reduced truck maintenance and road repair costs. For these reasons, digital monitoring programs are required to ensure the operational efficiency of mine haul roads.

A number of scientists and engineers from many countries have studied the problems of increasing the efficiency of heavy-duty trucks on mine roads. Thus, the work (Silva et al. 2024; Soufastai and Fouladgar 2022; Shroubek et al. 2021) examines the features of the influence of mine road unevenness on the operation of mine transport in the mining industry. This study used modern laser profiling to determine the condition of mine roads in two large Brazilian mines. It was found that an increase in the unevenness of the road surface can lead to a significant decrease in the average speed, a noticeable increase in travel time, a decrease in productivity and, accordingly, an increase in transportation costs. One of the main disadvantages of this monitoring method is the high initial cost of purchasing laser scanning equipment and software. This requires significant investment, especially for small mining enterprises.

Currently, researchers are using many advanced measurement systems and methods to detect roughness in mine roads. For example, work (Wen 2008; Hettiarachchi et al. 2023; Zhou et al. 2020) proposes the detection of road roughness using IMU (inertial measurement unit) data, based on the idea that road roughness generates roughness signals from sensors, the location and magnitude of the road roughness. The use of IMU continues to be a popular and growing area in road diagnostics and autonomous truck systems, but the information may be outdated, especially in the context of rapidly evolving signal processing and sensor systems.

The study (Douglas 2019; Sun and Nguyen 2023; Wang et al. 2020) proposes a relatively new innovative way to assess road roughness by recording the vibration of dump trucks caused by poor mine road conditions, which create many negative consequences for mining enterprises. The results of this study show that localized vibration levels can be used to objectively identify rough roads, making the method applicable to real-world operating conditions. Recording truck telemetry data is mainly used for fleet dispatching, collision avoidance, and geological survey, but as the authors note, telemetry data has not yet found wide application in mine road maintenance dispatching. Vibration data can be distorted due to differences in truck loading, technical condition, or driving speed. The researchers suggest continuing full-scale testing using fleet data over a longer period.

Many mine transport systems with long stretches of in-mine roads cannot record the condition of the entire road network frequently enough to adequately determine road conditions to make informed decisions on preventive maintenance. To address this issue, research has been conducted to develop low-cost technologies based on smartphones installed inside trucks to measure road conditions.

The authors of the study (Dimitrios 2024) note that machine learning algorithms, when properly trained, were able to reliably estimate road roughness on an integer rating scale at a level of detail suitable for strategic road asset management, provided that the truck type, speed, and smartphone type are considered. The use of a smartphone makes the method cheap and easily scalable, without the need for specialized equipment, and can be used by road services as part of crowdsourcing from drivers of mine dump trucks. However, compared to professional devices, smartphone accelerometers can be less sensitive and susceptible to noise, and the high variability of smartphone models, their location in the dump truck, and driving style complicate the standardization of the recorded data due to differences in hardware and software between smartphones. When processing the obtained data, there is a need to develop filtering, normalization, and synchronization algorithms, which increases the complexity of the analysis.

The unevenness of mine roads is a key factor influencing the occurrence of dynamic loads on the metal structures of dump trucks. To regulate the speed parameters of dump trucks in accordance with the unevenness of the road, methods for measuring unevenness in real time are becoming new relevant areas of research. Thus, the article (Grabowski et al. 2024; Fakhri et al. 2021) presents indicators and standards for assessing the unevenness of the road, both by direct measurement and by indirect identification. Among them, methods of indirect identification of road unevenness are distinguished, which are classified into recognition based on a laser sensor, recognition based on a vibration model and recognition based on a neural network.

The article focuses on the specifics of the mining industry, where the quality of mine roads is critical for efficiency and safety. The authors note that the laser profiler is expensive and easily affected by natural factors such as dust on the roads and is not suitable for long-term use. In addition to the laser method of recognizing road surface irregularities, it is also possible to install a vibration sensor to obtain the displacements and accelerations of the dump truck. The excitation of the truck, in turn, determines the road roughness. However, this method requires more sensors, is less accurate in real time than the laser identification method. The neural network-based method has a lower cost and higher accuracy in identifying road surface defects and road slope ranges. In the future, the recognition method based on deep learning and reinforcement learning will also become a priority research area.

Monitoring programs are required to assess the condition of mine roads and make informed decisions to improve productivity, safety, extend tire life, and reduce maintenance costs. Currently, new technologies using unmanned aerial vehicle (UAV) are becoming increasingly popular for data collection and decision making in the mining industry (Idrefors et al. 2021; Navarro Torres and Paniz 2022). The results of these studies show that aerial photographs and digital elevation models can be used to assess the smoothness condition of mine roads and verify the adequacy of the road structure. Aerial photography can detect surface water, rock spills, and potholes on the road, which can be quickly repaired and eliminated by a dedicated road maintenance team, which is of practical importance to improve the safety and efficiency of transportation operations (Silva Menezes and Navarro Torres 2021; Medinac, et al. 2020).

The use of UAV methods allows recording data with high accuracy and minimal time costs, which is a significant advantage compared to traditional methods (Dang and Nguyen 2023; Li et al. 2024). The use of new technologies in the mining industry demonstrates the potential of innovations to improve monitoring and assessment of the condition of mine haul roads. The authors note that despite all the advantages, the use of UAV for monitoring can be difficult in bad weather conditions or complex terrain of mine roads, which limits its use in various climatic and environmental conditions (Beretta et al. 2019; Dastgheibifard and Asnafi 2018; Nawaz et al. 2019). In addition, their implementation requires significant investments in equipment and personnel training, which may be impractical for small or start-up mining enterprises. The authors provide examples of data processing, visualization, and assessment of road conditions, which makes the research useful for practitioners, but the articles do not fully provide recommendations on the long-term effectiveness and reliability of UAV use, which requires additional research to confirm the long-term stability of such technology (Ghek and Choi 2020; Shahmoradi et al. 2020; Xiang et al. 2018).

An analysis of the works mentioned above in this review shows that the issues related to the study and justification of effective methods for monitoring and assessing the condition of mine haul roads in quarries have been studied quite extensively to date, and an insignificant number of works are devoted to the issues of optimizing individual road parameters. At the same time, it should be noted that the results of the studies performed are largely based on short-term or private data, which may limit the possibility of analyzing the long-term effects of using the proposed monitoring methods. Alternative methods or existing solutions have not been fully considered, which limits the understanding of how much new monitoring methods are superior to existing approaches (Veretta et al. 2018; Nguyen 2021; Singhal et al. 2018).

Based on the results of the analysis of the studies performed, it can be concluded that despite significant progress in solving the problem of improving the methods and means for establishing the condition of permanent mine haul roads, there are still many unresolved issues related to in-depth monitoring of the condition of mine roads with motor transport, the routes of which are not permanent during open-pit mining. Therefore, there remains a need for timely detection of road defect parameters, a more in-depth analysis of the parameters considering their integral negative impact on the durability and efficiency of dump trucks, tire mileage, traffic safety, as well as reducing dynamic loads on trucks. In this regard, one of the effective solutions to the problem of improving mine haul roads is further research aimed at. development and implementation of an integrated monitoring system for haul roads in coal deposits. This will improve the safety of transport operations, reduce operating costs and extend the service life of mining truck.

2 Introduction

The Ekibastuz coal deposit is one of the largest coal basins in the Republic of Kazakhstan and is of strategic importance for the country's energy sector. The development of the deposit provides a significant share of coal products used in Kazakhstan's thermal power industry. Coal mining in this region is carried out by an open-pit method, which requires efficient management of mine roads to increase productivity and reduce operating costs.

This study examines the experience of monitoring haul roads in the Bogatyr and Vostochny opencast mines of the Ekibastuz coal deposit. The quality of mine roads directly affects the safety, cost-effectiveness and durability of mine equipment. The research uses advanced monitoring technologies, including lidar scanning, unmanned aerial vehicle (UAV), GPS monitoring systems, VIMS System and Racelogic VBOX.

The objective of this study is to improve the efficiency of opencast coal mine transport systems by developing and implementing a comprehensive monitoring system for in-pit haul roads in the Ekibastuz deposit. This will improve the safety of transport operations, reduce operating costs and extend the service life of mining truck. To achieve this goal, the task of developing a comprehensive monitoring system for in-pit haul roads in the Ekibastuz deposit is solved, ensuring timely receipt of complete, objective and reliable information on the transport and operational condition of mine roads. The assessment of the technical condition of in-pit haul roads for their compliance with the regulatory requirements of technical regulation documents in the field of coal deposit transport systems is studied.

3 Methods

The research methodology is based on a systematic literature review combined with field experiments and the analysis of digital monitoring data, aimed at developing an integrated decision-support framework for assessing the condition of open-pit haul roads and improving the operational efficiency of haul trucks.

The study focuses on the development of a multi-agent hybrid digital monitoring system, in which individual agents representing structural loads acting on the metal components of haul trucks, tire wear characteristics, and parameters of haul road defects dynamically influence decision-making processes related to rock mass transportation in open-pit mining operations.

