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The “Engineer” publishes the most significant results of scientific and applied research carried out in universities of transport profile, as well as other higher educational institutions, research institutes, and centers of the Republic of Uzbekistan and foreign countries.

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Intelligent monitoring and predictive maintenance technologies in the railway transportation process management system

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Abstract: The article discusses modern approaches to ensuring the safety and efficiency of interaction between railway transport systems through the digitalization of technological processes and the implementation of intelligent monitoring and diagnostic subsystems. An analysis of the existing types of maintenance for transport infrastructure facilities is carried out, including preventive maintenance, condition-based maintenance, and predictive maintenance. The necessity of transitioning to a predictive model of transportation process management based on monitoring data processing and forecasting the technical condition of facilities is substantiated. The concept of a "smart railway station" integrating transportation, diagnostics, monitoring, and cargo parameter control processes into a unified digital management environment is proposed. Particular attention is paid to the implementation of automated weighing systems and the development of a program for intelligent control of wagon weight parameters at the Zavodskaya station of a metallurgical plant. The program provides digital support of wagons throughout the technological chain, intelligent verification of cargo weight data, and decision-making regarding the necessity of repeated weighing based on the analysis of previously obtained information. The research results demonstrate that the use of digital monitoring and intelligent control technologies makes it possible to reduce the number of repeated wagon weighings, decrease shunting operations and wagon idle time, improve the reliability of cargo information, reduce the influence of the human factor, and enhance train traffic safety. The proposed approach forms the basis of a predictive management model for the transport complex focused on failure prevention and optimization of operational processes.

Keywords: railway transport, digitalization, intelligent monitoring, diagnostics, predictive maintenance, traffic safety, weighing systems, smart railway station, digital wagon support, transportation process automation, failure prediction, transport system management

1. Introduction

To improve the efficiency of production activities, various management technologies are traditionally applied, including lean production, Six Sigma, Kaizen technologies, and others. These approaches are also applicable to transport systems. Previously, a process-oriented approach to the organization of transportation production was proposed [1, 2, 3]. Further development of this concept is associated with the implementation of advanced maintenance technologies for transport infrastructure facilities based on predictive condition monitoring and supported by digital monitoring and diagnostic subsystems [4, 5, 6].

2. Research methodology

Three main types of maintenance are used in the transport industry.

Scheduled maintenance. Currently, the transport sector is dominated by a preventive maintenance system. Inspection intervals are determined according to pre-established periods experimentally validated by safety indicators [7]. The disadvantage of this technology is the lack of consideration of the actual condition of the equipment, which leads either to excessive costs or to untimely detection of defects.

Condition-based maintenance. For each facility, a state feature space is formed in which it belongs to one of the following classes: "R" – normal condition; "M" – maintenance required; "W" – withdrawal from operation required.

The object is characterized by a state vector:

$$X = (x_1, x_2, \dots, x_n) \tag{2.1}$$

where x_i – are the parameters reflecting the properties of the object.

To unify the analysis, the parameters are scaled:

$$x_i^* = \frac{x_i - min(x_i)}{max(x_i) - min(x_i)} \tag{2.2}$$

$$x_i^* = \frac{max(x_i) - x_i}{max(x_i) - min(x_i)} \tag{2.3}$$

After transformation, all features take values within the range [0;1].

State classification is performed using pattern recognition methods based on reference patterns and separating boundaries [8]. The most advanced approach is predictive maintenance technology. An example is the "Smart Locomotive" system capable of detecting more than 60 types of faults and predicting equipment failures [9]. Modeling of changes in the object's condition is carried out using time series of features [10, 11]. Stationary objects include railway switches, compressor stations, signaling and interlocking devices, and power supply systems [7]. Each parameter xi is divided into three zones: operating zone (1–α), maintenance zone (α–β), and emergency zone (β–0). The values of α and β are determined based on operational

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experience [7]. The forecasting algorithm is presented in Figure 1.

3. Results and Discussion

Based on observation results, a time series xit is formed and an autocorrelation model is constructed:

$$x_{it} = \sum_{k=1}^{n} a_k x_{i(t-k)} \quad (2.4)$$

where the coefficients ak reflect the inertia of the system state.

Fig. 1. Forecasting Algorithm

As a result, the moment by which maintenance should be performed is determined. Mobile objects include freight cars, locomotives, and train consists.

The task is to classify the object into one of the following categories:

"R" – operation;

"M" – maintenance;

"W" – withdrawal from service.

For example, wheelset diagnostics can be performed using a thermal imaging device. Temperature parameters form an n-dimensional feature space. The current state is determined by the position of a point within the state space. In this case, the forecast is generated not as a numerical value but as a state class [12].

