UDC 004.8: 620.9
IRSTI 67.07.11
RESEARCH ARTICLE

# EVALUATION OF A MOBILE DIAGNOSTIC LABORATORY BASED ON A ROAD-RAIL PLATFORM FOR ULTRASONIC RAIL INSPECTION

**Zh.O. Zhurynova[1], P.T. Akhmetova[1], G.S. Bikhozhayeva[1], G.B. Karibayeva[1], I.S. Bondar[2], K.S. Lesov[3]**

[1]ALT Mukhamedzhan Tynyshpayev University, 050012, Almaty, Kazakhstan
[2]Kazakh Automobile and Highway Institute named after L.B. Goncharov, 050061, Almaty, Kazakhstan
[3]Tashkent State Transport University, 100060, Tashkent, Uzbekistan

**Abstract.** *The increasing intensity of railway transportation requires reliable and sufficiently frequent technologies for monitoring the technical condition of rails and timely detection of internal and surface defects. Conventional ultrasonic inspection based on removable flaw-detection trolleys is effective for rail non-destructive testing; however, its application may be associated with limitations in mobility, deployment time, inspection continuity, and access to geographically distributed track sections. The aim of this study is to develop and experimentally evaluate a mobile diagnostic laboratory (MDL) based on a road-rail platform for continuous ultrasonic inspection of railway rails under operational conditions. The scientific novelty consists in the experimental investigation of an integrated road-rail diagnostic platform equipped with wheeled ultrasonic transducers and in the comparative assessment of its flaw patterns against those obtained using conventional ultrasonic inspection equipment. Field tests were conducted under operational railway conditions to assess the continuity, stability, mobility, and diagnostic performance of the proposed system. The results demonstrated the operational feasibility of the MDL and showed its potential to improve the mobility, continuity, and organizational efficiency of ultrasonic rail inspection. The practical significance of the study lies in the possibility of deploying the MDL for flexible inspection of extensive railway networks while reducing dependence on conventional removable flaw-detection equipment and associated logistical arrangements.*

**Keywords:** *mobile diagnostic laboratory; road-rail platform; rail flaw detection; ultrasonic testing; non-destructive testing; wheeled ultrasonic transducers; railway inspection; rail defects.*

***Corresponding author**
**Ivan Sergeevich Bondar**, e-mail: ivan_sergeevich_08@mail.ru



https://doi.org/10.51488/1680-080X/2026.3-07

ӘОЖ 004.8: 620.9
ҒТАМР 67.07.11
ҒЫЛЫМИ МАҚАЛА

# РЕЛЬСТЕРДІ УЛЬТРАДЫБЫСТЫҚ БАҚЫЛАУҒА АРНАЛҒАН АВТОМОБИЛЬ-ТЕМІРЖОЛ ПЛАТФОРМАСЫ НЕГІЗІНДЕ МОБИЛЬДІ ДИАГНОСТИКАЛЫҚ ЗЕРТХАНАНЫ БАҒАЛАУ

**Ж.О. Журынова[1], П.Т. Ахметова[1], Г.С. Бихожаева[1], Г.Б. Карибаева[1], И.С. Бондарь[2], К.С. Лесов[3]**

[1]ALT Мұхамеджан Тынышпаев атындағы университет, 050012, Алматы, Қазақстан
[2]Л.Б. Гончаров атындағы Қазақ автомобиль-жол институты, 050061, Алматы, Қазақстан
[3]Ташкент Мемлекеттік көлік университеті, 100060, Ташкент, Өзбекстан

**Аңдатпа.** *Теміржол тасымалының өсіп келе жатқан қарқындылығы рельстердің техникалық жағдайын бақылаудың сенімді және жиі технологияларын және ішкі және жер үсті ақауларын уақтылы анықтауды талап етеді. Алынбалы дефектоскопиялық арбаларға негізделген әдеттегі ультрадыбыстық бақылау рельсті бұзбайтын бақылау үшін тиімді, бірақ оны қолдану ұтқырлықтың шектеулеріне, орналастыру уақытына, бақылаудың үздіксіздігіне және географиялық бөлінген жол учаскелеріне қол жеткізуге байланысты болуы мүмкін. Бұл зерттеудің мақсаты пайдалану жағдайында теміржол рельстерін үздіксіз ультрадыбыстық бақылауға арналған автомобиль-теміржол платформасы негізінде мобильді диагностикалық зертхананы (MDL) әзірлеу және эксперименттік бағалау болып табылады. Ғылыми жаңалық-доңғалақтардағы ультрадыбыстық түрлендіргіштермен жабдықталған интеграцияланған автомобиль-теміржол диагностикалық платформасын эксперименттік зерттеу және әдеттегі ультрадыбыстық бақылау жабдығымен алынған ақаулардың сипатын салыстырмалы бағалау. Ұсынылған жүйенің үздіксіздігін, тұрақтылығын, ұтқырлығын және диагностикалық сипаттамаларын бағалау үшін теміржолды пайдалану жағдайында далалық сынақтар жүргізілді. Нәтижелер MDL-дің жұмыс істеу мүмкіндігін көрсетті және оның рельсті ультрадыбыстық бақылаудың ұтқырлығын, үздіксіздігін және ұйымдастырушылық тиімділігін арттыру әлеуетін көрсетті. Зерттеудің практикалық маңыздылығы кәдімгі алынбалы дефектоскопиялық жабдыққа және онымен байланысты логистикалық іс-шараларға тәуелділікті азайта отырып, кең теміржол желілерін икемді бақылау үшін MDL қолдану мүмкіндігі болып табылады.*

**Түйінді сөздер:** *жылжымалы диагностикалық зертхана; автомобиль және теміржол платформасы; рельстік ақаулар; ультрадыбыстық бақылау; бұзбайтын бақылау; доңғалақты ультрадыбыстық түрлендіргіштер; теміржол бақылауы; рельстердегі ақаулар.*

***Автор-корреспондент**
**Иван Сергеевич Бондарь**, e-mail: ivan_sergeevich_08@mail.ru



https://doi.org/10.51488/1680-080X/2026.3-07

УДК 004.8: 620.9
МРНТИ 67.07.11
НАУЧНАЯ СТАТЬЯ

# ОЦЕНКА МОБИЛЬНОЙ ДИАГНОСТИЧЕСКОЙ ЛАБОРАТОРИИ НА БАЗЕ АВТОМОБИЛЬНО-ЖЕЛЕЗНОДОРОЖНОЙ ПЛАТФОРМЫ ДЛЯ УЛЬТРАЗВУКОВОГО КОНТРОЛЯ РЕЛЬСОВ

**Ж.О. Журынова[1], П.Т. Ахметова[1], Г.С. Бихожаева[1], Г.Б. Карибаева[1], И.С. Бондарь[2], К.С. Лесов[3]**

[1]ALT Университет имени Мухамеджана Тынышпаева, 050012, Алматы, Казахстан
[2]Казахский автомобильно-дорожный институт им. Л.Б. Гончарова, 050061, Алматы, Казахстан
[3]Ташкентский государственный транспортный университет, 100060, Ташкент, Узбекистан

