THE TEST-BASED EVALUATION OF THE DIAGNOSTIC ACCURACY OF BRAKE SYSTEMS IN PASSENGER CARS

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Resume
In this article is dealt with the ways of improving the diagnostic accuracy of braking systems of passenger cars, taking into account the operational factors. A diagnostic system that monitors the pneumatic processes and transmits the data in real time has been implemented. The method proposed has provided an increase of reliability from 83.1% to 87.6%.

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1 Introduction

The development of railway transportation necessitates the implementation of solutions aimed at ensuring traffic safety [1-3]. One of the most important components of the rolling stock, on which traffic safety depends, are brakes [4]. Therefore, this component of the rolling stock design should be given special attention, not only from the point of view of strength [5], reliability [6], but also monitoring.

According to the operational data, up to 25-30% failures in brake systems of passenger cars are caused by their untimely detection. This requires better diagnostic methods and higher efficiency of monitoring. The main features of the environment in which the rail transport operates today are higher speeds, heavier traffic and more complex operational factors. Therefore, the issue of ensuring traffic safety and reliability of rolling stock has become a top priority. The braking system of passenger cars is one of the key components, the efficiency of which determines the stability of braking processes and the operational safety; this necessitates higher standards for the accuracy of assessing its technical condition.

Today the maintenance of braking systems of passenger cars are primarily based on scheduled inspections, which cannot always detect faults at an early stage. This results in lower braking efficiency, faster wear and tear of components, and a more frequent failures in operation. An additional challenge is the diagnostics of pneumatic and electro-pneumatic braking systems, which are characterised by non-linear processes, dynamic changes in parameters and a significant number of interrelated factors.

A promising area of development is remote monitoring systems for braking equipment, which integrate measuring, processing and transmitting capabilities into a single information environment. The use of such systems makes it possible to continuously monitor parameters, detect deviations from standard operating conditions, and create the basis for forecasting the technical condition of passenger cars. In these circumstances, evaluating the reliability of diagnostics becomes of paramount importance as an integral qualitative indicator of the control systems' performance.

A key scientific and practical challenge is the development and investigation of methods and tools used for diagnostics of the braking systems of passenger cars and aimed at improving the accuracy, speed and reliability of monitoring in real operating conditions.

2 The analysis of recent research and publications

Under the current conditions, in which passenger car operates, there is a growing need to improve the efficiency and reliability of braking systems, in particular by studying the dynamics of processes within the pneumatic components such as air distributors. Majority of current research is focused on developing appropriate mathematical models based on physical principles and experimental data, as well as on methods for diagnosing the technical condition of systems in real time.

The use of anti-skid devices with electro-pneumatic valves in passenger cars is examined in [7]. The study substantiates the use of systems for monitoring the technical condition of braking equipment and examines the operational characteristics of electro-pneumatic assemblies under various speed modes. However, the issue of automated diagnostics of malfunctions of air distributors was not considered.

A comprehensive methodology for assessing the performance of braking systems in passenger and freight cars, which combines theoretical and experimental approaches, is proposed in [8]. The study presents mathematical models developed with computer simulation, which can be used to determine the braking distance while taking into account the influence of operational factors. However, the author did not analyse the operation of air distributors at the level of individual cars.

The theoretical basis for development of the new types of braking systems with improved performance, particularly taking into account higher speeds, is presented in [9]. The impact of design parameters on the reliability of components and their costs is highlighted. However, the issue of using on-board diagnostic systems for the braking equipment of passenger cars was not considered.

A parallel computational diagram for modelling processes in pneumatic braking systems is described in [10]. It is found that the use of parallel computing makes it possible to increase the speed of calculations without compromising the accuracy of determining pressure parameters. However, the methods for the rapid diagnosis of the technical condition of the braking system in passenger cars during operation were not examined.

The modern approaches to the modelling of pneumatic braking systems are studied in [11], in particular empirical, hydrodynamic and hybrid models are analysed. Their advantages and disadvantages, in terms of accuracy and computational complexity, are also identified. Moreover, the models of individual components of the braking system were examined. However, the issue of applying these approaches to passenger rolling stock was not studied sufficiently.

A method for detecting faults in the braking system of an electric train at their early stage using the Variable Control Limit algorithm is proposed in [12]. It is demonstrated that it is possible to improve the diagnostic accuracy and reduce the number of false alarms in real time. However, the findings of the study dealt with electric trains, but the specific characteristics of the passenger cars operated on Ukrainian Railways were not taken into account.

