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Technical paper

Enhancing RCF rail defect inspection on the Serbian railway network

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ABSTRACT

The interaction between the wheel and the running rails within the railway system introduces intricate stress patterns, resulting in the formation of rolling contact fatigue (RCF) rail defects. The magnitude of this stress is contingent upon factors such as track performance, vehicle characteristics, and service conditions. While advancements in rail metallurgy can mitigate the issue to some extent, no economically viable steel composition currently exists that can completely withstand the repetitive stresses associated with RCF. It is more cost-effective to properly maintain rails for longer use rather than replace them entirely. The paper emphasizes the importance of classifying and coding RCF rail defects in light of their potential adverse effects on rail transport safety. It provides an analysis of the available inspection methods for RCF rail defects and recommends the ones that should be implemented on the Serbian railway network. A combination of proposed inspection methods is preferred to increase detection efficiency for different types of RCF defects.

1 Introduction

The Serbian railway network is a crucial link connecting Southeast Europe to the broader European railway network. Serbia, as an essential transportation corridor, plays a crucial role in facilitating efficient connections between Eastern and Western Europe. Its strategic geographical location makes it a pivotal trade hub, allowing for the efficient transportation of goods and passengers. Improvements and modernization of the railway infrastructure in Serbia directly impact the overall efficiency of the European transportation system [1]. This, in turn, fosters economic cooperation, trade, and mobility within Europe. Therefore, investments in the Serbian railway network not only contribute to the country's regional development but also strengthen its integration into the European transportation system.

The railway density in Serbia is 49.2 km/1000km^2, similar to the EU average of 50.1 km/1000km^2. The Serbian railway network spans 3819 km.The crucial part of this network is the European Corridor X (Figure 1), which has two branches leading towards Hungary (Belgrade-Budapest) and Bulgaria (Niš-Sofia). Corridor X is an important part of the southeastern multimodal axis, which connects the following countries: Austria/Hungary, Slovenia/Croatia, Serbia, and Bulgaria/North Macedonia/Greece. The modernization and reconstruction of the railway infrastructure on Corridor X through Serbia aim to increase train speeds to 200 km/h and axle loads to 225 kN.

An increase in vehicle speed, traffic density, and axle loads on the railway lines in Serbia could lead to the significant appearance and development of rail defects caused by rolling contact fatigue (RCF), which adversely affects maintenance costs, noise, and vibration emissions and could endanger traffic safety. RCF implies rail damage caused by the complex stresses that are characteristic of rail-wheel rolling contact (Figure 2). To ensure safe railway transport, efficient inspection methods are crucial in detecting RCF rail defects.

In their previous paper [2], the authors presented and described representative types of non-destructive inspection methods, both conventional and innovative, with a focus on their basic characteristics, advantages, and disadvantages. The research [2] was based on numerous international research studies and representative published papers. The purpose of the research [2] was to identify practical applications for inspection methods in the railway industry and suggest ways to enhance equipment and software for better results in rail inspection. The authors recommended combining multiple inspection methods to improve rail defect detection performance [2].

In this paper, the authors focus on improving the RCF rail defect inspection procedure by using modern, non-destructive methods to detect these defects on the railway network in Serbia. The goal is to efficiently detect RCF defects on in-service running rails using manual or installed equipment on commercial or inspection vehicles. The effective inspection of RCF rail defects should be the basis for reactive, scheduled, and predictive maintenance of rails in service.