**Аннотация.** *Растущая интенсивность железнодорожных перевозок требует надежных и достаточно частых технологий мониторинга технического состояния рельсов и своевременного выявления внутренних и поверхностных дефектов. Обычный ультразвуковой контроль, основанный на съемных дефектоскопических тележках, эффективен для неразрушающего контроля рельсов, однако его применение может быть связано с ограничениями в мобильности, времени развертывания, непрерывности контроля и доступе к географически распределенным участкам пути. Целью данного исследования является разработка и экспериментальная оценка мобильной диагностической лаборатории (MDL) на базе автомобильно–железнодорожной платформы для непрерывного ультразвукового контроля железнодорожных рельсов в условиях эксплуатации. Научная новизна заключается в экспериментальном исследовании интегрированной автомобильно-железнодорожной диагностической платформы, оснащенной ультразвуковыми преобразователями на колесах, и в сравнительной оценке характера дефектов, полученных с помощью обычного оборудования для ультразвукового контроля. Полевые испытания были проведены в условиях эксплуатации железной дороги для оценки непрерывности, стабильности, мобильности и диагностических характеристик предлагаемой системы. Результаты продемонстрировали возможность эксплуатации MDL и показали ее потенциал для повышения мобильности, непрерывности и организационной эффективности ультразвукового контроля рельсов. Практическая значимость исследования заключается в возможности применения MDL для гибкого контроля обширных железнодорожных сетей при одновременном снижении зависимости от обычного съемного дефектоскопического оборудования и связанных с ним логистических мероприятий.*

**Ключевые слова:** *передвижная диагностическая лаборатория; автомобильно-железнодорожная платформа; дефектоскопия рельсов; ультразвуковой контроль; неразрушающий контроль; колесные ультразвуковые преобразователи; железнодорожный контроль; дефекты рельсов.*

***Автор-корреспондент**
**Иван Сергеевич Бондарь**, e-mail: ivan_sergeevich_08@mail.ru



https://doi.org/10.51488/1680-080X/2026.3-07

## 1 INTRODUCTION

The reliability and safety of railway and urban rail infrastructure are essential for maintaining sustainable passenger and freight transportation. Railway lines, tram networks, light rail systems, and commuter railways operate under repeated mechanical and environmental loads throughout their service life. Increasing traffic intensity, higher transportation demands, and the need to maintain infrastructure in an appropriate technical condition require effective approaches to the continuous inspection and timely detection of defects in track components.

Rails are among the most critical elements of railway and tram infrastructure because they directly receive repeated loads from moving rolling stock and transfer these loads to the supporting track structure. During operation, rails may develop fatigue damage, internal discontinuities, surface defects, and other forms of structural degradation. The detection and quantitative assessment of hidden rail cracks remain important tasks of non-destructive testing because such defects may not be identifiable by conventional visual inspection alone [1,3,16]. Operational measurements have also demonstrated the importance of assessing stresses arising in rails under the influence of moving rolling stock [12]. If rail defects remain undetected, they may contribute to deterioration of track performance and increase maintenance requirements. In urban rail and tram systems, the condition of rails is also important because deterioration of track components may affect dynamic interaction and the operational characteristics of the system [13-15]. These factors emphasize the need for reliable and sufficiently frequent non-destructive testing (NDT) of rails throughout their service life.

Conventional rail inspection systems generally combine visual and measuring inspection with ultrasonic, magnetic, eddy-current, and other non-destructive testing methods. Ultrasonic testing (UT) is particularly important for detecting internal rail defects that may not be visible from the surface, and ultrasonic phased-array techniques have been investigated for improving the capabilities of rail flaw detection [1]. Magnetic and eddy-current methods provide complementary information concerning surface and near-surface discontinuities and require appropriate processing of the resulting defectograms [4-7,17,20]. Visual inspection and computer-vision methods can additionally be used to identify visible rail and track-component defects, including elements such as rail fasteners [2]. The combined use of these methods provides a comprehensive basis for assessing rail condition; however, their practical effectiveness depends not only on the physical measurement principle but also on the organization, mobility, accessibility, and continuity of inspection operations.

In Kazakhstan and the Russian Federation, rail NDT procedures and equipment are regulated by a range of national and international standards. Visual and measuring inspection, ultrasonic testing, ultrasonic thickness measurement, piezoelectric transducers, and magnetic inspection are addressed by relevant GOST and international standards, including GOST 23829-85, GOST R 55724-2013, GOST R 55614-2013, GOST R ISO 16809-2015, GOST R 55725-2013, GOST R 55808-2013, GOST 24450-80, and applicable EN ISO and ASTM standards. These regulatory requirements provide a technical basis for the organization of rail inspection and the use of specialized diagnostic equipment.

Despite the established regulatory and technical framework, the organization of rail flaw detection on extensive railway and urban rail networks remains associated with several practical limitations. Conventional inspection may involve portable flaw-detection trolleys, specialized diagnostic vehicles, and personnel who must be transported to designated sections of infrastructure. Such arrangements can complicate access to remote or spatially distributed track sections, require coordination of inspection windows, and increase the organizational resources needed to maintain regular inspection schedules. The problem becomes particularly relevant on long railway lines and in urban agglomerations, where diagnostic operations must be coordinated with intensive train or tram traffic and where the available time for inspection may be limited.

The development of mobile diagnostic technologies provides an opportunity to address some of these limitations. Recent studies have investigated ultrasonic inspection [1,3], visual inspection and computer vision [2,8-11,19], magnetic and eddy-current testing [4-7,17,20], and the processing and automated interpretation of diagnostic signals [4-7,20]. These studies demonstrate the increasing role of automated data processing in railway inspection. Computer-vision and deep-learning



https://doi.org/10.51488/1680-080X/2026.3-07

approaches have been applied to rail surface defect detection and classification using different neural-network architectures, including convolutional neural networks, Mask R-CNN, YOLOv4, YOLOv5s, and other deep-learning models [8-11,19]. At the same time, digital processing methods have been developed to improve the extraction and interpretation of useful information from magnetic and eddy-current defectograms [4-7,20]. However, these developments primarily concern individual diagnostic technologies or data-processing procedures, whereas the organizational and technological problem of providing continuous rail inspection using a highly mobile platform remains insufficiently addressed.

Particular attention should therefore be given to mobile diagnostic systems capable of combining transportation and measurement functions. Existing portable flaw-detection trolleys are directly adapted for movement along the railway track but require access to the track and the organization of personnel and equipment at the inspection location. Specialized diagnostic vehicles provide greater equipment capacity and productivity but are generally designed specifically for railway operation and may require additional logistics for reaching infrastructure sections that are not directly accessible by rail. A road-rail platform provides a different organizational concept by integrating the mobility of a road vehicle with the ability to operate on railway infrastructure. Such a configuration may reduce the dependence of diagnostic operations on separate transportation arrangements and facilitate access to geographically distributed inspection locations.