A hybrid model for the real-time monitoring of the condition of air brakes on freight trains is described in [13]. The model combined hydrodynamic equations with empirical relationships, enabling accurate forecasting of pressure changes in the brake cylinder and the detection of malfunctions. However, the proposed approach did not take into account the specific operational characteristics of the pneumatic brakes of passenger cars.

An analysis of current scientific research has demonstrated that the main focus is on modelling of pneumatic processes and developing diagnostic methods, primarily for freight rolling stock, whilst the issue of evaluation of the technical condition of pneumatic systems in passenger cars, particularly air distributors, is yet to be studied. Therefore, there is a need for further research aimed at developing improved methods for diagnosing the braking systems of passenger cars. These methods must take the specific operational conditions and more stringent requirements regarding the reliability of technical decisions, which is vital for ensuring the reliability and safety of passenger rolling stock.

The purpose of this study was to improve the diagnostic reliability of the braking systems of passenger cars by developing a diagnostic system and a method for evaluating reliability based on experimental research.

To achieve this purpose, the following objectives were set:

- to analyse the current systems used for monitoring and diagnosing the braking equipment of passenger cars and identify their main shortcomings;
- to develop a diagnostic system for passenger car brakes for testing components and assessing their performance; and
- to develop an approach for evaluating the reliability of diagnosis and to carry out a quantitative assessment of effectiveness of the proposed system based on experimental data.

3 Development of a diagnostic system for passenger car brakes

To control the automatic braking systems of rolling stock, both fixed (external) and on-board systems were developed; they can monitor individual components and key parameters of the rolling stock's braking systems. To evaluate the current state of the on-board control systems, it is advisable to examine the implementation of such systems using a high-speed rail vehicle as an example.

The braking system of the ICE high-speed electric train ensures a high level of operational readiness, coordinated operation of all types of brakes, and speed control both manually by the driver and automatically in accordance with infrastructure signals [14]. The system warns the driver of brake faults and recommends appropriate actions; it automatically prepares and fully tests the brakes, records the results in a data logger and displays them on the screen; it also provides the option of switching to pneumatic control in the case of a failure in the electronic system. The system is operated by a modern microprocessor-based brake control and monitoring system; its structural organisation for motor and trailer cars is shown in the form of a block diagram in Figure 1.

The on-board control system of a motor car (Figure 1, a) consists of the following: AFB - automatic control system for traction and braking modes; ZSG - train control device; DAVID - central diagnostic computer; LWL - fibre-optic communication line between the brakes and the controller; AST - traction drive control system; Af - failure-signal; GS - anti-skid protection; HSM - electronic module of the driver's lever; P-Bt - switch to the pneumatic mode; Pn - pneumatic equipment; HL - brake line; SV - air diffuser; Eld - electrodynamic brake; SB - disc brake.

The on-board control system for a trailer car (Figure 1, b) consists of the following: ZEUS - diagnostic computer; SVB - signal processing device of the brake system; GS - anti-skid protection; KL - air conditioning system; Tr - door systems; SL - sensors; Bt - battery; eLS - electrical network; PnS - pneumatic network; EP - electro-pneumatic valves; HL - brake line; Mg - magnetic rail brake.

The functional architecture shown in Figure 1 is based on the interaction of several control and diagnostic modules. The driver's controller (HSM) generates braking commands, which are transmitted to the on-board control units of the motor and trailer cars via the train control unit (ZSG) and the fiber-optic communication network (LWL). The central diagnostic computers DAVID and ZEUS continuously receive information from the braking equipment, process diagnostic data and monitor the technical condition of the system during train operation. The signal processing units (SVB) collect information from sensors (SL), electro-pneumatic valves (EP) and pneumatic equipment (Pn, PnS), and the anti-slip protection modules (GS) analyze the behavior of the wheels and intervene in the braking process in the event of slippage. The generated commands are implemented through the air distributor (SV), brake line (HL), disc brakes (SB) and magnetic rail brakes (Mg). This design provides a combination of brake control functions, technical condition monitoring, fault detection and transmission of diagnostic information within a single on-board system, which increases operational reliability and traffic safety.