The proposed methodological framework integrates several complementary components: digital monitoring of the geometric characteristics and defects of haul roads; real-time analysis of vehicle dynamics together with measurements of structural loads acting on haul trucks; and a mathematical model of dump-truck motion used to optimize vehicle speed while considering mine conditions and operational transport constraints.

The integration of these components enables a comprehensive assessment of the technical, economic, and environmental performance indicators of rock mass transportation systems in open-pit mining operations.

Field experiments were conducted at the Vostochny coal mine. Two sections of in-pit haul roads characterized by the highest traffic intensity during the observation period were selected for experimental investigation.

Route No. 1: transportation of overburden from mining face No. 4626 to waste dump No. 2, with a total route length of 3.05 km.

Route No. 2: transportation of overburden from mining face No. 4627 to the crushing unit DU-2, with a total route length of 3.0 km.

On both routes, loaded haul trucks travelled downhill, while empty trucks moved uphill. During the experimental campaign, three complete trips were recorded for each route, allowing the collection of representative datasets on vehicle dynamics, structural loads, and haul road conditions.

The objective of the present study was to test and validate an integrated digital approach for monitoring the condition of open-pit haul roads rather than to obtain exhaustive statistical data covering all operating regimes.

Each trip was accompanied by high-frequency data acquisition, including vehicle speed, acceleration, pressure in the suspension hydraulic cylinders, and loads acting on the truck metal structures. This ensured the formation of representative time-series datasets. Consequently, the actual volume of experimental data significantly exceeds the number of trips themselves.

An increase in the number of trips is planned for the next stage of the research in order to expand the statistical database and to support the training of machine-learning models.

The schematic layout of the selected haul road sections is presented in Figs. 1(a, b).

The route (Fig. 1. a) is characterized by the following parameters: total length – 3050 m; elevation difference from mining face No. 4626 to temporary waste dump No. 2 – 116 m; number of bends or defect zones – 9 sections; road gradient up to 10% (including gradients of less than 8% – 500 m, 8–9% – 1300 m, 9–10% – 960 m, and more than 10% – 290 m). The total number of irregularities with amplitudes ranging from 5 to 15 cm was 7 defects, including 3 elevations and 4 depressions. Road narrowing is observed along approximately 90% of the route. In addition, the absence of road widening at curves and turns was identified at 5 sections.

The route (Fig. 1. b) is characterized by the following parameters: total length – 3000 m; elevation difference from mining face No. 4627 to temporary waste dump No. 2 – 102 m; number of bends or defect zones – 10 sections; road gradient up to –15%. The total number of surface irregularities with amplitudes ranging from 5 to 15 cm was 7 defects, including 3 elevations and 4 depressions. Road narrowing is observed along approximately 95% of the route. In addition, the absence of road widening at curves and turns was identified at 4 sections.

To identify the influence of haul road defect parameters on the techno-economic performance indicators of rock mass transportation processes in open-pit mining operations, three complementary digital monitoring methods were simultaneously applied.

1. LiDAR surveying using an unmanned aerial vehicle (UAV) was employed to obtain high-resolution three-dimensional models of the surfaces of in-pit technological haul roads. This method enables the detection and quantitative assessment of various road defects, including potholes, rutting, subsidence zones, surface irregularities, erosion, water accumulation areas, and washouts. Data processing was performed using specialized software (Trimble Business Center) to reconstruct detailed terrain models of the haul road surface.

2. The Racelogic VBOX GNSS-based data acquisition system was used to record the kinematic parameters of haul trucks in real time, including vehicle speed, acceleration and deceleration, travelled distance, trip duration, road gradient, curve radii, and vehicle speeds while passing through curves and bends. These data were used to generate slope and speed maps in order to identify potentially hazardous sections of the haul road.

3. The Caterpillar VIMS system installed on the haul truck provided continuous measurements of vehicle dynamics, load distribution on the haul truck's metal structures, and variations in suspension strut pressure.

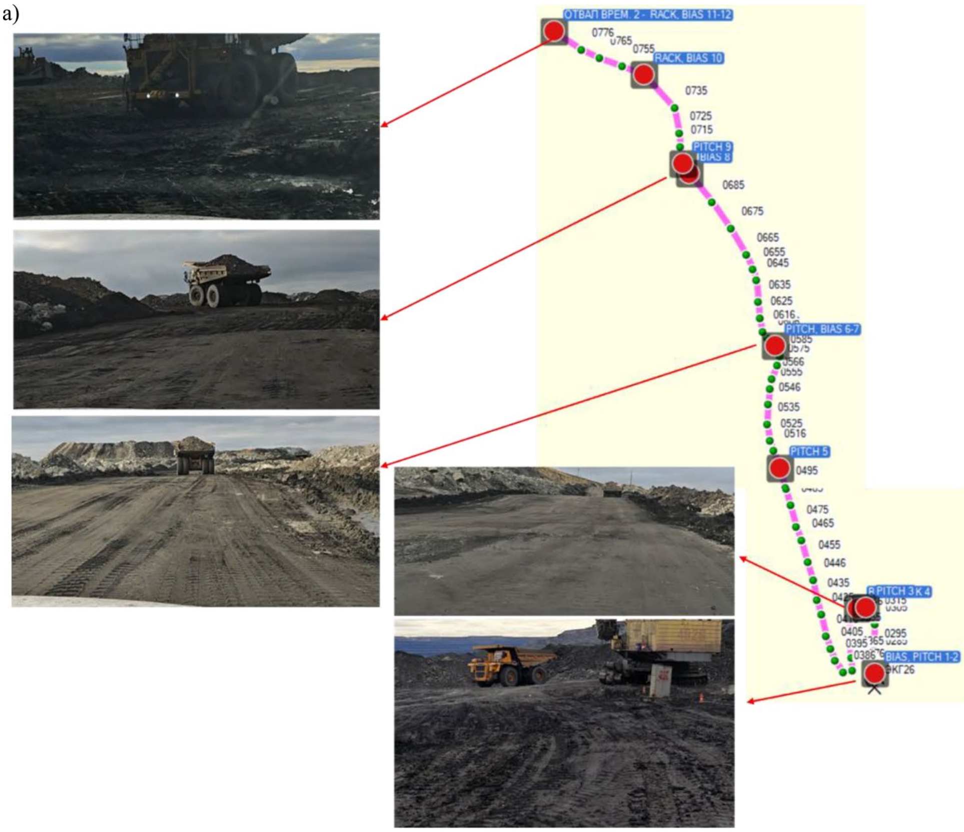
During the experimental runs, the following kinematic parameters were continuously recorded along the entire transportation route: longitudinal acceleration and deceleration, lateral acceleration during cornering, haul-truck speed, and travelled distance. These measurements were obtained using the Racelogic VBOX.

The analysis was primarily focused on road sections characterized by pronounced surface irregularities, such as waviness, potholes, and transition zones between straight segments and curves. These sections were identified based on digital road models obtained using UAV surveys and were subsequently correlated with peaks in acceleration signals and suspension strut pressure measurements VIMS.

This approach enabled the authors to establish relationships between specific geometric defects of the road surface and increased dynamic loads acting on the suspension system of the haul truck.

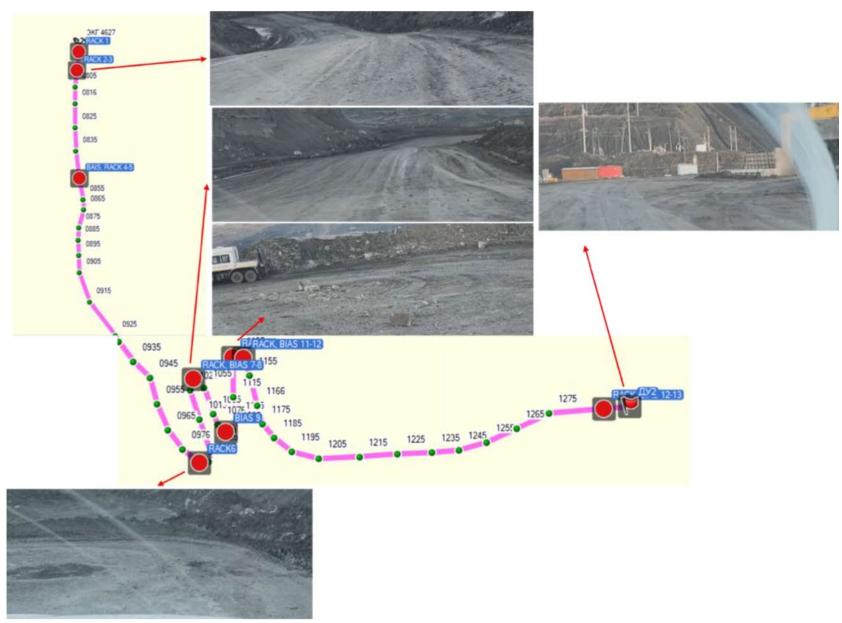
The object of the study was a CAT 785 mining haul truck with a payload capacity of 136 t, operating on the selected road sections between mining faces No. 4626 and No. 4627 and the corresponding unloading and crushing facilities. The haul truck was equipped with onboard VIMS and Racelogic VBOX.

a)



Route 1 – Road 201

b)



Route 2 – Road 210

◂**Fig. 1** Layout of the selected haul road sections for overburden transportation: Route 1 – from mining face No. 4626 to temporary waste dump No. 2; Route 2 – from mining face No. 4627 to the crushing unit DU-2

Experimental data processing included regression analysis to establish relationships between structural loads acting on the metal structures of the haul truck and the geometric characteristics of haul road defects. Regression models were developed to describe the dependence of load amplitude on the height of the defect and the parameters of haul road irregularities.