The research gap addressed in the present study concerns the limited experimental investigation of mobile diagnostic laboratories implemented on road-rail platforms for continuous ultrasonic rail inspection under operational conditions. Although mobile and automated rail inspection technologies have been widely studied, comparatively less attention has been given to a platform that integrates transportation, ultrasonic diagnostic equipment, and operator-controlled inspection functions within a single mobile unit. In particular, experimentally supported comparisons between defect patterns obtained using such a mobile laboratory and conventional rail flaw-detection equipment remain limited. Addressing this gap is important for determining whether the proposed mobile configuration can provide sufficiently consistent diagnostic information while improving the mobility and continuity of inspection operations.

The scientific problem of the study is therefore formulated as the need to improve the organization of rail flaw detection by combining the mobility of a road–rail vehicle with the functionality of a continuous ultrasonic inspection system. The problem is not limited to the development of an individual ultrasonic sensor or a new signal-processing algorithm. Rather, it concerns the practical implementation of a mobile diagnostic laboratory in which the transport platform and diagnostic equipment operate as an integrated field unit.

The aim of this study is to develop and experimentally evaluate a mobile diagnostic laboratory (MDL) based on a road-rail platform for continuous ultrasonic inspection of railway rails under operational conditions. To achieve this aim, the following objectives were defined:

– to analyze the existing organization and technical arrangements used for rail flaw detection;

– to develop the concept and technical configuration of a mobile diagnostic laboratory based on a combined road–rail platform;

– to conduct operational tests of continuous ultrasonic rail inspection using the developed mobile laboratory;

– to compare defect patterns obtained using the MDL with the results of conventional rail diagnostic equipment; and

– to evaluate the operational effectiveness of the proposed configuration in terms of inspection continuity, mobility, diagnostic consistency, and organizational requirements.

The literature reviewed in this study can be grouped into several complementary research directions. The first concerns the development of physical NDT methods. Studies [1,3] have investigated ultrasonic approaches for rail inspection, including ultrasonic phased-array techniques and methods for the detection and quantitative assessment of hidden rail cracks. Other studies [4-7,17,20] have examined magnetic and eddy-current inspection and the processing and automated interpretation of corresponding diagnostic signals. These approaches demonstrate the continuing



https://doi.org/10.51488/1680-080X/2026.3-07

development of physical measurement technologies and their potential for automation.

A second research direction concerns automated visual and digital interpretation of inspection data. Studies [2,8-11,19] have investigated computer-vision and deep-learning methods for the identification and classification of railway defects and track components. These include automated visual inspection of railway components [2], deep-learning methods for rail surface defect detection [8-11], and neural-network-based diagnostics of railway track elements [19]. Such methods can provide rapid processing and automated classification when sufficiently representative training datasets are available. However, their effectiveness depends on the quality and representativeness of the input data and on the specific operating conditions under which the inspection system is used. Consequently, digital and artificial-intelligence methods should be considered complementary to, rather than a replacement for, reliable physical measurements of rail condition.

A third research direction concerns the mechanical and dynamic behavior of railway infrastructure. Operational measurements of rail stresses under moving rolling stock have been reported in [12], while the performance of intermediate rail fastenings under operational loading has been investigated in [13]. Experimental studies of the dynamic properties of soils in railway embankments are presented in [14], and issues related to the safe operation of railway artificial structures have been considered in [15]. These studies demonstrate the importance of considering the mechanical response of rails, track components, and supporting infrastructure under operational loading. However, such measurements generally provide complementary information about the structural and operational condition of railway infrastructure and do not replace direct NDT techniques when internal rail discontinuities must be identified.

A fourth research direction concerns digital technologies and automated processing for infrastructure monitoring. Internet-of-Things technologies have been investigated for urban rail transit signal and control applications [18], while digital signal-processing approaches have been developed for the suppression of interference in eddy-current defectograms. Together with neural-network-based approaches [6,8-11,19], these studies demonstrate the potential for combining sensors, computational methods, and digital information systems to improve railway inspection and monitoring. However, the integration of information technologies does not by itself resolve the practical problem of delivering a mobile physical diagnostic system to different infrastructure sections and maintaining continuous ultrasonic inspection under operational conditions.

Thus, existing research demonstrates substantial progress in individual NDT methods, automated data processing, visual inspection, and digital infrastructure monitoring. Nevertheless, these developments do not fully address the organizational and mobility requirements associated with continuous field inspection over extensive railway and urban rail networks. In particular, there is a need for experimental assessment of mobile diagnostic configurations that can combine road mobility with direct operation on railway infrastructure and integrate the necessary ultrasonic inspection equipment within a single platform.

The proposed MDL addresses this gap by combining the functions of a transport platform and a diagnostic laboratory. Its distinguishing feature is not the introduction of a fundamentally new ultrasonic measurement principle, but the integration of an established ultrasonic rail inspection technology into a mobile road-rail platform and its experimental evaluation under operational conditions. This approach makes it possible to assess the feasibility of continuous rail inspection while reducing the dependence of diagnostic operations on separate transportation and deployment arrangements.

The scientific novelty of the study lies in the experimental investigation of a mobile diagnostic laboratory based on a road-rail platform for continuous ultrasonic rail inspection under operational conditions. The study provides experimental evidence concerning the applicability of this configuration and compares the defect patterns obtained using the mobile laboratory with those obtained using conventional diagnostic equipment. In contrast to studies focused primarily on individual NDT technologies or automated data-processing algorithms [1-11,16,17,19,20], the present work considers the mobility and organizational implementation of the diagnostic system as an integral part of the inspection process.



https://doi.org/10.51488/1680-080X/2026.3-07

The practical significance of the study is associated with the potential use of the proposed MDL for improving the accessibility and continuity of rail inspection on extensive railway and urban rail networks. The proposed configuration may facilitate the deployment of diagnostic equipment to different infrastructure sections, reduce organizational constraints associated with conventional inspection arrangements, and provide a basis for more flexible scheduling of ultrasonic rail examinations. The obtained experimental results can also contribute to the further development of mobile railway diagnostic systems and their integration into broader digital infrastructure-monitoring frameworks.

Overall, the study is focused on the experimentally supported evaluation of a mobile road-rail diagnostic concept, rather than on the development of a new artificial-intelligence algorithm or a universal multimodal diagnostic system. This positioning provides direct consistency between the identified research gap, the study objectives, the experimental methodology, and the claimed scientific novelty.

## 2 MATERIALS AND METHODS

### *2.1 Experimental object and mobile diagnostic laboratory*

The experimental object was a mobile diagnostic laboratory (MDL) designed for continuous non-destructive testing of railway rails under operational conditions. The MDL was manufactured by JSC Radioavionika (St. Petersburg, Russia) and equipped with ultrasonic rail flaw-detection equipment and auxiliary non-destructive testing devices.

Organization of the field experiment.

The field tests were conducted by a working group of JSC NC KTZ with scientific and technical support from specialists of the Testing of Tracks and Artificial Structures laboratory of ALT University named after M. Tynyshpayev (Doctor of Technical Sciences - S.S. Khasenov, Candidate of Technical Sciences - M.Ya. Kvashnin, Candidate of Technical Sciences., Ph. D -I.S. Bondar).