The system can also control the brakes automatically or manually, coordinate the operation of the electrodynamic and pneumatic brakes, monitor continuously the technical condition, warn the driver of faults, conduct automatic testing, and record the parameters.

The air distributors KE Td KSL.So together with the electro-pneumatic valves EPZ 6 form a single control unit for the electro-pneumatic brake. The basis of the system is the driver's brake lever HSM, equipped with microprocessor electronics.

The HSM electronic equipment in a power car is connected via the ZSG unit using a fibre-optic communication channel with the driver's controller,

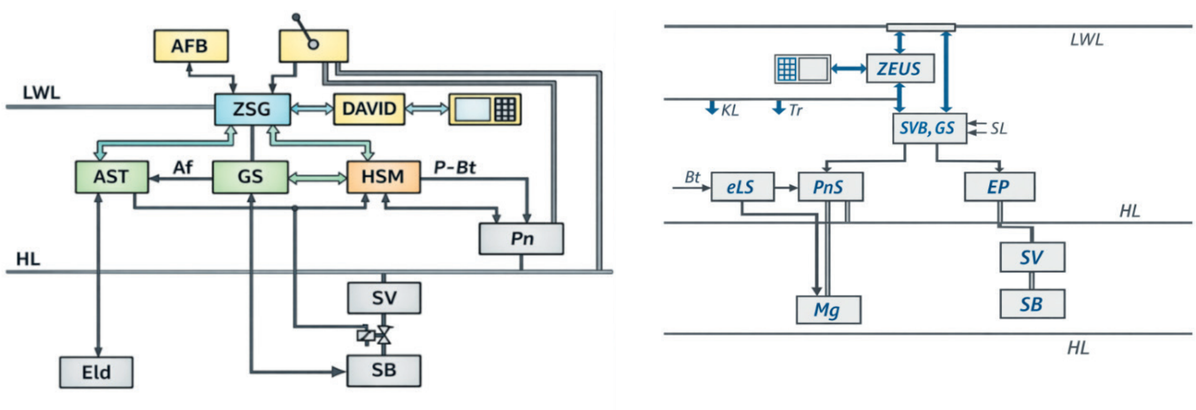

***Figure 1** The brake control diagram for a motor car (a) and a trailer car (b) of an ICE train*

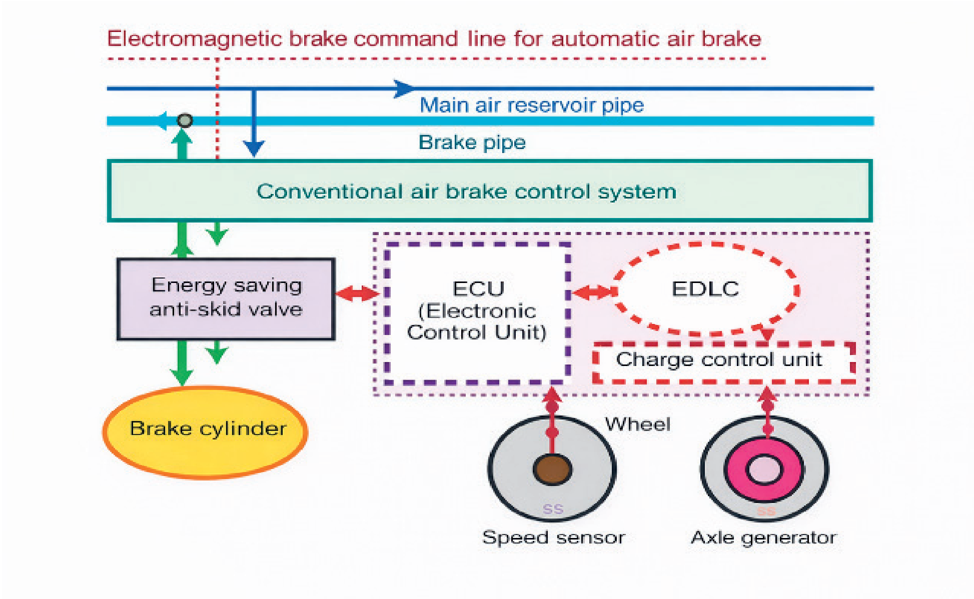

Figure 2 *The brake control system with electronic anti-skid braking system*

which enables communication between the power car, the central diagnostic system, the traction drive control system and the regenerative braking system. The second communication channel provides the data exchange between ZSG and signal processing devices SVB, located in each trailer car. These devices collect diagnostic data on the braking system and interact with the anti-skid system.