In particular, the analytical relationship describing the loads acting on the metal structures of a moving haul truck (1) as a function of variations in haul road irregularities under 100% payload loading can be expressed as follows:

$$Y = b_0 X b_1 \text{.......kPa}, \tag{1}$$

where.

b_0 and b_1 are regression coefficients;

X is the main parameter characterizing the haul road defect, mm.

The values of the coefficients b_0 and b_1 for different types of haul road defects were determined on the basis of experimental data obtained at the coal deposit during the survey and characterization of haul roads along **Routes 1 and 2**.

Based on data on haul road geometry, haul-truck motion dynamics, and structural loads acting on the metal structures of haul trucks caused by haul road defects, a mathematical model of the longitudinal motion of the haul truck was developed to support decision-making for optimizing vehicle speeds and accelerations.

The model accounts for rolling resistance, road gradient, and operational constraints, making it possible to determine optimal vehicle speeds along haul road sections characterized by different mining conditions.

The primary objective of the mathematical model is to determine the optimal speed regime for haul-truck operation that minimizes energy and operational costs while satisfying technological constraints.

The optimized speed profiles are used to:

- limit excessive structural loads acting on the metal structures of haul trucks caused by haul road defects;
- reduce fuel consumption;
- ensure environmentally efficient transportation by minimizing unnecessary acceleration and braking on haul road sections with surface defects.

In general form (2), the motion of a haul truck is described by the longitudinal vehicle dynamics equation, which considers traction forces, rolling resistance, aerodynamic drag, as well as the influence of road gradient and haul-truck mass (Carvalho et al. 2022; Berrueta et al. 2015).

In general form, the motion of the haul truck can be expressed by the following equation:

$$m\frac{dv}{dt} = F_t(v) - F_r(v) - F_g - F_a(v), \tag{2}$$

where.

$m-$ mass of the haul truck including rotating masses;

$v-$ vehicle speed;

$F_t(v)-$ engine tractive force;

$F_r(v) = mgf -$ rolling resistance force;

$F_g = mg\sin\alpha -$ grade resistance force (due to ascent or descent of the road);

$F_a(v) = \frac{1}{2}\rho C_d A v^2 -$ aerodynamic drag force.

The optimization problem is formulated as the minimization of the total energy or fuel consumption per trip (3). The objective function can be expressed as follows:

$$J = \int_0^T P(v,t)\mathrm{dt} \rightarrow \min, \tag{3}$$

subject to operational constraints:

$$v_{\min} \le v(t) \le v_{max}, \quad a_{min} \le \frac{dv}{dt} \le a_{max}, \quad T \le T, \quad \sigma_{dyn} \le \sigma$$

Here, $P(v,t)$ represents the **instantaneous engine power**, which depends on vehicle speed, load, and the operating conditions of the haul road. The optimization determines the **optimal speed profile** $v(t)$ along a given section of the haul road.

The integration of digital monitoring enables real-time updating of the parameters of the mathematical model and allows the optimal speed regime to be adjusted in order to reduce fuel consumption, tire wear, and dynamic loads acting on the metal structures of haul trucks caused by haul road defects. This transforms the mathematical model into a practical tool for intelligent management of open-pit truck transportation systems and contributes to improving the overall operational efficiency of mining enterprises.

The proposed mathematical model links theoretical speed optimization with digital monitoring and practical haul-truck operation management, ensuring economic, energy, and operational efficiency of transportation processes. Real-time data on road conditions and vehicle operating parameters are used to update the mathematical model of vehicle motion and to optimize speed profiles considering operational constraints. This approach makes it possible to reduce fuel consumption and greenhouse gas emissions for heavy mining haul trucks. A decision-oriented framework, integrating digital operational monitoring, haul-truck speed optimization, and environmental impact modelling, is presented in Fig. 2.

The integration of digital monitoring data and the mathematical model of vehicle motion within a unified decision-support system, illustrated in Fig. 2, demonstrates the relationship between haul road condition monitoring, speed optimization, and the assessment of the transport and operational condition of haul roads. This process is implemented in the following sequence.

1. Sensors for data acquisition are installed on the haul truck to record: structural loads acting on the metal structures of the haul truck caused by road defects; vehicle speed and acceleration parameters; as well as onboard data collection systems (Block 1, Fig. 2).

Pressure sensors (Fig. 3) installed on the suspension hydraulic cylinders of the haul truck operate in a frequency modulation mode, in which the output signal frequency is a function of the hydraulic pressure in the suspension cylinders. The system provides stable and reproducible measurements, allowing reliable determination of relative load variations and overload conditions during haul-truck operation.

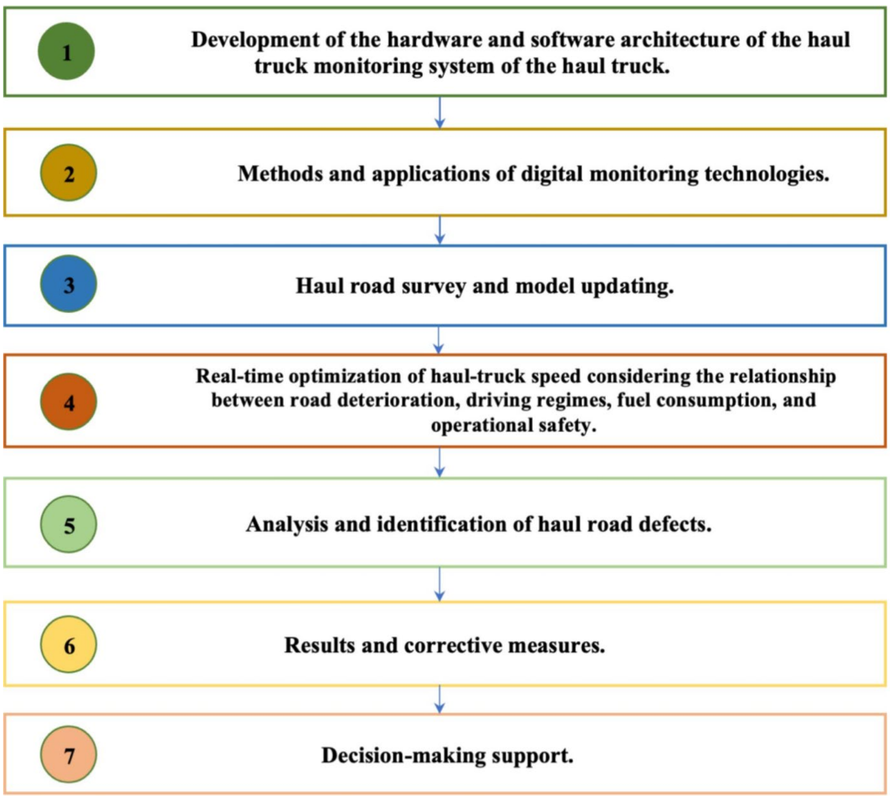
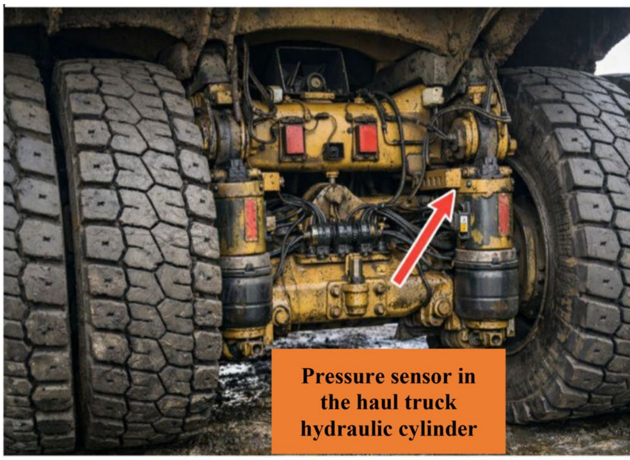


Fig. 2 General methodological framework of the study



- **Signal range:** 1–5 or 9 VDC (connected in the circuit)
- **Zero-pressure frequency:** 186–214 Hz (connected, removed from the cylinder)
- **Sensor interchangeability test:** sensors are swapped between positions; pressure monitoring is performed using **"VIMSps View Real Time"** or **"Datalogger"**. All sensors must respond in a similar and proportional manner
- **Pressure difference:** $Pl - Pr < 345\,\text{kPa}$ (across the axles)
- **Reference voltage:** 5 V tracking voltage
- **ECM response modulation:** jumper – **04**, open circuit – **03**

Fig. 3 General view of the pressure sensor installation on the mining haul truck

The pressure sensors operate from a 24 V power supply and generate a frequency-modulated output signal in the range of approximately 186–214 Hz under no-load conditions, while the signal frequency increases proportionally with the hydraulic pressure in the suspension cylinders.