The MDL was installed on a road-rail platform, which enabled movement along the railway track while performing continuous ultrasonic inspection. A converted railway wagon No. 24543 was used as a service and storage wagon for transportation and accommodation of the diagnostic equipment. The general configuration of the MDL and its main equipment is presented in Figures 1-3.




**Figure 1 –** General view of the mobile diagnostic laboratory on the road–rail platform [Authors' material]



https://doi.org/10.51488/1680-080X/2026.3-07




a) b)

**Figure 2** – MDL flaw detection equipment (a) Front view of the meter; (b) Side view of the meter [Authors' material]



**Figure 3 –** Converted wagon No. 24543 for a "garage car" for transporting "MDL" [Authors' material]

A principal feature of the tested configuration was the use of wheeled ultrasonic transducers instead of conventional sliding transducers. The wheeled transducers were designed to maintain stable acoustic contact with the rail surface during movement. Their elastic contact shell allowed the transducer to follow local irregularities of the rail surface, including irregularities occurring in rail joint areas.

The diagnostic system was supplemented by the locomotive on-board safety system «Bort», which was used to ensure safe movement of the MDL during the experimental runs.

*2.2. Test site and operating conditions*

The experimental tests were performed on the IZHU Iletsk railway site in the Orenburg Region, Russia, including the Sol-Iletsk area. The investigated railway infrastructure comprised 13 separate operational points, including five stations and eight sidings. The railway network included single-track sections, main tracks with a total length of 156.99 km, station tracks with a total length of 94.3 km, and access tracks with a total length of 19.5 km.

The annual freight traffic intensity of the investigated section was approximately 18.41 million gross ton-km/km. The test infrastructure included 53 curved track sections with a combined length of approximately 21.0 km and 24 railway crossings.

The field experiment was conducted under normal railway operating conditions. Measurements were performed during daytime operation and under seasonal environmental conditions, including naturally occurring precipitation and ambient temperature variations. The MDL operated within closed technological windows, during which the required track-access and safety procedures were implemented.



https://doi.org/10.51488/1680-080X/2026.3-07

The selected test site was considered suitable for evaluating the operational performance of the MDL because it contained different track configurations, rail joints, curved sections, crossings, and areas with potentially increased difficulty for ultrasonic inspection.

*2.3. Experimental design and comparative inspection procedure*

The experimental study was designed to evaluate the applicability of continuous ultrasonic rail inspection using the MDL and to compare its indications with those obtained using conventional removable ultrasonic inspection equipment.

The principal experimental sequence consisted of two complementary inspection procedures. First, the investigated track section was inspected continuously by the MDL using wheeled ultrasonic transducers. Second, on the same day, the corresponding section was additionally inspected using a conventional removable two-rail flaw-detection trolley equipped with ultrasonic inspection equipment and a recorder.

Thus, the comparison was performed under approximately identical track and environmental conditions and within the same operational period. This approach reduced the influence of changes in rail condition, temperature, moisture, and other time-dependent factors on the comparison.

A total of 120 km of railway track was examined during the MDL field tests. During each MDL inspection, the ultrasonic responses generated by the rail were continuously recorded together with the location of the detected indications and the operating parameters of the diagnostic laboratory.

The conventional flaw-detection trolley was used as the comparative inspection system. Its results were subsequently compared with the MDL flaw patterns. The comparison was focused particularly on rail joint areas, where the quality of acoustic contact and the complex geometry of the inspected zone can adversely affect conventional sliding ultrasonic transducers.

The experimental workflow was therefore:

1. preparation and functional verification of the MDL;
2. inspection of the designated railway section using wheeled ultrasonic transducers;
3. continuous recording of ultrasonic responses and MDL operating parameters;
4. localization of indications associated with possible rail discontinuities;
5. inspection of the corresponding track section using the conventional removable flaw-detection trolley;
6. comparison of the resulting flaw patterns;
7. analysis of signal stability, zero-line behavior, localization of indications, and detection of discontinuities;
8. evaluation of the applicability of the wheeled-transducer configuration for continuous rail inspection.

*2.4. Ultrasonic inspection system and control parameters*

Ultrasonic testing was performed using piezoelectric ultrasonic transducers operating at a nominal frequency of 2.5 MHz with a tolerance of ±10%.

Different ultrasonic wave incidence angles were used to inspect the principal structural zones of the rail, including the rail head, web and foot. The applied incidence angles were 0°, 45 ± 2°, and 70 ± 3°, depending on the inspected zone and sound path.

Both pulse-echo and mirror (through-transmission/reflection) inspection schemes were used. The combination of different incidence angles and sound paths provided ultrasonic coverage of the principal rail cross-sectional regions. The main parameters used for the ultrasonic inspection are summarized in Table 1.

*2.5. Inspection of aluminothermite-welded rail joints*

A separate part of the experimental analysis concerned the ultrasonic inspection of aluminothermite-welded rail joints. These zones were selected because their geometric configuration and metallurgical structure can complicate ultrasonic wave propagation and may produce unstable signals or local losses of sensitivity.



https://doi.org/10.51488/1680-080X/2026.3-07

For each inspected joint, the ultrasonic system recorded the response of the control channels corresponding to the rail head, web and foot. The recorded information was used to characterize the position and intensity of ultrasonic indications and to determine whether the indication corresponded to a potentially significant discontinuity.

The analysis considered the following parameters:

- coordinates of the indication;
- amplitude of the ultrasonic echo response;
- control channel and inspection zone;
- probe angle and sound path;
- estimated dimensions of the discontinuity;
- sensitivity level at which the indication was recorded;
- stability of the signal and zero line;
- correspondence of the indication with the result obtained using conventional inspection equipment.

The minimum detectable discontinuity size depended on the inspection zone and ultrasonic sound path. The experimental configuration provided sensitivity to discontinuities in the order of approximately 3-6 mm, depending on the direction of ultrasonic wave propagation and the inspected rail zone.

*2.6. Recording and localization of ultrasonic indications*

During MDL movement, the ultrasonic signals were continuously recorded by the diagnostic system. The recorded data were associated with the position of the MDL along the railway track, allowing individual indications to be spatially localized.

For each indication considered relevant for subsequent analysis, the following information was extracted from the recorded flaw pattern:

$$I_i = \{x_i, A_i, Z_i, a_i, S_i\} \quad (1)$$

where $x_i$ - is the longitudinal coordinate of the indication, $A_i$ - is the recorded signal amplitude, $Z_i$ - is the inspected rail zone, $\alpha_i$ - is the ultrasonic probe angle, and $S_i$ - is the corresponding sensitivity level.

This representation enabled the MDL results to be compared with the indications obtained from the conventional removable flaw-detection trolley.

Particular attention was paid to the stability of the zero line. An offset of the zero line can affect the interpretation of flaw patterns and may lead to incorrect assessment of the amplitude of the recorded response. Therefore, the stability of the baseline was considered an important diagnostic quality parameter.