The technical solutions considered indicate the widespread use of integrated microprocessor-based brake control systems, which provide not only control functions but also real-time diagnostics. Further development of these approaches involves the use of electronic anti-skid systems, which improve braking efficiency and enhance the train stability. An example of how this approach is implemented is shown in Figure 2.

In Japan is being developed the brake control systems for passenger and freight trains that work in conjunction with electronic anti-skid devices [15]. The vehicle brakes are controlled via a radio signal, while the signals from sensors fitted to the wheel sets and in the brake cylinder, are processed by a microcontroller, which generates the control signals for the anti-skid system.

The analysis of the diagram shows that the use of an electronic anti-skid braking system, combined with microcontroller-based signal processing, enables the adaptive braking control based on data received from the wheel sensors and the brake cylinder. This approach ensures more precise control of braking force, reduces the likelihood of skid and improves braking performance.

Similar solutions have become widespread in other countries around the world, where electronic-pneumatic braking systems, with advanced control and diagnostic functions, are being introduced.

In the US, Canada, Australia, South Africa and China, electronically controlled air brakes are being introduced. The use of electro-pneumatic brakes on the Quebec Cartier Mining (QCM, Canada) and Spoornet (South Africa) railways enables a 5-15% reduction in fuel consumption, a 20% increase in railway capacity, improved train controllability, increased speeds, improved traffic safety, reduced longitudinal forces (which improves cargo preservation), and reduced wear of the mechanical parts of the brakes (brake shoes) by 25-35 [16]. This electro-pneumatic braking system comprises equipment of the locomotive and the car, including an ER-60 air distributor.

In the age of digitalisation of rail transport, intelligent diagnostic braking system systems, which combine pneumatic, electronic and digital components, are becoming particularly important. Such systems provide real-time monitoring of pressure, air leaks, temperature and the wear level of brake components.

In spite of the facts that the existing brake control systems are highly developed, they have a number of significant shortcomings. In particular, most of them mostly deal with recording existing failures rather than predicting them at an early stage, which limits preventive maintenance. Many of these systems are very complex to be used for the existing rolling stock fleet, particularly given the variety of railcar types and the lack of standardised data exchange interfaces. Importantly, they have limited functionality regarding the real-time transmission of diagnostic information and do not provide sufficient data to support decision-making by the staff.

Taking into account the shortcomings identified in existing brake equipment monitoring systems, and the aim to improve diagnostic efficiency, a new approach to the development of a diagnostic system for railcar brakes (DSRB) is developed [17]. The main idea behind the proposed solution is to combine the measurement of key braking system parameters with intelligent data processing and the ability to transmit this data

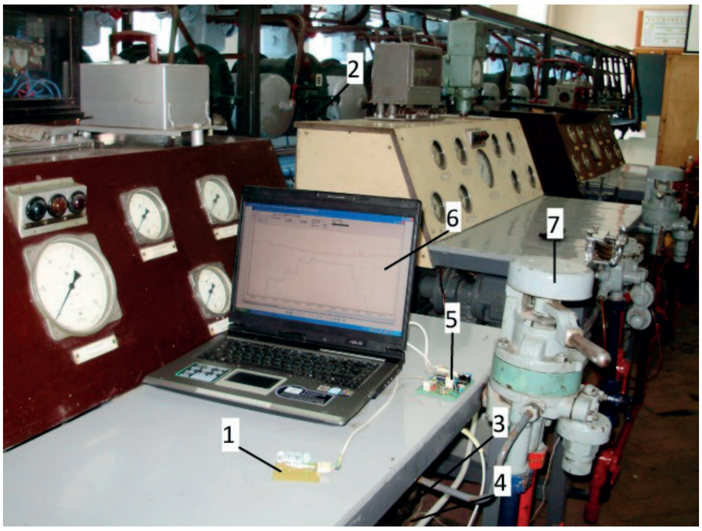

Figure 3 *The diagnostic system for the brakes of a passenger car in the testing laboratory: 1 - light indication of a car; 2 - brake cylinder sensor; 3 - brake line sensor; 4 - electro-pneumatic brake sensor; 5 - microcontroller; 6 - laptop with software; 7 - driver's lever*

in real time. This approach makes it possible not only to monitor the current condition of the brakes, but to identify potential causes of failure at an early stage, as well. This necessitates the development of new approaches to diagnosing the brake equipment of passenger cars.