2. Experimental studies are carried out to identify analytical relationships between the loads acting on the metal structures of a moving mining haul truck and variations in the parameters of possible types of haul road defects. These relationships are used to predict the service life of haul trucks and to determine rational vehicle speeds on problematic sections of haul roads. A reference database of haul road parameters is created using a satellite positioning system as a georeferenced baseline (Block 2, Fig. 2).
3. Prior to commissioning the haul road for operation, a haul road survey and certification procedure is carried out by recording the loads acting on the metal structures of a moving haul truck caused by road defects under different payload conditions and vehicle speeds. The condition of a potential road surface defect is evaluated based on the degree of deviation of the loads acting on the metal structures of the moving haul truck from the nominal value to the maximum permissible limit recommended by the manufacturer. The criterion for assessing the type and parameters of detected haul road defects is the maximum allowable loads acting on the metal structures of the haul truck, determined from pressure sensor data. In this system, the pressure sensors act as recorders of changes in loads acting on the metal structures (kPa) of the moving haul truck caused by the presence of haul road defects in real time (Block 3, Fig. 2).
4. During the process of updating the parameters of the mathematical model while the haul trucks are in motion, conclusions about the current condition of detected haul road defects are obtained by comparing the current and reference records of loads acting on the metal structures of the moving haul truck, resulting from variations in the parameters of emerging types of haul road defects at identical points along the haul road route. These data can be displayed on a computer screen in the haul-truck cabin, uploaded to a PC, or transmitted via a wireless network to the central computer for further analysis and production decision-making (Block 4, Fig. 2).
5. When loads acting on the metal structures of a moving haul truck caused by haul road defects exceed the permissible limits, a decision is made either to perform repair work on the affected haul road section or to issue recommendations to reduce the vehicle speed regime. Since both the reference and current records of loads acting on the metal structures of the moving haul truck due to haul road defects are georeferenced to road coordinates, LiDAR surveying using UAV is additionally carried out to predict and refine the

scope of repair works on problematic road sections (Block 5, Fig. 2).

4 During vehicle operation, the haul-truck driver receives informational and advisory messages on the mobile device display regarding changes in the condition of emerging haul road defects.

These messages may include the following types:

First, a notification indicating the occurrence of a haul road defect, recommending that the driver take note of the information without applying corrective actions.

Second, a warning in the form of a signal lamp with a recommendation to reduce the vehicle speed at the specified road picket.

Third, a signal lamp accompanied by an audible warning indicating that further movement may lead to hazardous or dangerous situations.

The integration of digital monitoring makes it possible to: update the parameters of the mathematical model in real time; receive data from GNSS, inertial systems, and onboard sensors measuring pressure, speed, and acceleration; adjust the optimal speed regime in order to reduce fuel consumption, tire wear, and dynamic loads acting on the metal structures of haul trucks; and improve the economic, energy, and operational efficiency of mining transportation equipment (Block 6, Fig. 2).

7. The results of the proposed method for integrating digital monitoring include: increased durability of haul-truck metal structures due to the elimination of peak loads caused by defects in haul road surfaces; reduction of operational costs associated with repair of haul-truck metal structures and improvement of their energy efficiency; the possibility of reliably forecasting and recommending the service life of haul road surfaces; and the determination of rational haul-truck speeds for problematic sections of in-pit haul roads (Block 7, Fig. 2).

5 Results

Currently, a wide range of methods are used to assess the condition of mine roads, differing in accuracy, labor costs and implementation costs. The most common is visual inspection, which is simple, efficient and low-cost, but it suffers from subjectivity and depends on the qualifications of the personnel. Geodetic measurements provide high accuracy and allow for a detailed analysis of the longitudinal and transverse profile of the road, but require significant time and labor resources, as well as specialized equipment. Lidar scanning provides highly detailed data suitable for automatic analysis but is accompanied by high equipment costs and the need to process large arrays of information. The method of using GNSS and inertial navigation systems (IMU) allows for automated monitoring of road surface irregularities and slopes with high accuracy but requires the installation of equipment on moving objects and can be affected by external factors (e.g. weather conditions). Thus, the choice of monitoring method depends on the specific operating conditions, the required accuracy, and available resources.

A modern and promising direction is the use of unmanned aerial vehicle (UAV). One of the eight existing areas of UAV application in the mining industry is the optimization of monitoring the condition of mine haul roads.

Under the monitored mining conditions, UAV-based surveys were carried out on a regular basis, typically 1–2 times per month, depending on the intensity of road usage and the observed rate of road surface degradation. Additional UAV flights were conducted after blasting operations, heavy precipitation, or road maintenance activities. The flight routes were not determined by the operator during the survey. Instead, they were predefined and executed automatically using mission-planning software. Identical flight parameters (altitude, speed, trajectory, and image overlap) were maintained for all surveys in order to ensure data comparability across different monitoring periods and to enable the analysis of defect evolution over time.

The study primarily focuses on operational problems associated with haul roads, such as water accumulation and surface deterioration, which lead to increased haulage cycle time, reduced productivity, and higher maintenance costs for both haul trucks and haul roads.

In the present study, the flights were performed using DJI Matrice 300 RTK UAV equipped with a LiDAR system, following a predefined trajectory aligned with the central axis of the haul road at a constant altitude of 50 m, which ensured high repeatability of the acquired data. The resulting point clouds had an average density of 5–10 cm per point and achieved horizontal and vertical accuracy of approximately ± 10 mm. Road surface defects (including potholes, rutting, surface irregularities, subsidence zones, erosion features, and water accumulation areas) were detected based on the analysis of local elevation deviations, surface curvature, and cross-sectional geometry derived from high-precision 3D digital models of haul roads. Each detected defect was spatially referenced to a unified geodetic coordinate system, which enabled the generation of defect maps and stationing tables with an interval of 20 m on straight road sections and 10 m on curved sections.

The use of the high-frequency hybrid camera Zenmuse L1 made it possible to generate highly detailed 3D point clouds and terrain models of the road surface in near real time. This approach facilitated the identification of defects such as potholes, surface irregularities, and pavement wear, while reducing operational costs (Fig. 4).

Lidar data obtained using UAV were processed through filtering, classification, and surface reconstruction stages to generate high-resolution digital models of the road surface. Based on these models, longitudinal and transverse profiles, local gradients, and roughness indicators were calculated, which enabled the quantitative characterization of road surface defects. The spatial data obtained from UAV surveys were subsequently integrated with measurements acquired onboard the haul truck. The kinematic parameters of the haul truck were recorded using the Racelogic VBOX, while dynamic loads acting on the metal structures and suspension responses were obtained using the Caterpillar VIMS system. This integrated dataset made it possible to identify statistically significant relationships between the geometry of road defects and the ranges of dynamic loads acting on the haul truck metal structures. The results show that local surface irregularities of haul roads represent the dominant factor causing excessive dynamic loads, which often exceed the permissible limits recommended by the manufacturer. Regression-based and machine learning models were developed to predict load variations and the evolution of road defects. These models support the transition toward predictive maintenance of haul roads and facilitate proactive decision-making in open-pit mining operations.

Digital road section models obtained by UAV enable the rapid and accurate detection of road surface anomalies, and.

aerial photography can be used to assess road surface smoothness conditions and verify their compliance with the road.

plan. UAV have been found to be the best option for quantifying the condition of an extensive road mine network,

including surface roughness, washouts, and slope irregularities, in order to maximize the restoration of poor condition.

and reduce overall road costs.