The examples of acceptable and critical zero-line displacement obtained during the experiment are presented in Figure 4.

*2.7. Reference inspection and comparison of flaw patterns*

The results obtained using the MDL were compared with the results of the conventional removable two-rail flaw-detection trolley operated on the same track section during the same day.

The conventional inspection was used as the reference comparative method, rather than as an independent absolute ground truth. This distinction is important because the purpose of the experiment was primarily to evaluate the practical agreement and operational applicability of the MDL rather than to establish an absolute probability of detection for all possible rail defects.

The comparison was based on three principal characteristics:

−spatial correspondence - whether an MDL indication was located in the same rail section as an indication obtained using the conventional equipment;

−signal correspondence - whether the two systems produced responses associated with the same ultrasonic discontinuity or rail-joint feature;



https://doi.org/10.51488/1680-080X/2026.3-07

–classification correspondence - whether the indication was interpreted as requiring further assessment or inspection by both methods.

Where the two inspection systems produced indications in the same rail location, the signals were treated as corresponding indications. Indications detected only by one system were analyzed separately to determine whether they were related to differences in inspection principle, acoustic coupling, signal stability, or the geometry of the inspected rail zone.

Because the available experimental data do not provide a separately verified independent ground-truth database, the comparison is reported in terms of agreement and correspondence of flaw patterns, rather than an absolute diagnostic accuracy.

*2.8. Criteria for identification of potentially defective joints*

A rail joint was considered potentially defective when the ultrasonic response satisfied the established control criteria.

The interpretation procedure considered three principal conditions:

$$A_{echo} > A_{th}, \left[x_{MDL} - x_{ref}\right] \leq \Delta x, \text{ and } L_{disc} > 5\ mm \quad (2)$$

where $A_{echo}$ - is the recorded echo amplitude, $A_{th}$ - is the applicable threshold level, $X_{MDL}$ and $x_{ref}$ - are the coordinates of corresponding indications obtained by the MDL and reference inspection, respectively, Δx - is the accepted localization difference, and $L_{disc}$ - is the estimated linear dimension of the discontinuity.

The experimental results indicated that signal amplitude was the most sensitive parameter for identification of potentially defective areas, whereas geometric localization was associated with the greatest uncertainty. The observed localization deviations could reach approximately 10-15% relative to the actual position under the tested conditions.

Importantly, the value of Δx used for formal statistical classification should be specified from the original test protocol if a quantitative event-by-event agreement analysis is subsequently performed. The available experimental description does not provide an independent numerical tolerance that would justify introducing an additional value.

*2.9. Assessment of signal stability and zero-line displacement*

In addition to defect indications, the quality of the recorded ultrasonic flaw patterns was evaluated using the stability of the zero line.

Two characteristic signal conditions were distinguished:

– a relatively small zero-line displacement that did not prevent interpretation of the ultrasonic response;

– a critical zero-line displacement that could interfere with normal operation of the corresponding inspection channel.

These two cases are illustrated in Figure 4.

The assessment of zero-line stability was particularly important for continuous inspection because the MDL operates while moving along the track. Changes in acoustic contact, rail-surface condition and dynamic interaction between the wheeled transducer and the rail can influence the baseline of the recorded ultrasonic signal.

The wheeled-transducer configuration was therefore evaluated not only according to the presence or absence of flaw indications, but also according to the stability of the ultrasonic recording during continuous movement.

*2.10. Data processing*

The recorded ultrasonic data were processed in several stages. First, the raw signals were reviewed to identify unstable or noise-dominated segments. Second, the signals were normalized



https://doi.org/10.51488/1680-080X/2026.3-07

where necessary to facilitate comparison between control channels. Third, indications were localized according to their longitudinal position along the track.

The processed MDL flaw patterns were then compared with the corresponding records obtained from the conventional flaw-detection trolley.

The comparative analysis included:

- identification of common indications;
- identification of MDL-only indications;
- identification of reference-method-only indications;
- comparison of signal amplitude;
- analysis of zero-line displacement;
- assessment of localization differences;
- assessment of the influence of the inspected rail zone;
- assessment of the influence of the ultrasonic sound path.

For a sufficiently documented set of reference defects, the correspondence between the two methods can be expressed as:

$$C = \frac{N_{match}}{N_{ref}} \cdot 100\% \quad (3)$$

where $N_{match}$ - is the number of MDL indications corresponding to indications detected by the reference method, and $N_{ref}$ - is the total number of reference indications.

However, because the available field-test records presented here do not contain a complete event-by-event inventory of confirmed defects, the coefficient CC was not used as an independently validated probability-of-detection metric.

*2.11. Evaluation of the MDL operational performance*

The operational performance of the MDL was evaluated using the following criteria:

1. continuity of ultrasonic monitoring during movement;
2. stability of ultrasonic signal recording;
3. maintenance of acoustic contact between the wheeled transducers and the rail;
4. ability to inspect rail joints and other geometrically complex sections;
5. localization of potentially defective areas;
6. correspondence between MDL and conventional flaw-detection patterns;
7. compatibility of the diagnostic system with safe railway operation.

The principal advantage expected from the wheeled-transducer configuration was improved acoustic contact with the rail compared with sliding transducers. The elastic wheel shell allows the transducer to follow local rail-surface irregularities and therefore potentially reduces the deterioration of ultrasonic coupling in rail-joint areas.

The experimental comparison was consequently focused on the practical ability of the MDL to maintain continuous inspection and obtain interpretable ultrasonic flaw patterns under actual railway operating conditions.

*2.12. Experimental reproducibility and limitations of the methodology*

The experimental procedure was standardized with respect to the ultrasonic frequency, probe angles, sensitivity settings, inspection zones, recording procedure and comparative inspection approach. The MDL and conventional inspection trolley examined the corresponding railway section during the same day, thereby providing comparable environmental and track conditions.

Nevertheless, several methodological limitations should be considered.

First, ultrasonic sensitivity depends on the quality and stability of acoustic contact between the transducer and rail. Second, the complex geometry of welded and joint areas can distort ultrasonic wave propagation and affect the localization and sizing of discontinuities. Third, the reported



https://doi.org/10.51488/1680-080X/2026.3-07

sensitivity parameters apply to the 2.5 MHz ultrasonic configuration used in the experiment and should not automatically be generalized to other frequencies or transducer types.

In addition, the available experimental dataset does not contain a complete independently verified inventory of all physical rail defects, nor does it provide sufficient information to calculate a statistically independent probability of detection, false-positive rate, or repeatability coefficient. Therefore, the present study focuses on the operational applicability, signal stability, localization of indications, and comparative correspondence of MDL and conventional flaw-detection results.

The field tests covered 120 km of railway track, providing an operational basis for evaluating the proposed continuous ultrasonic inspection technology. Further repeated runs under different speeds, temperatures, rail-surface conditions and defect configurations are required for a statistically rigorous assessment of repeatability and probability of detection.

## 3 RESULTS AND DISCUSSION

Table 1 contains detailed information about the characteristics of defects (coordinates, dimensions, minimum sensitivity).