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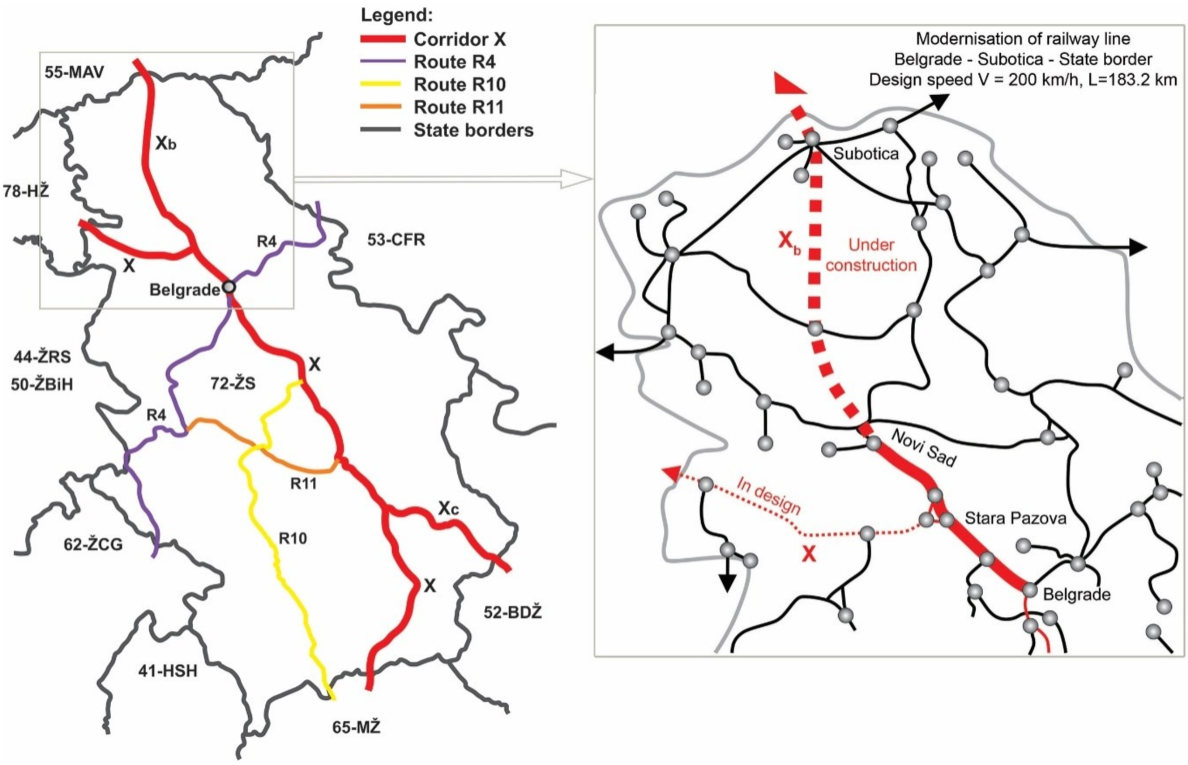

Figure 1. Main railway lines through the Republic of Serbia (left) and modernised railway line for speeds up to 200 km/h (right)

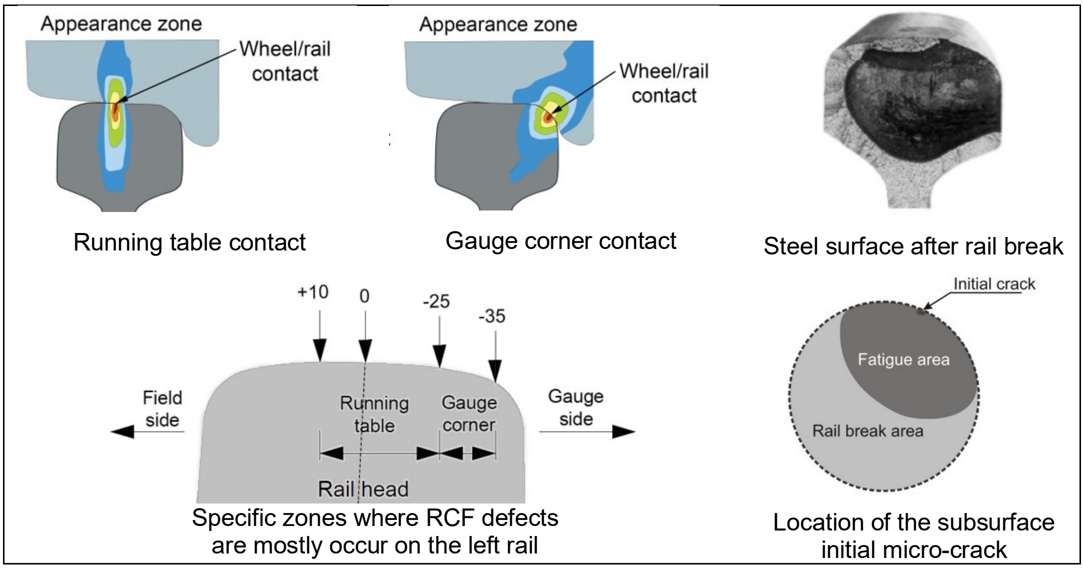

Figure 2. Contact zones with complex RCF stress on the left running rail

2 Brief review of RCF rail defects and coding system

In 2018, the general classification and coding system for the RCF rail defects caused by the complex stresses that are characteristic of rail/wheel contact were provided by IRS 70712 [3] and EN 16729-3 [4]. Furthermore, EN 13231-5 [5] provides defect definitions without a coding system. The paper [6] deals with the incompatibility of European standards [4,5] with UIC recommendations [3, 7, 8], which could create difficulties and misunderstandings in applying coding system (Table 1).