The DSRB system, developed at the Ukrainian State University of Railway Transport (UkrSURT) in the brake testing laboratory of the Department for Rolling Stock Engineering and Product Quality, can be used to simulate the performance of brakes of passenger cars and freight wagons (Figure 3).

For the experimental research into the braking equipment of passenger cars, 20 air distributors No. 292 and electric air distributors No. 305 were selected, which were in use for the rolling stock on Ukrainian Railways. Prior to the tests, the selected devices were inspected, which included a visual inspection, a check for completeness and an evaluation of the technical condition of the main units and components. Thus, the selection was representative and reliable regarding the results obtained.

The experiments were carried out using a special test bench for simulating operating conditions for braking equipment that closely resemble real operating conditions [18-19]. Each sample was mounted on the test bench, all the data were recorded automatically using measuring and recording equipment, which ensured accuracy and reproducibility of the data obtained.

The results of experimental studies show that, after the two-stage braking, the pressure in the brake cylinder of the electro-pneumatic brake reaches 0.53 MPa. The value obtained exceeds the permissible values for this equipment type, which may indicate a malfunction in the system of control or regulation. An increase in pressure makes the brake pads exert greater force on the wheels, which leads to rapid wear of the friction components and increases the risk for wheel sets to seize up, which has a negative impact on the safety of the rolling stock.

During the research, the operating time parameters of the electro-pneumatic brake were also recorded at the brake, lock and release modes. The duration of the respective modes was determined on the basis of an analysis of the levels and time characteristics of the electrical signals in the control circuit. The time parameters obtained characterised the response time of the braking system and helped to identify the potential delays or inconsistencies in the operation of individual system components.

The performance assessment of the proposed approach and visualisation of the diagnostics results were conducted by means of an analysis of the experimental data obtained during the investigation of the braking system (Figure 4). The results of this analysis are presented in the form of a distribution chart of diagnostic solutions, with which the ratio of correct-to-incorrect solutions can be evaluated.

It has been found that the use of the proposed diagnostic system reduces the number of incorrect solutions and ensures a more even distribution of diagnostic results. A comparison to the baseline version shows an increase in the proportion of correct solutions, which directly contributes to improved diagnostic accuracy.

The DSRB system for monitoring the braking systems of passenger cars provides a visual indication of the status of the braking equipment, enabling the current operating mode to be assessed promptly. Specifically, a green signal indicates the brake release, a yellow signal indicates partial braking, and a red signal indicates full braking, while a white or blue signal indicates that the pressure in the system has exceeded the permissible limit. This display system ensures that information is

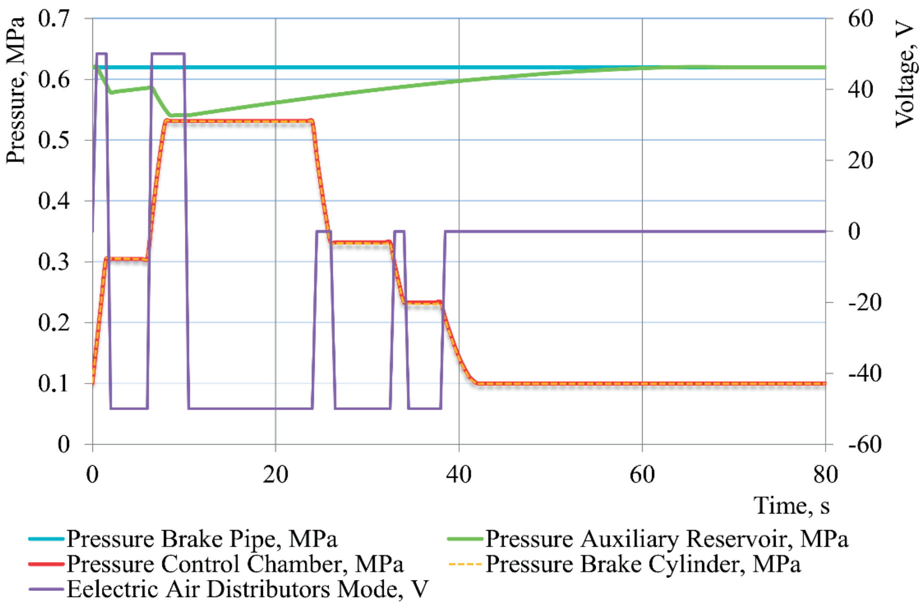

Figure 4 *The curves of pressures in the brake units during application of the electro-pneumatic brakes*

clearly visible and can quickly be understood by the support staff.