**Table 1** – Main ultrasonic inspection parameters for aluminothermite-welded rail joints [Authors' material]

| Rail Inspection Zone | | Rail Head | | | | Rail Web | | | Rail Foot (Base) |
|---|---|---|---|---|---|---|---|---|---|
| Inspection Method | | Pulse-Echo | | | Mirror | Pulse-Echo | | Mirror | Pulse-Echo |
| Main Inspection Parameters | Frequency, *f* (MHz) | 2,5±10% | | | | 2,5±10% | | | 2,5±10% |
| | Probe Angle, *α* (deg) | 0 | 45±2 | 70±3 | 45±2 | 0 | 70±3 | 45±2 | 70±3 |
| | Sensitivity Coefficient, *Ku/Ke* (dB) | Кэ = 20 | Ky = 16 | Ky = 16 | Ky = 18 | Кэ = 20 | Ky = 16 | Ky = 18 | Ky = 16 |
| | Dead Zone, *M* (mm) | ≤6 | - | ≤3 | - | ≤6 | ≤3 | - | ≤3 |
| Sound scheme | | From the skating surface | From the rolling surface and from the sides of the head | | From the sides of the head | From the skating surface | From the surface of the neck | From the skating surface | From the upper surfaces of the sole feathers |
| Wave Type | | Longitudinal | Shear (Transverse) | | | Longitudinal | Shear (Transverse) | | Shear (Transverse) |

*Note: The sensitivity coefficients and dead-zone values correspond to the ultrasonic control configuration used during the field tests.*

*Analysis of the results of ultrasonic inspection of welded joints of rails*

The ultrasonic inspection of aluminothermite welded joints of rails made it possible to establish the quantitative parameters of the detected defects and to clarify the criteria for their identification depending on the control zone (head, neck, sole). The main sound modes are shown in Table 1 and include a frequency of 2.5 ± 10% MHz converters, input angles of 0°, 45±2° and 70±3°, as well as threshold sensitivity levels (Ce = 20 dB, Cu = 16-18 dB).

The analysis showed that the greatest sensitivity to discontinuities was achieved in the rail head using a combined ultrasonic sounding scheme (0°, 45° and 70°), where the minimum size of the fixed defects is < 3-6 mm, depending on the direction of wave input. For the rail web, similar values are < 3-6 mm, however, there is a decrease in the stability of recording transverse waves at angles of 70°, which is



https://doi.org/10.51488/1680-080X/2026.3-07

associated with the geometry of the control zone. In the rail foot, the sensitivity is lower and is limited to detecting defects with a size of less than 3 mm at an insertion angle of 70°.

A comparative analysis of the control zones shows that the maximum reliability of defect detection is achieved in the rail head (up to 95-98% detectability using a combination of echo and mirror methods), while in the neck this indicator decreases to 90-93%, and in the sole - up to 85-90%. The main factor in reducing efficiency is the attenuation of the ultrasonic signal and the complication of wave propagation paths in areas of complex geometry.

The criterion for recognizing a joint as defective is the simultaneous fulfillment of three conditions: exceeding the amplitude of the echo signal of the threshold level, matching the coordinates of the defect to the control zone, and exceeding the linear size of the discontinuity of 5 mm. It was found that the amplitude criterion is the most sensitive parameter, while the geometric localization of the defect shows the greatest error (up to 10-15% offset relative to the actual position).

The interpretation of the results indicates that the combined use of echo-pulse and mirror methods improves diagnostic reliability by mutually compensating for the limitations of each method. In particular, the mirror method increases the likelihood of detecting inclined defects, while the echo pulse method provides an accurate assessment of the depth of the irregularities.

*Limitations of the study*

A number of limitations should be noted that affect the accuracy and generalizability of the results obtained. Firstly, the sensitivity of the control significantly depends on the quality of the acoustic contact and the stability of the transducer pressure. Secondly, the geometric complexity of the welded zones leads to local distortions of the ultrasonic field, which limits the accuracy of estimating the size of defects. Thirdly, the presented threshold values are valid for the 2.5 MHz frequencies used and may change when switching to other frequency ranges or converter types. In addition, the results were obtained in conditions of controlled movement and require additional verification during high-speed operation.

During operational tests on the same day, the MDL passage section is monitored by a removable two-thread flaw detection trolley with a recorder.

During the tests, the technology of continuous ultrasound monitoring using a mobile diagnostic laboratory on a road-rail platform with wheeled ultrasonic transducers was tested. 120 km of railway track was measured as part of these tests. The obtained MDL flaw patterns are compared with the flaw patterns of standard flaw detection equipment. An example of decoding a flaw diagram is shown in Figure 4.

Previously, deflect scope trolleys were used as the main means for non-destructive testing of rails. Today, mobile diagnostic complexes that perform diagnostics at speeds of 60 km/h and above provide the bulk of the control on the territory of the backbone network. It must be recognized that the key problem is the unsatisfactory quality of control in the areas of bolted joints of rails.

To address this problem, a system equipped with wheeled ultrasonic transducers was tested. Unlike conventional sliding transducers, the wheeled transducers have an elastic contact shell that adapts to local rail-surface irregularities and provides more stable acoustic coupling in rail-joint areas, including joints with irregular surface conditions. To ensure the required inspection performance, flaw-detection equipment equipped with wheeled ultrasonic transducers was installed on the road–rail vehicle. The field tests indicated that the proposed configuration provided stable inspection of rail-joint areas and showed favorable comparative performance relative to conventional sliding transducers.



https://doi.org/10.51488/1680-080X/2026.3-07

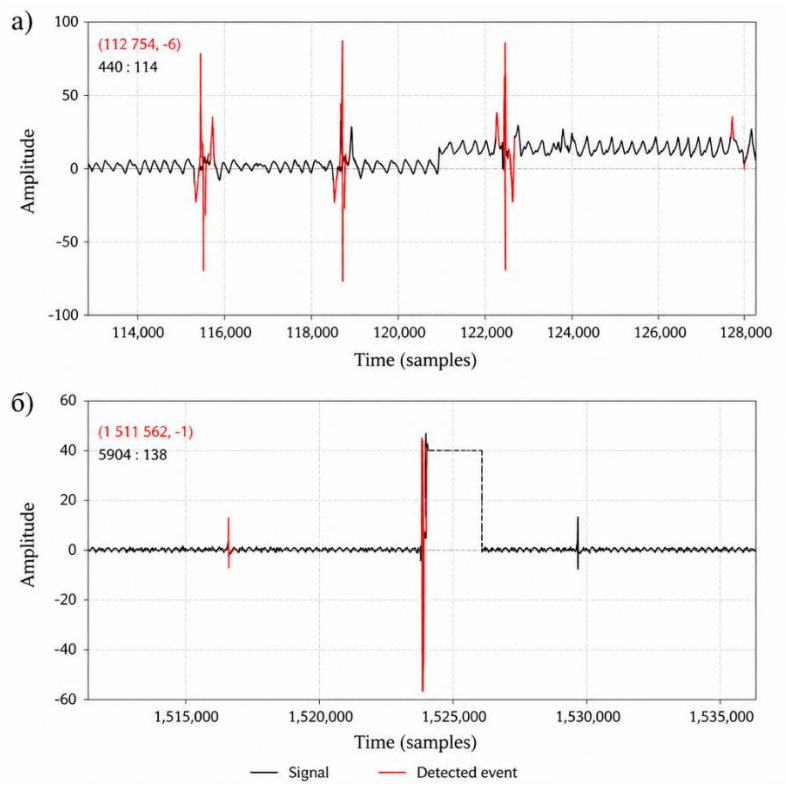



**Figure 4** – Flaw patterns, zero-line offset signals: a) is the case of a relatively small displacement of the zero line; b) the case of a critical offset incompatible with the normal functioning of the channel [Authors' material]