To ensure comparability, all measurements were conducted under reproducible conditions, including identical haulage routes, similar loading states (loaded and unloaded trips), predefined UAV flight trajectories, and standardized sensor configurations. In addition, the use of relative indicators, such as load ranges, pressure fluctuation amplitudes, and

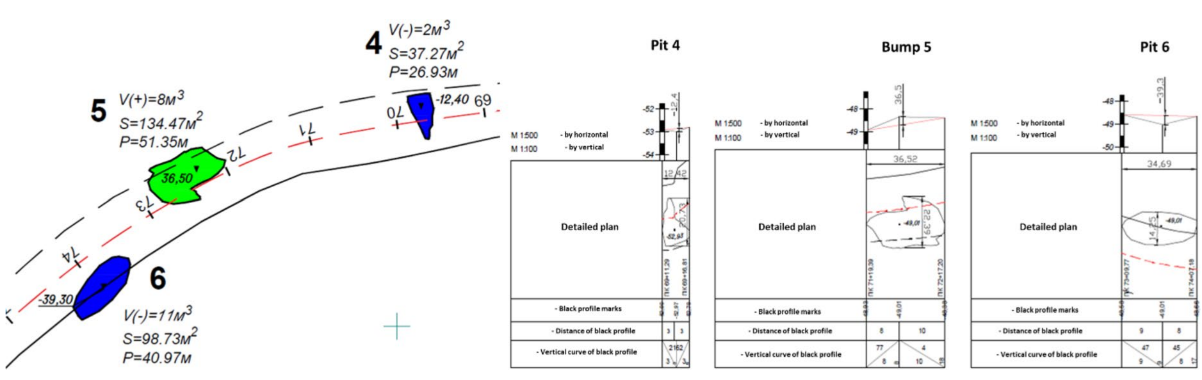


Fig. 4 Haul road defects identified using UAV-based LiDAR scanning with a DJI Matrice 300 RTK and Zenmuse L1 system

normalized acceleration peaks, enabled reliable comparisons between trips even in the presence of unavoidable operational variability. This approach ensured that the observed differences were primarily associated with changes in road conditions rather than with measurement artifacts.

The Racelogic VBOX enabled the recording of road gradients, vehicle speeds, and road surface irregularities, which allowed the analysis of their influence on haulage traffic flows (Fig. 5).

On the first route (CAT 785 No. 201, from EKG 4626 to the temporary waste dump No. 2), the average vehicle speed during the trip was 19 km/h under loaded conditions and 23 km/h in the unloaded state. A reduction in speed on uneven road sections was recorded in five cases. The use of the Caterpillar VIMS Application system made it possible to record data on the operating dynamics of mining haul trucks, load distribution, and the ranges of loads acting on the metal structures of the haul trucks caused by defects in haul roads during vehicle operation (Fig. 6).

Although the VIMS system is not a laboratory-grade measurement system, its accuracy and reliability are sufficient for long-term field monitoring, comparative analysis between trips, and the identification of hazardous operating conditions, which is consistent with the objectives of the present study.

The results obtained using the onboard Caterpillar VIMS system indicate the following: the number of load events acting on the metal structures of the haul trucks during movement over haul road defects that exceeded the permissible limits specified by the manufacturer averaged 11 cases per trip on the first route (from EKG 4626) and 12 cases per trip on the second route (from EKG 4627). Fragments of the histograms showing the distribution of load ranges acting on the metal structures of the haul trucks due to haul road defects are presented in Figs. 7 and 8.

The procedures for verifying the experimental data included: verification of speed and acceleration data obtained from the VBOX and the onboard VIMS system; statistical validation of the adequacy of regression models describing possible haul road defects; and comparison of the recorded loads acting on the metal structures of haul trucks caused by haul road defects with the limit values specified by the haul truck manufacturer.

Based on statistical data, regression relationships were established between the loads acting on the metal structures of haul trucks and the types and characteristics of haul road defects. These relationships make it possible not only to organize planned preventive maintenance of haul roads, but also to reduce the costs associated with overburden transportation processes.

The regression equation describing the load ranges acting on the metal structures of haul trucks as a function of the height of road surface irregularities for haul road Routes 1 and 2 is presented in Fig. 9 and Table 1.

Similarly, analytical relationships were developed for other possible types of haul road defects, including potholes, longitudinal waves, subsidence zones, and others. These models make it possible

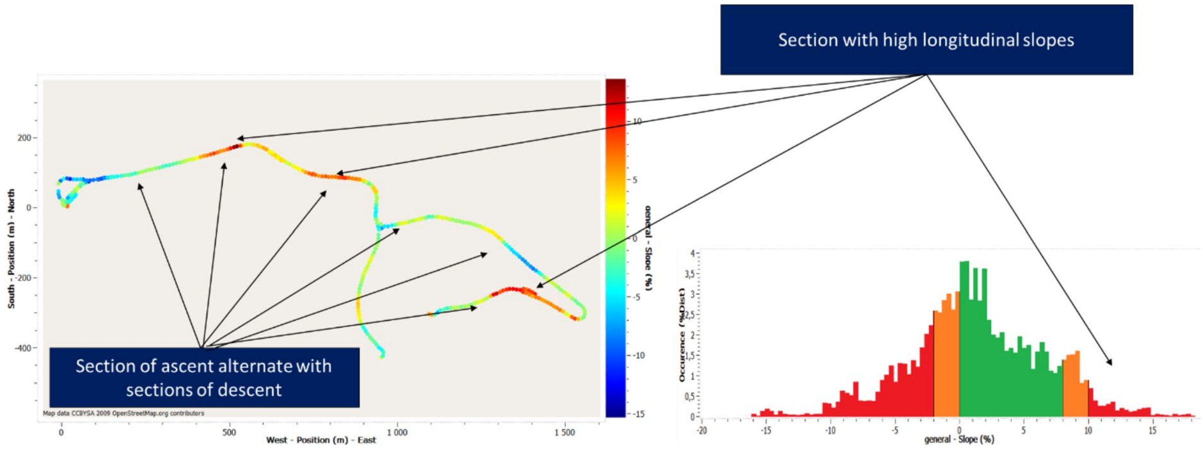


Fig. 5 Distribution of road gradients recorded using the Racelogic VBOX

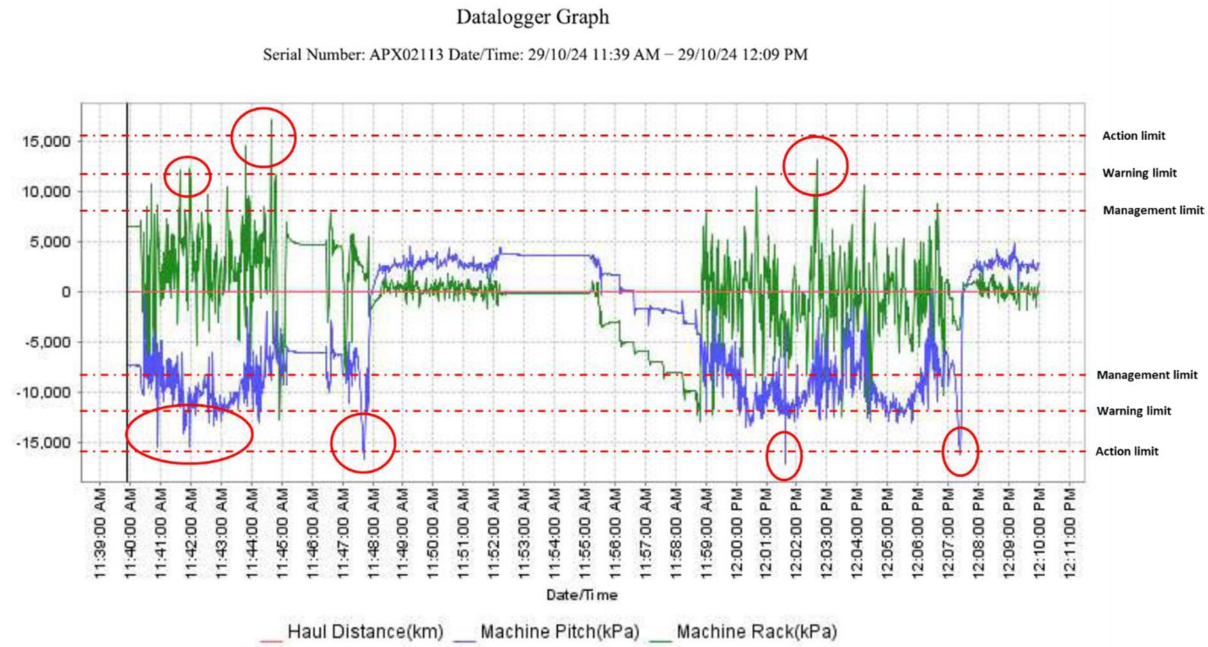


Fig. 6 Data on the operating behavior of the suspension systems of CAT 785 haul trucks obtained using the Caterpillar VIMS system

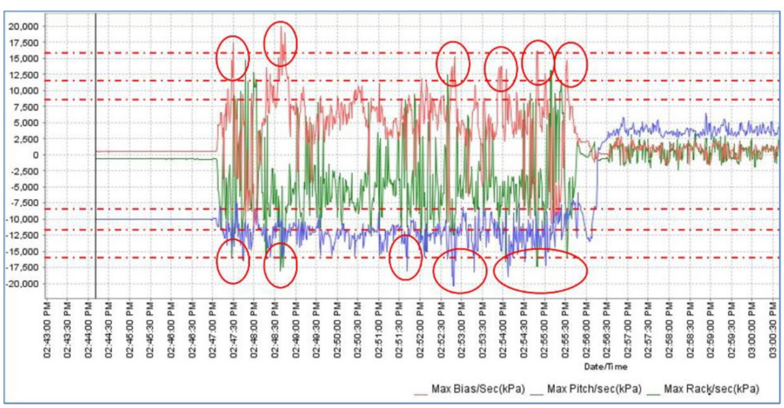


Table 2 – Composite pressure limits for Caterpillar OHT (Pressures in kPa)