The diagnostic data is transmitted via both wired and wireless communication channels using modern telecommunications technologies, in particular GPS/GSM/GPRS and Wi-Fi, with the subsequent accumulation and storage of data on the server. This enables centralised monitoring of the condition of braking systems and subsequent analysis of the data collected.

The use of DSRB offers the following advantages:

- real-time diagnostics of electro-pneumatic braking systems;
- automatic detection and identification of malfunctions and faults;
- generation and transmission of alarm signals when parameters exceed permissible limits;
- timely information for the support staff on the current condition of the braking equipment; and
- collection and record of data on operating cycles of the brake systems for predicting their service life and technical condition.

The functional analysis of the capabilities of the DSRB shows that it plays a vital role in improving the road safety. In particular, during a simulated brake test, the system provides objective information on the actual condition of the brakes, shows the data on the driver's display and stores them in the archive.

The DSRB is a universal system and can be installed on passenger cars of various types and years of manufacture. From an economic perspective, the use of DSRB ensures the timely detection of faults and the transmission of information to maintenance depots or train making-up centres, thereby improving the efficiency of repair operations.

The use of DSRB in the operation of passenger cars on Ukrainian Railways makes it possible to improve the effectiveness of monitoring the technical condition of braking equipment; however, it requires a quantitative evaluation of the stability and reliability of the diagnostic results obtained, which requires the evaluation of the reliability of the control mechanisms.

The key criterion for evaluating the effectiveness of DSRB is the diagnostics accuracy rate. The accuracy of diagnosis is an integral measure of the quality of the DSRB's performance; it is determined by the correlation between the technical condition evaluated to the actual technical condition.

On the whole, the diagnostics accuracy reflects the reliability of solutions regarding the further use of brake system components. A high level of reliability helps to minimise the risks associated with both the unjustified removal of serviceable components and the further use of potentially faulty components, which is critical to ensuring the safety of passenger train operations.

In accordance with the adopted methodology [20], the total number of units to be diagnosed is denoted as A. Based on the results of the diagnostic test, one of the two recommendations can be given to each component:

- authorised for use, and
- use is prohibited.

The number of units approved for further operation is indicated as B, while the number of units for which the use is prohibited is indicated as C. This approach allows the decision-making process to be formalised and enables further quantitative analysis.

Once the diagnosis is complete, there are various possible options, which should be categorised according to the solution taken and the actual technical condition of the component.

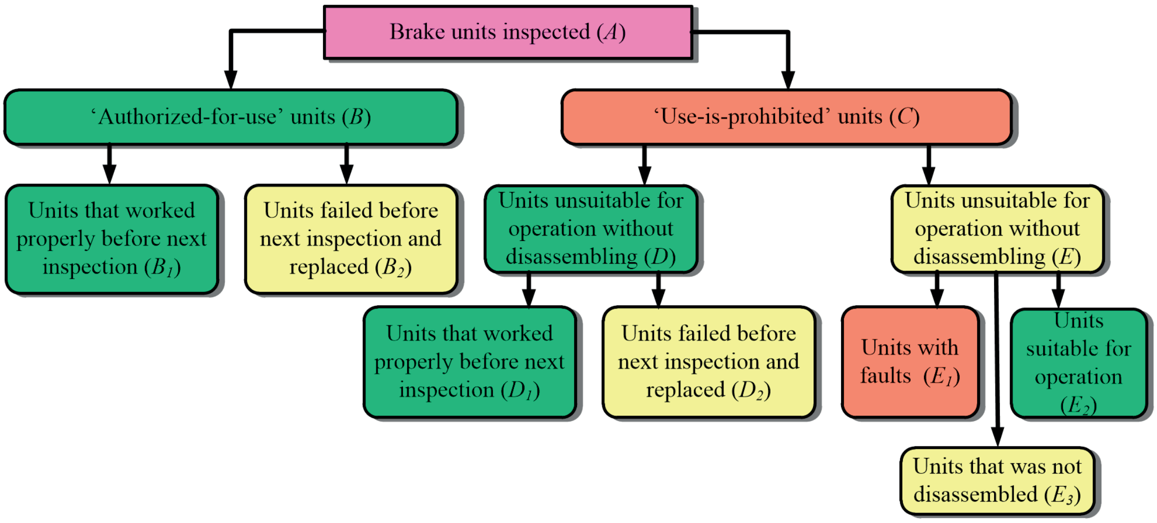

Figure 5 *The flowchart of events following diagnosis*

The units marked as use is prohibited must be removed from service (indicated as E):