The transition to predictive maintenance creates new processes such as infrastructure monitoring, equipment diagnostics, and failure prediction. These processes require coordination with transportation operations based on the process-oriented approach. Integration of monitoring subsystems with transportation processes makes it possible to prevent emergency situations, reduce the influence of the human factor, optimize the utilization of equipment resources, decrease repair costs, and reduce train delays.

The new management model takes into account not only the current state of the transportation system but also its predicted dynamics, thereby improving traffic safety and transportation process efficiency. The implementation of digital monitoring and diagnostic subsystems forms a predictive management model for the transport complex. Transportation efficiency is achieved through failure prevention rather than reaction to failures. Therefore, predictive maintenance technologies are a key tool for ensuring the safety and efficiency of interaction between railway transport systems.

The essence of the conducted research lies in the transition from the traditional approach to transportation process management, based on preventive maintenance and fragmented technological solutions, to an integrated digital model that combines transportation, monitoring, diagnostics, and cargo parameter control into a single managed environment. Unlike existing approaches, the concept of a "smart railway station" based on digital monitoring technologies and intelligent data analysis is proposed.

A key element of this concept is the implementation of automated weighing systems integrated into the station management system, enabling real-time:

control of wagon weight upon arrival and departure;

detection of discrepancies between actual cargo parameters and shipping documents;

identification of overloads, underloads, and cargo data distortions;

generation of digital alerts for operational decision-making.

Within the proposed smart station model, weighing systems are considered part of the overall monitoring and diagnostics subsystem of transport infrastructure, and their data are included in the state vector of transportation system objects. During operation, the above-mentioned parameters change in different directions: some increase, while others decrease. Furthermore, they are measured in different value ranges. To unify the analysis, all variables are scaled to the interval [0;1] and transformed into a decreasing form with equipment wear. Scaling formulas are applied separately for decreasing and increasing variables.

The addition of wagon loading parameters to the state vector makes it possible to:

improve the reliability of transportation process assessment;

consider the impact of commercial factors on traffic safety;

expand predictive management capabilities by identifying hidden risks;

ensure integration of technological and information processes.

Discussion. As a result, a digital model of station operation is formed, in which control, diagnostics, and management processes are integrated into a unified intelligent system capable not only of responding to deviations but also of preventing their occurrence. Within the framework of the study, the development of an intelligent wagon weight control program for the Zavodskaya station of a metallurgical plant is proposed. The purpose of the program is to reduce the number of repeated wagon weighings while maintaining the required level of reliability of cargo weight data and transportation safety.

In the existing technological process, wagons undergo multiple weighings at different processing stages: upon arrival, after unloading, after cleaning, and before reloading. This organization leads to additional shunting operations, increased wagon idle time, higher utilization of weighing equipment, and increased operating costs. To optimize this process, a program is proposed that provides digital support for wagons throughout the entire technological chain and replaces part of the repeated weighing operations with intelligent data verification procedures.

At the initial stage, the station operator enters the wagon number, cargo weight, and destination facility into the system. After arrival at Zavodskaya station, the wagon is weighed and the obtained data are automatically recorded. The system calculates the total wagon weight as the sum of the tare weight and cargo weight and compares the calculated value with the measured value. If the deviation is within acceptable limits, the information is confirmed and the wagon is allowed to proceed further.

At the cargo facility, the operator confirms or adjusts the cargo weight and updates the wagon tare weight if necessary. If the wagon number, cargo weight, tare weight, destination, and previous weighing results correspond and contain no

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critical discrepancies, the system decides that repeated weighing before loading is not required. Thus, the program enables the elimination of a portion of repeated weighing operations that were previously mandatory. The main principle is that the decision to perform another weighing operation is based on digital verification of existing data rather than automatic weighing of every wagon.

4. Conclusion

Implementation of the proposed program will reduce the number of repeated wagon weighings, decrease unnecessary shunting movements, lower the workload of weighing facilities and operators, reduce wagon idle time, improve the reliability of cargo data, minimize the influence of the human factor in transportation operations, and enhance traffic safety by preventing wagon overloading and cargo data discrepancies.

Thus, cargo weight control becomes not only an element of commercial accounting but also a crucial component of railway traffic safety, since wagon overloading directly affects train dynamics, infrastructure wear, and the risk of accidents. The proposed program represents a digital tool for wagon support throughout the technological chain with an intelligent weight verification function. Unlike the current practice based on multiple mandatory weighings, the proposed approach allows decisions on repeated weighing to be made through analysis of already available data. This ensures a reduction in weighing operations, accelerates wagon processing, and improves the operational efficiency of the Zavodskaya station of the metallurgical plant.

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