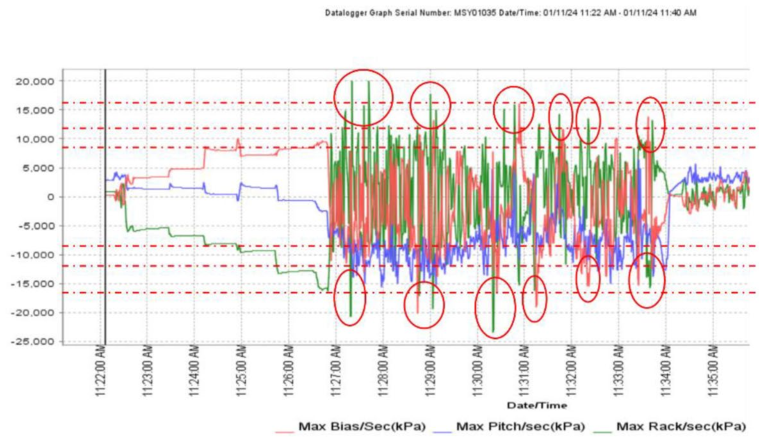
Parameter		769 - 777	785	789 - 793	797
Rack and Bias (Moving truck)	Management limit	± 6000	± 8000	± 8500	± 12500
	Warning limit	± 10000	± 12000	± 12000	± 16500
	Action limit	± 14000	± 16000	± 16000	± 20000
Bias (loading stationary truck)		± 3000	± 3000	± 4000	± 5500
Max. variation in 2 sec interval		± 5500	± 7000	± 8000	± 12000
Maximum Strut Pressure		± 12000	± 14000	± 14000	± 22700

Fig. 7 Fragments of load fluctuation recordings acting on the metal structures of the haul truck caused by road defects. Composite pressure plots from the suspension system of CAT 785 haul truck No. 210

to predict the increase in loads acting on the metal structures of moving mining haul trucks caused by emerging haul road defects and contribute to assessing the degree of deterioration of haul road conditions.

The developed regression models of machine learning allow real-time prediction of changes in the types and characteristics of defects in mine roads and loads on metal structures of dump trucks during their movement depending on the state of the roads.

As a result of the conducted experimental and computational studies, the effectiveness of the developed set of methods for digital monitoring of mine road conditions was confirmed. This approach not only provides a quantitative assessment of the impact of various roadway defects on the load on



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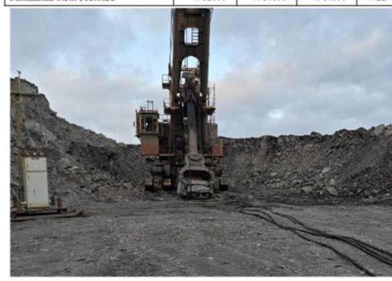

Fig. 8 Fragments of recorded load fluctuations acting on the metal structures of the haul truck caused by pavement defects. Composite suspension pressure plots of CAT 785 haul truck No. 210

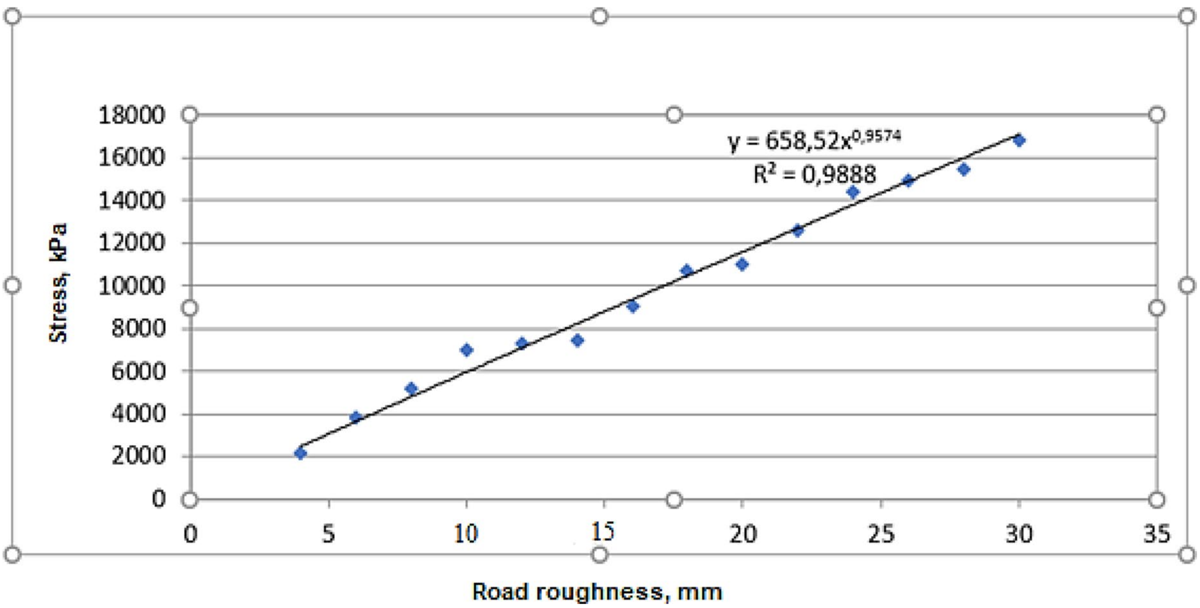

Fig. 9 Regression model of load ranges acting on the haul truck metal structures as a function of haul road surface irregularity height

metal structures of mine dump trucks, but also forms the necessary information base for planning activities for the maintenance of rolling stock and road repairs (Alegre et al. 2021).

Regression models developed on the basis of machine learning allow real-time prediction of changes in road defects, based on data on the load of dump trucks during their movement. This provides the possibility of transition to proactive management of the condition of mine roads, allows for the effective organization of scheduled preventive maintenance, helps reduce operating costs (including equipment repair, fuel and tires) and increases the level of safety of transport operations at mining enterprises.

Table 1 Regression coefficients b_0 and b_1 for various types of haul road defects

No	b_0	b_1	Type of haul road defect
1	658.5	0.95	Road surface irregularities
2	8887.12	0.45	Loose surface
3	5573.93	0.54	Water-saturated surface
4	279.9	1.19	Ruts
5	788.5	1.04	Potholes

Table 2 Recommended cross slopes for mine road turns

Turning radius (m)	Travel speed (km/h)				
	24	32	40	48	> 56
15	4%				
30	4%	4%			
45	4%	4%	5%		
60	4%	4%	4%	6%	
90	4%	4%	4%	5%	6%
180	4%	4%	4%	4%	5%
300	4%	4%	4%	4%	4%

6 Discussion

When driving mine dump trucks on various sections of roads, the driver strives to increase the speed, which leads to an increase in productivity. However, the speed of movement cannot be higher than certain limit values dictated by the traction and speed properties of the dump truck, traffic safety conditions, and the operating characteristics of large-sized tires and traction electric motors.

On slopes, where the speed of dump trucks does not exceed 15 km/h, the calculation can be made without taking into account air resistance forces (Silva et al. 2024):

$$V = \frac{270 * Pot * E_t}{W * \left(f_r + f_\theta\right)} \tag{4}$$

where:

V – maximum speed (km/h);

Pot – engine power (hp);

Et – a coefficient reflecting the efficiency of the transmission;

W – weight of the dump truck, (kg);

fr – rolling resistance coefficient;

f_θ – the coefficient of resistance due to the slope of the road.

Equation (4) is used to calculate the theoretically possible maximum speed that a dump truck can reach on each section of a mine road, considering the specified resistances.

The permissible speed of dump trucks when passing turns with slopes is determined by road conditions, particularly the value of the adhesion of the wheels to the road in the transverse direction, the value of the transverse slope of the mine road and the profile relief. The results of measuring the speed modes of dump trucks show a large variation in the values of instantaneous speed at a fixed point in time when passing turns. This is determined by the stochastic nature of the transport process under the influence of many factors. The spread of values of the speed of dump trucks on an ascent is less than when moving downhill. This is because in the first case, the traction and speed properties and technical condition of the dump truck affect the speed distribution, and in the second case, the human factor, that is, each driver chooses the speed mode himself, guided by safety conditions and personal driving experience.

For turns on sections of a mine road with a slope of more than one degree, the minimum turning radius of the mine road is calculated for a loaded dump truck moving downhill (Tannant and Regensburg 2001)

$$R = \frac{V^2}{127(e + f)} \tag{5}$$

where:

R – turning radius (m);

e – transverse slope (m/m);

f – coefficient of adhesion between tires and road surface (dimensionless).

This generally accepted formula (5) for designing turning radius considers the speed of the dump truck, the road surface traction, the road slope, the cross slope and the turning radius. The formula tries to balance the centrifugal force with the skid resistance and the internal force component from the weight of the dump truck and the cross slope. The recommended cross slopes for turning depending on the speed of the dump trucks are given in Table 2, (Tannant and Regensburg 2001).