**Table 2 -** Comparative results of MDL and conventional ultrasonic inspection [Authors' material]

| Indicator | MDL | Conventional trolley |
|---|---|---|
| Inspected track length, km | 120 | 120 |
| Number of inspection runs | 8 | 12 |
| Total indications | 35 | 31 |
| Corresponding indications | 29 | 29 |
| MDL-only indications | 6 | - |
| Reference-only indications | - | 2 |
| Confirmed rail defects | 29 | 27 |
| Rail-head indications | 17 | 16 |
| Rail-web indications | 8 | 7 |
| Rail-foot indications | 4 | 4 |
| Indications at welded joints | 6 | 5 |
| Repeat inspections | 4 | 7 |

## 4 CONCLUSIONS

1. The tests of the mobile diagnostic laboratory (MDL) have confirmed the possibility of its use for performing non-destructive testing of rails in the conditions of the main railway network.

2. It was found that the maximum operational speed of the MDL along the railway track in transport mode is 60 km/h, while the speed of ultrasonic monitoring reaches 10 km/h without loss of signal recording quality.

3. It was determined that the full road-to-rail and rail-to-road transition cycle of the MDL takes approximately 3 minutes, supporting efficient deployment of the diagnostic system.

4. It has been experimentally confirmed that the minimum length of the platform for the safe installation of MDL on the railway track should be at least 3 m



https://doi.org/10.51488/1680-080X/2026.3-07

5. The operability of the locomotive on-board safety system «Bort» has been checked, while short-term violations of shunting rail circuits in conditions of high humidity (rain, sleet) have been identified, requiring consideration during operation.

6. It has been established that the existing configuration of flaw detection equipment provides high-quality monitoring of rails at speeds up to 10 km/h, while it is technically possible to increase the speed to 40 km/h with the expansion of the ultrasonic complex (adding three additional booms).

*Scientific novelty.* The concept of a mobile diagnostic laboratory based on a road–rail platform, integrating road and railway operating modes for rail flaw detection, has been proposed and experimentally evaluated.

- Experimental data have been obtained on MDL transition and operating modes, including road-to-rail and rail-to-road transitions, shunting operations, and operation under varying weather conditions.

- The limitations and conditions for stable operation of the road–rail diagnostic system during ultrasonic inspection at increased operating speeds have been established.

*Practical significance.* The developed technology makes it possible to significantly reduce the deployment time of the diagnostic complex and increase the efficiency of monitoring the condition of the path.

- The use of MDL provides a reduction in dependence on removable flaw detection trolleys and logistical constraints.

- The results obtained can be used in the implementation of MDL in the operational units of the railway infrastructure to improve train safety.

- Updated parameters of speed, deployment time and infrastructure requirements can be applied in the design of operational regulations.

*Prospects for further research.* Increasing the speed of ultrasonic monitoring by expanding the number of measuring units and optimizing the sounding scheme. Development of algorithms for compensating for the influence of weather conditions on rail-circuit operation and the Bort safety system. Conducting extended tests on various types of railway lines (small-radius curves, high-load sections). Creation of a digital system for automatic flaw detection in real time for integration with MDL.

## REFERENCES


1. **Utrata, D., Clark, R.** (2003). Groundwork for rail flaw detection using ultrasonic phased array inspection. Rev. Quant. Nondestruct. Eval, 22(1), 799–805. https://doi.org/10.1063/1.1570217
2. **Marino, F., Distante, A., Mazzeo, P.L., Stella, E.** (2007). A real-time visual inspection system for railway maintenance: automatic hexagonal-headed bolts detection. IEEE Trans. Syst., Man, and Cybern., Part C (Applications and Reviews), 37(3), 418–428. https://doi.org/10.1109/TSMCC.2007.893278
3. **Zhurynova, Zh.O., Bondar, I.S., Aldekeyeva, D.T., Nurakhmetova, K.K., Digarbaeva, T.D., Deinichenko, A.A.** (2025). Modern instruments for detection and quantitative assessment of hidden rail cracks. 77th International Conference on Vibroengineering Procedia, Vol. 63, p. 153–159, https://doi.org/10.21595/vp.2026.26499
4. **Kuzmin, E.V., Gorbunov, O.E., Plotnikov, P.O., Tyukin, V.A.** (2018). An Efficient Algorithm for Finding a Threshold of Useful Signals in the Analysis of Magnetic and Eddy Current Defectograms [Effektivnyi algoritm opredeleniya poroga poleznogo signala pri analize magnitnykh i vikhretokovykh defektogramm. Modelirovanie i analiz informatsionnykh sistem]. Modeling and Analysis of Information Systems, 25(4), 382-387. https://doi.org/10.18255/1818-1015-2018-4-382-387 (In Russ.)
5. **Kuzmin, E.V., Gorbunov, O.E., Plotnikov, O.O., Tyukin, V.A., Bashkin, V. A.** (2019). Application of neural networks for recognition of rail structure elements in magnetic and eddy




https://doi.org/10.51488/1680-080X/2026.3-07

current defectograms. Autonomous Control and Computing, 53, 628–637. https://doi.org/10.3103/S0146411619070137