- a unit disassembled during an inspection; a fault was confirmed (E_1);
- a unit disassembled; certified as in working order (E_2), misdiagnosed;
- a unit could not be dismantled; actual technical condition is unclear (E_3).

The units marked as use is prohibited, but approved for use without additional monitoring (marked as D):

- a unit operated without fault until the next inspection (D_1);
- a unit failed in operation (D_2), which could cause accidents or reduced road safety.

The quantitatively evaluation of the diagnostic accuracy was conducted with the ratio of correct diagnostic solutions to the total number of tests.

The diagnostic accuracy was evaluated using analytical dependency in Equation (1), which included the correct-to-incorrect solution ratio within the overall set of results.

$$H = \frac{E_1}{C} \times 100\% \,. \tag{1}$$

It should be noted that the standard calculation did not include the results for units marked as authorised for use (B). However, a significant number of such units (B1) functioned smoothly until the next inspection, but some of them (B2) failed, which indicated failures of the second kind (missed failures).

The range of possible outcomes following the diagnostic assessment can be conveniently presented as a flowchart (Figure 5), which allows all scenarios to be organised and their impact on the overall reliability index to be evaluated.

The overall diagnostic accuracy is determined using Equation (2) with the weight coefficients K_1, K_2, K_3, which indicate the extent of losses or damage due to incorrect solutions. Here, the normative condition is:

$$H = \left(K_1 \frac{B_1}{B} + K_2 \frac{E_1}{E - E_3} + K_3 \frac{D_2}{D} \right) \cdot 100\% \,, \tag{2}$$

where: K_1, K_2, K_3 are the coefficients characterizing the level of loss or damage due to incorrect solutions, and $K_1+K_2+K_3=1$.

The values of the specified coefficients K_1, K_2, K_3 depend on the type of rolling stock and the failure criticality. In particular, for passenger cars, the consequences of failures are more significant in terms of transport safety than for freight rolling stock, a factor that must be taken into account when selecting weight coefficients.

To simplify calculations in practical conditions, events D_2, D, E_3 are often neglected, since their probability is insignificant. In this case, a simplified version of Equation (3) is used, which provides sufficient accuracy in the estimation.

$$H = \left(K_1 \frac{B_1}{B} + K_2 \frac{E_1}{E} \right) \cdot 100\% \,. \tag{3}$$

Based on the results of tests, carried out in the laboratory of the Department of Rolling Stock Engineering and Product Quality at UrkSURT, the diagnostic equipment was tested and used at the rolling stock repair facilities of JSC "Ukrzaliznytsia" to assess the operational performance of the braking systems of passenger cars. Thus, the objective data on the technical condition of braking systems were obtained and the accuracy of the diagnostic equipment was assessed.

During the tests, 1,348 brake units (air distributors No. 292 and electric air distributors No. 305) of passenger cars were inspected, which provided a sufficient statistical selection for the further analysis. To improve the accuracy and reproducibility of measurement results, pressure sensors were fitted to each pneumatic cylinder and in the brake line. The measurements were taken at two control points for each unit, which made it possible to account for any local deviations in parameters and improve the informative value of the data obtained.

The approach adopted enabled a comprehensive diagnostic inspection to be carried out, during which each set of braking equipment underwent a full cycle of measurements, and key performance parameters were recorded. The results obtained can be used for further analysis of the technical condition of braking systems, as well as for assessing their reliability and performance under operational conditions, thereby providing a basis for a quantitatively substantiation of the accuracy of the measurements taken. In view of this, it is advisable to calculate the reliability of the results obtained using appropriate statistical methods [20].