As a result of processing and analyzing the recorded experimental data for the first route, from the loading point to waste dump No. 2 (unloading zone), problematic sections of the haul road were identified, together with their illustration and location along the GNSS route (Fig. 10). Exceedances of the loads acting on the metal structures of the haul truck caused by road defects are indicated on the graph by circles. The graph clearly demonstrates the presence of problematic sections of the haul road, in particular revealing a high degree of road surface waviness. The curved lines on the graph that extend beyond the boundary of the white zone indicate that, in these sections of the road, excessive loads were acting on the haul-truck suspension due to defects in the haul road, exceeding the permissible limits. This results in frequent gear shifting (Fig. 11), accelerated tire wear, and increased deterioration of the main components of the haul truck.

On certain sections of Route 210 from EKG 4627, excessive variations in the longitudinal gradients of the haul road were identified, reaching 10–12% when the haul truck was operating in the loaded downhill mode. Under these conditions, variations in vehicle speed, acceleration, and braking lead to accelerated tire wear, reduced haul-truck productivity, and increased fuel consumption (Fig. 12 a, b).

Frequent abrupt braking and acceleration associated with poor road conditions increase the load on the transmission and braking systems of haul trucks (Fig. 13).

Thus, improving the quality of road surfaces and regular monitoring of the condition of mine roads will not only reduce operating costs, but also increase the efficiency of haul trucks by extending the service life of tires and reducing fuel consumption.

High vibration loads increase the wear rate of tires and suspension, which leads to increased operating costs. The vibration spectrum of the road is analyzed using IMU sensors and then compared with the permissible values according to technical standards.

Based on the developed mathematical models, it is possible to optimize the speed of dump trucks depending on the road slope and rolling resistance, which will help reduce fuel consumption and extend the service life of tires by regulating the speed limit on critical sections of mine roads.

The results of the analysis of the conducted experimental studies allow us to state that the actual condition of the selected sections of mine roads generally corresponds to the design solutions, however, to improve the condition of mine roads, it is necessary to reliably, efficiently and promptly identify and eliminate critical defects that have a negative impact on the operational characteristics of roads, contributing to a decrease in operational

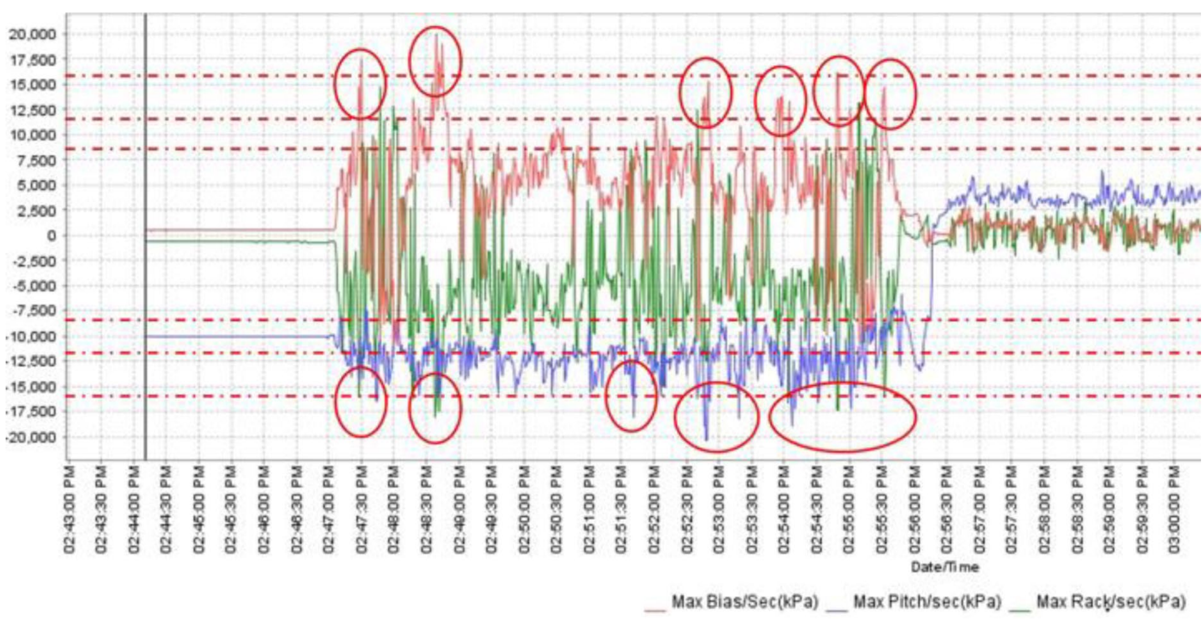

Fig. 10 Total suspension pressure measurements of a loaded CAT 785 haul truck along Route 1 (Road 201)

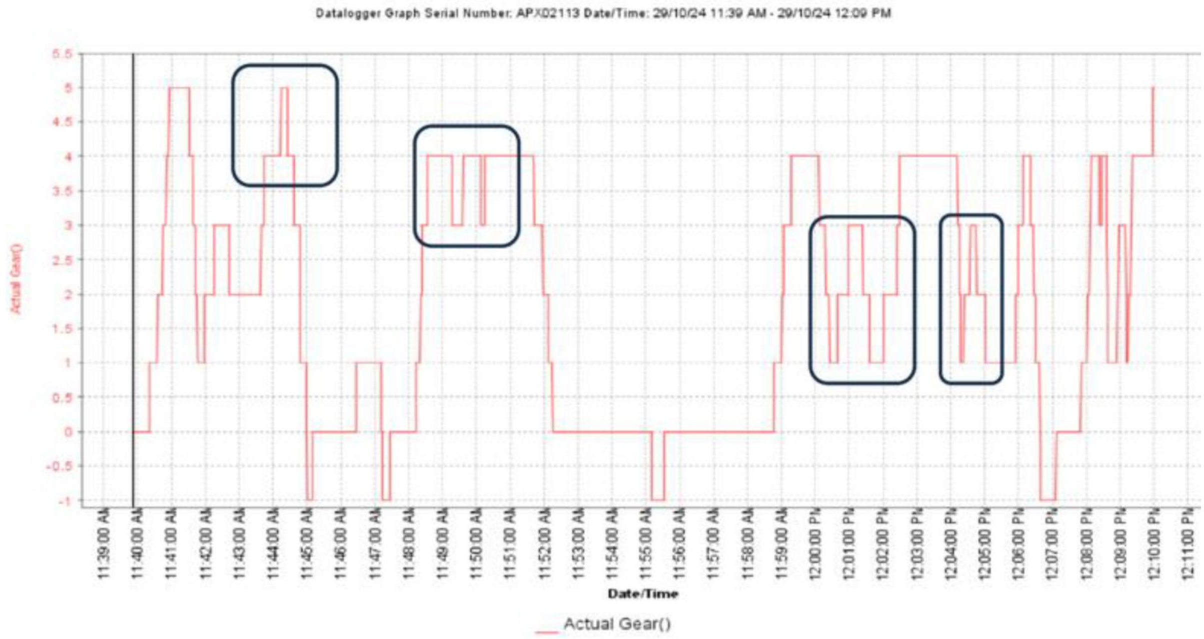

Fig. 11 Speed profile of a loaded CAT 785 haul truck along Route No. 2 with gear-shift events on uneven haul road sections

efficiency. Its integration into the existing production management system is planned, followed by scaling to other mine operations.

The statement regarding the system's readiness for phased implementation is based on the results of pilot tests conducted on several key haulage routes of the coal mine. The system operated in an autonomous mode without interfering with the standard operating regimes of the haul trucks. Data acquisition was performed using industrial-grade sensors and standard onboard systems, while automatic data transmission and processing were carried out in a mode close to real time. The results of the analysis were used to identify priority road sections requiring maintenance and repair, which confirmed the practical applicability of the proposed system.

The main limitations of the study on the condition of in-pit technological haul roads include the use of standard onboard sensors instead of laboratory-grade measurement equipment, consideration of the influence of external factors such as weather conditions, and the variability of loads acting on the metal structures of haul trucks caused by haul road defects. However, these limitations reflect real operating conditions and do not reduce the practical significance or applicability of the proposed monitoring system.

The planned integration of the system into the existing production management system is based on the following factors: the modular architecture of the digital platform; compatibility with existing fleet monitoring systems; and the possibility of system scalability through the expansion of data sources without modifying the core data processing logic.

7 Conclusions

Constant monitoring of the condition of haul roads plays a key role in increasing the efficiency of mine transport. Regular analysis and control of the quality of the road surface allows for the timely detection of defects, optimization of routes and reduction of maintenance costs.

The completed set of experimental and computational experiments, confirming the operability of the adopted set of methods for digital monitoring of mine roads, allows not only to assess the degree of influence of individual defects of mine roads on the load of metal structures of dump trucks, but also ensures the creation of the necessary information base for forecasting work on the maintenance of dump trucks and the repair of mine roads.