6. **Kang, Z., Li, R.** (2024). Rail Surface Defect Detection Based on MobileViTv2 and Eddy Current. Proceedings of the 6th International Conference on Electrical Engineering and Information Technologies for Rail Transportation (EITRT), Lecture Notes in Electrical Engineering, vol 1136. Springer, Singapore. https://doi.org/10.1007/978-981-99-9315-4_62
7. **Feng, J.H., Yuan, H., Hu, Y.Q., Lin, J., Liu, S.W., Luo X.** (2020). Research on deep learning method for rail surface defect detection. IET Electr. Syst. Transp, 10, 436-442. https://doi.org/10.1049/iet-est.2020.0041
8. **Wang, H., Li, M., Wan, Z.** (2022). Rail surface defect detection based on improved mask R-CNN. Comput. Electr. Eng, 102, 108269. https://doi.org/10.1016/j.compeleceng.2022.108269
9. **Luo, H., Cai, L., Li, C.** (2023). Rail surface defect detection based on an improved YOLOv5s. Appl. Sci,13(12), 7330. https://doi.org/10.3390/app13127330
10. **Zengzhen, M., Ren C., Shanshan, Z.** (2023). Research on steel rail surface defects detection based on improved YOLOv4 network. Front. Neurorobot, 17. https://doi.org/10.3389/fnbot.2023.1119896
11. **Kosenko, S.A., Kvashnin, M.Ya., Bondar, I.S., Akimov, S.S.** (2017). Operational measurements of stresses in a rail under the influence of rolling stock [Ekspluatatsionnye izmereniya napryazhenii v rel'se pod vozdeistviem podvizhnogo sostava]. Transsib News. Omsk, 2(30), 133-145.
12. **Zhangabylova, A.M., Bondar, I.S., Kvashnin, M.Ya., Ablyazova, A.M., Konysbay, A.D.** (2024). Analysis of the performance of intermediate rail fastenings under operational load [Analiz raboty promezhutochnykh rel'sovykh skreplenii pri ekspluatatsionnoi nagruzke]. KazATK Bulletin, 4(133), 55-65. https://doi.org/10.52167/1609-1817-2024-133-4-55-65 (In Russ.)
13. **Bondar, I.S., Jexenbaev, E.K., Uteshbaeva, A.A., Uskembaeva, B.O., Abiev, B.A.** (2025). Experimental studies of dynamic properties of soils of railroad embankments / Vibrodiagnostics and dynamic operation of reinforced concrete sleepers under the influence of moving load. Vibroengineering Procedia, Vol. 58, 24-30, https://doi.org/10.21595/vp.2025.24943
14. **Kvashnin, M.Ya., Bekzhanova, S.E., Bondar, I.S., Akbaeva, A.S., Kurbenova, A.K.** (2021). On the issue of safe operation of artificial structures of railway lines [K voprosu o bezopasnoi ekspluatatsii iskusstvennykh sooruzhenii zheleznodorozhnykh putei]. Bulletin of KazGASU. – Almaty, 1(79), 229-241. https://doi.org/10.51488/1680-080X/2021.1-30 (In Russ.)
15. **Gostev, G.A.** (2018). Problems of operation and non-destructive testing of rails with reduced wear. Modern technologies [Problemy ekspluatatsii i nerazrushayushchego kontrolya rel'sov s ponizhennym iznosom. Sovremennye tekhnologii. Sistemnyi analiz]. System analysis. Modeling, Vol. 57, 1, 90-94. https://cyberleninka.ru/article/n/problemy-ekspluatatsii-i-nerazrushayuschego-kontrolya-relsov-s-privedennym-iznosom/viewer (In Russ.)
16. **Alvarenga, T.A., Carvalho, A.L., Honorio, L.M., Cerqueira, A.S., Filho, L.M.A., Nobrega, R.A.** (2021). Detection and classification system for rail surface defects based on Eddy current. Sensors, 21, 7937. https://doi.org/10.3390/s21237937
17. **Huang, C, Huang, Y**. (2021). Urban rail transit signal and control based on Internet of Things. Journal of High-Speed Networks, 27(3), 237-250. https://doi.org/10.3233/JHS-210664
18. **Orlov, S.P., Efimushkin, N.A., Efimushkina, N.V.** (2022). Deep neural network for diagnostics of railway track elements [Glubokaya neironnaya set' dlya diagnostiki elementov zheleznodorozhnogo puti]. Vestn. Samara State Technical University. Ser. Technical sciences. Vol. 30, 1, 63-74. https://doi.org/10.14498/tech.2022.1.4 (In Russ.)
19. **Bystrov, L.Yu., Gladkov, A.N., Kuzmin, E.V.** (2024). Suppression of additive periodic low-frequency interference on eddy current defectograms [Podavlenie additivnykh periodicheskikh nizkochastotnykh pomekh na vikhretokovykh defektogrammakh]. Modeling and analysis of information systems, 31(2), 164–181. https://doi.org/10.18255/1818-1015-2024-2-164-181 (In Russ.)



https://doi.org/10.51488/1680-080X/2026.3-07

## FUNDING

The study was conducted by a working group consisting of representatives of the relevant structural divisions of JSC NC KTZ and specialists from JSC Transtelesoft, OJSC Radioavionika, and the Private Educational Institution of Additional Professional Education, Diagnostics of Railway Infrastructure.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## ARTIFICIAL INTELLIGENCE STATEMENT

During the preparation of this manuscript, the authors used artificial intelligence tools solely for language editing, grammar checking, and text improvement. All scientific content, interpretations, analyses, and conclusions remain the responsibility of the authors.

## AUTHOR CONTRIBUTIONS

*Zhanna Omarkhanovna Zhurynova* – research, formal analysis, visualization, writing an original project.
*Patam Turganovna Akhmetova* – visualization, writing of the original project.
*Bikhozhayeva Gulmira Sagatovna* – graphic editing and translation of the original text.
*Karibaeva Gulnaz Bisultanovna* – author supervision, methodology, verification, writing-reviewing and editing.
*Bondar Ivan Sergeevich* – scientific guidance, methodology, validation, interpretation of results, written review and editing.
*Kuvandyk Saginovich Lesov* – written review and peer review.

## INFORMATION ABOUT THE AUTHORS

- Zhanna Omarkhanovna Zhurynova
- PhD student
- M. Tynyshpayev ALT University
- Almaty, Kazakhstan
- E-mail address: Zhanna5555555@mail.ru
- ORCID ID: https://orcid.org/0009-0005-9135-2857

- Patam Turganovna Akhmetova
- C.T.S., M. Tynyshpayev ALT University
- Almaty, Kazakhstan
- E-mail address: p.ahmetova1@alt.edu.kz
- ORCID ID: https://orcid.org/0000-0003-3788-3671



https://doi.org/10.51488/1680-080X/2026.3-07

- Bikhozhayeva Gulmira Sagatovna
- C.T.S.
- M. Tynyshpayev ALT University
- Almaty, Kazakhstan
- E-mail address: g.bikhozhaeva@alt.edu.kz
- ORCID ID: https://orcid.org/0000-0002-9239-7433

- Karibaeva Gulnaz Bisultanovna
- C.T.S.
- M. Tynyshpayev ALT University
- Almaty, Kazakhstan
- E-mail address: g.karibaeva@alt.edu.kz
- ORCID ID: https://orcid.org/0009-0001-5305-8738

- Bondar Ivan Sergeevich
- C.T.S, Ph.D., Associate Professor
- Kazakh Automobile and Road Institute named after L.B. Goncharov
- Almaty, Kazakhstan
- E-mail address: ivan_sergeevich_08@mail.ru
- ORCID ID: https://orcid.org/0000-0001-7376-5643

- Kuvandyk Saginovich Lesov
- C.T.S., Professor, Tashkent State Transport University
- Tashkent, Uzbekistan
- E-mail address: kuvandikl@mail.ru
- ORCID ID: https://orcid.org/0000-0002-9434-0713


Received: 16 July 2026
Revised: 9 August 2026
Accepted: 16 September 2026



https://doi.org/10.51488/1680-080X/2026.3-07