Two options were considered for determining the reliability index:

1) based on the results of tests carried out in the testing laboratory on the test bench for diagnosing the braking systems of passenger cars, the relevant parameter values, characterising the diagnostic results, are:
   $A = 1348, E = 48, E_2 = 16, E_1 = E - E_2 = 32, B_2 = 5, B = A - E = 1300, B1 = B - B2 = 1295.$
2) based on the use of the test bench together with measures designed to improve the efficiency of brake system diagnostics. It is characterised by a reduction in the number of incorrect solutions and an improvement in the accuracy of assessing the technical condition of units:
   $A = 1348$, $E = 37$, $E_2 = 9$, $E_1 = E - E_2 = 28$, $B_2 = 5$, $B = A - E = 1311$, $B_1 = B - B_2 = 1306$.
   In accordance with Equation (3)
   for option 1)

$$H_1 = \left(K_1 \frac{1295}{1300} + K_2 \frac{32}{48}\right) \cdot 100\%\,, \tag{4}$$

for option 2)

$$H_2 = \left(K_1 \frac{1306}{1311} + K_2 \frac{28}{37}\right) \cdot 100\%\,, \tag{5}$$

at $K_1 = K_2 = 0.5$

for option 1)

$$H_1 = \left(0.5 \cdot \frac{1295}{1300} + 0.5 \cdot \frac{32}{48}\right) \cdot 100\% = 83.1\%\,, \tag{6}$$

for option 2)

$$H_2 = \left(0.5 \cdot \frac{1306}{1311} + 0.5 \cdot \frac{28}{37}\right) \cdot 100\% = 87.6\%\,. \tag{7}$$

The calculation using the Equation (1):
- for option 1)

$$H_1 = \frac{32}{48} \cdot 100\% = 66.7\%\,, \tag{8}$$

- for option 2)

$$H_2 = \frac{28}{37} \cdot 100\% = 75.7\%\,. \tag{9}$$

The calculations performed using Equations (3) and (6) - (9) demonstrated that, if taking additional factors into account, it had a significant impact on the reliability index. In particular, the difference between the calculation results is up to 16.4% and 11.9%, which highlights the importance of a comprehensive approach.

An analysis of the consequences of incorrect solutions shows that an “authorised-for-use” error is more critical than a “use-is-prohibited” error. In this regard, it is advisable to take the values of the coefficients $K_1 = 0.3$ and $K_2 = 0.7$, which reflect the greater weight of the risk of a missed fault.

By substituting in Equations (2) and (3) the new values of the coefficients K_1 and K_2, the following can be obtained:
for option 1)

$$H_1 = \left(0.3 \cdot \frac{1295}{1300} + 0.7 \cdot \frac{32}{48}\right) \cdot 100\% = 76.6\%\,, \tag{10}$$

for option 2)

$$H_2 = \left(0.3 \cdot \frac{1306}{1311} + 0.7 \cdot \frac{28}{37}\right) \cdot 100\% = 87.6\%\,. \tag{11}$$

The substitution of the refined coefficients into the calculation equations has revealed that the application of the developed measures can improve the diagnostics accuracy for brake units by approximately 6.3% compared with the baseline scenario.

4 Conclusions

1. An analysis of current braking control systems in passenger cars has revealed that they have limited efficiency in the early detection of technical faults. It has also been found that the typical shortcomings of control systems include the lack of detail in the monitored parameters, the difficulty of adapting these systems to different types of vehicles, and the limited capacity regarding the rapid transmission of diagnostic data. This reduces the efficiency of decision-making in terms of maintenance and hinders the implementation of preventive repair strategies.
2. A diagnostic system for the passenger car brakes has been developed, which provides comprehensive real-time monitoring of the operational parameters of the braking equipment and automatically detects faults. Experimental studies on a selection of 1,348 brake units have revealed that, if the pressure in the brake cylinder exceed 0.53 MPa during two-stage braking, it indicates malfunctions in the system and confirms the need to improve the diagnostic accuracy. The proposed system improves the

accuracy of diagnostics, ensures the timely detection of potential faults and lays the groundwork for more effective maintenance.

3. An approach has been developed for assessing the accuracy of diagnostics for the brake system, which is based on an analysis of the structure of diagnostic solutions and takes into account their correspondence to the actual technical condition and the weight factors of error criticality. The calculations show that the reliability index rises from 83.1% to 87.6%, and, when the weight factors are taken into account, the reliability index is in a range from 76.6% to 82.9%. The 6.3% improvement in reliability confirms the effectiveness of the solutions developed and the feasibility of their use in enhancing the operational reliability of the braking systems of passenger cars.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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