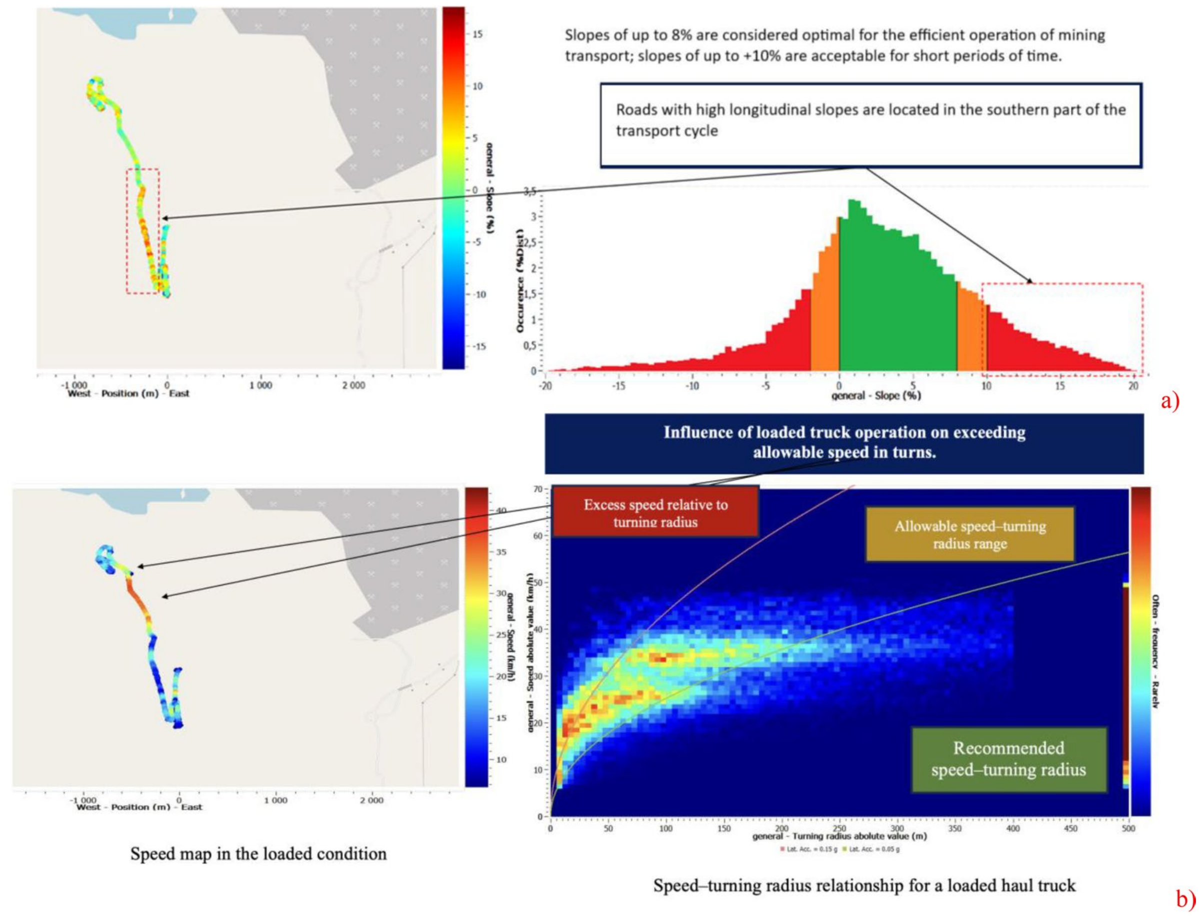

Fig. 12 Map and profile of longitudinal road gradients: **a** gradient distribution; **b** speed and acceleration profiles

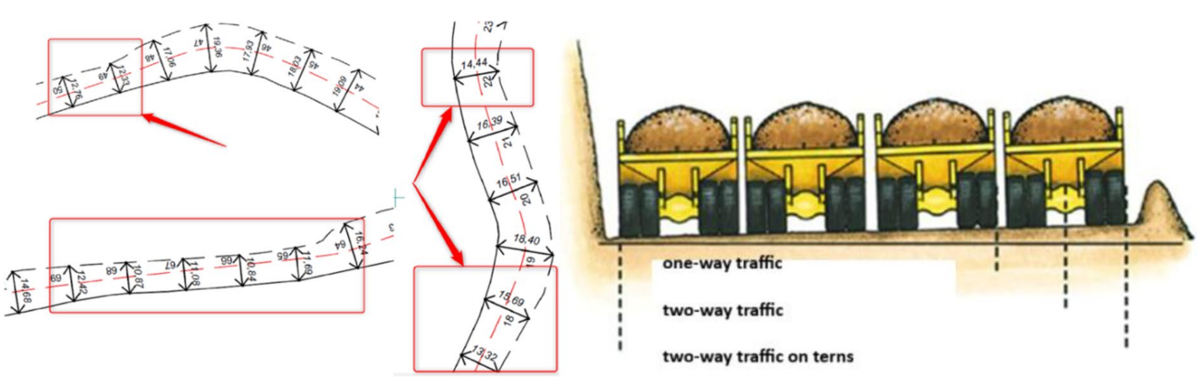

Fig. 13 Haul road defects identified at curves with insufficient road widening

The implementation and support of modern monitoring technologies, such as lidar scanning, GNSS tracking and vibration load analysis, are integral elements of the efficient operation of mine transport. Further development of these systems will increase the economic profitability of mining enterprises and reduce the impact on the environment.

All sensors used in this study are industrial-grade components designed for continuous operation under the harsh mining and geological conditions typical of open-pit mining enterprises. The pressure sensors installed in the suspension hydraulic cylinders and the VIMS system represent standard equipment for large mining haul trucks and are certified for long-term industrial use. The proposed monitoring approach does not require the installation of experimental or prototype sensors. Instead, it relies on existing onboard systems, which significantly reduces implementation costs. Additional expenses are primarily associated with the infrastructure required for data extraction, storage, and processing, making this approach economically feasible for large-scale deployment. The estimated cost of the integrated monitoring system ranges from USD 40,000 to 53,000.

The use of comprehensive monitoring of the condition of mine roads at the Bogatyr and Vostochny open pits made it possible to identify key problems with the road surface and develop recommendations for its improvement. The use of UAV, lidar scanning and GNSS monitoring systems has proven its effectiveness in identifying defects and planning repair work. The implementation of the proposed measures will improve the safety and economic efficiency of mine transport operation.

Regression models developed on the basis of machine learning allow real-time prediction of changes in road defects, based on data on the load of dump trucks during their movement. This provides the possibility of transition to proactive management of the condition of mine roads, allows for the effective organization of scheduled preventive maintenance, helps reduce operating costs (including equipment repair, fuel and tires) and increases the level of safety of transport operations at mining enterprises.

The achieved accuracy of predicting changes in defect characteristics is up to 85–90%, which is confirmed by the results of validation on experimental data. The developed digital monitoring and analytics system has successfully passed pilot testing at several sites of the coal mine and is currently being prepared for phased implementation into industrial operation. It is planned to integrate it into the existing production management system with subsequent scaling to other coal deposit facilities.

The reported prediction accuracy of 85–90% was obtained through the validation of regression and machine-learning models using experimental data recorded under real operating conditions. The dataset was divided into training and validation subsets (70/30 split) without overlap between trips. The predictive performance was evaluated using the coefficient of determination (R^2); for the main types of haul road defects, the obtained values ranged from 0.85 to 0.90. The derived relationships are physically interpretable and are supported by the dynamic load measurements recorded by the onboard Caterpillar VIMS monitoring system.

The proposed concept of long-term monitoring is based on the continuous acquisition of strut suspension pressure data from haul trucks using the VIMS system, combined with periodic surveys of road surface geometry using UAV-based monitoring. The integration of these datasets enables continuous assessment of road conditions and their influence on the loads acting on the metal structures of haul trucks without interrupting the normal operation of mining enterprises. Over time, the accumulated datasets can be used to develop regression and machine-learning models capable of predicting the evolution of road defects and the associated increase in loads acting on the metal structures of haul trucks. Such an approach supports the transition from reactive road repair to predictive and proactive road management strategies.

The developed digital monitoring and analytical system has successfully undergone pilot testing at several sections of coal open-pit mines and is currently being prepared for phased implementation in industrial operation. Its integration into the existing production management system is planned, followed by scaling to other coal mining sites. In this context, the term “readiness for implementation” refers to the technological and functional maturity of the prototype, rather than the completion of full industrial-scale deployment.

In the future, the monitoring system can be expanded to include additional haul trucks and road networks, integrate fatigue and damage accumulation models for the structural elements of haul trucks, and further improve machine-learning algorithms for real-time prediction of road surface defects and load spectra.

Further research may also focus on the economic optimization of maintenance schedules based on predicted road surface degradation trends.

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Author contributions Author 1. Numerical processing of experimental results, preparation of figures; Author 2. General research management; Author 3. Methodology and conduct of the experiment; Author 4. Manuscript writing, algorithm development.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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