RCF defects can be extremely dangerous for railway traffic, causing harm to both human lives and the environment. They can result in injuries, material damage, and other catastrophic incidents [9, 10]. Therefore, it is essential to have an accurate coding system to track the occurrence of such defects. A uniform coding system used throughout the EU network would be beneficial for statistical analysis purposes and help identify the areas that require immediate attention to prevent any further damage.The Infrastructure Manager (IM) has to define a Rule book with the following data about a rail defect to achieve successful inspection and maintenance of rail defects:

– the official name of the rail defect in both Serbian and English,
– a standard benchmark photo indicating the characteristic appearance and location of the defect on the rail
– a brief description, including data on the location and cause of the occurrence,
– recommended methods for detection,
– recommendations for condition monitoring and maintenance,
– a unique numerical code, and
– necessary comments indicating the degree of danger it poses to railway transport safety.

Table 1. Inconsistencies in the RCF rail defect coding system

Benchmark photo	Brief definition by EN 13231-5	Numbering codes and comments
	**Head checking (HC)** Small parallel cracks on the rail head near the gauge corner.	– 1223, 2223 by IRS 70712 – 2223 by EN 16729-3, UIC Code 712 and UIC CODE 725
	**Belgrospi** A network of cracks developing on the rail head of track with a speed greater than 160 km/h affected by short-pitch corrugation.	– 2271 by EN 16729-3 – Not consider by IRS 70712
	**Squat** Rolling contact fatigue defect whose main characteristics are a blackish patch on the rail head, a lateral flow of steel and a collapsed and widened rolling band.	– 127, 227, 417, 427 by IRS 70712 and EN 16729-3 – 2271,437 by IRS 70712
	**Flaking** Surface condition consisting of the gouging of metal on the railhead.	– 2222 Shelling of the gauge corner by UIC Code 712, – 1221, 2221 by IRS 70712
	**Spalling** Cracking and chipping on the top of the rail.	– 1211, 2211 by IRS 70712
	**Side cutting** Wear occurring on high rails in small radius curves where wheel flanges contact the rail.	– 2203 by IRS 70712

	**Lipping** Plastic metal flow occurring on the rail head under conditions of high axle load and high gross tonnage.	Not consider by IRS 70712 The lippingdefect is a manifestation of HC defect on a track with variable traffic direction (e.g. single track line).
	**Short pitch corrugation** Quasi-periodic irregularities on the running surface. The wavelength usually is 10 mm to 100 mm. The short-pitch corrugation is typically encountered in the straight track on both rails and large radius curves on the high rail.	2201 Code by IRS 70712 and definition as follows: Short-pitch corrugation is characterised by a pseudo-periodical sequence of bright ridges and dark hollows on the running surface with a pitch generally less than 8 cm. This defect can appear at any location.
	**Short wave corrugation** Depressions in the running surface which are pronounced. The wavelength usually is 30 mm to 300 mm.	2202 Code by IRS 70712 and definition as follows: Long-pitch corrugation is characterised by depressions in the running surface of the railhead of lower rail in curves and tangential tracks. The pitch varies between 8 and 30 cm. The progression of the corrugation depends on curve radius, cant deficiency/excess, steel grade, friction in wheel/rail contact, and vehicle characteristics.
	**Long wave corrugation** Irregular unevenness on the running surface. The wavelength usually is 300 mm to 1000 mm.	Short-wave corrugation and long-wave corrugation are not included in IRS 70712.
	**Wheel burn** Abrasive, plastic and thermal damage occurring in zones where trains start to move.	– 2251, 2251 by IRS 70712 – 125, 2251, 2252, 445 by EN 16729-3

To prevent misunderstanding, the names *head checking*, *squat*, and *belgrospi* are used universally in scientific and professional documents without translation, due to the proven danger of causing multiple rail breaks under the vehicle. A significant number of research papers worldwide [11-19] deal with HC and squat rail defects due to their threat to railway safety.

In addition, corrugation is the topic of many scientific and professional papers. It has a direct impact on railway traffic comfort and initiates the deterioration of the railway infrastructure. Alternative forms of fatigue deterioration may arise due to the continuous interaction of the wheel with corrugation peaks, giving rise to a distinctive form of structural impairment referred to as "belgrospi". These rail defects manifest as cracks forming on the wave peaks and if left untreated, progress into more severe anomalies known as squats. This entails the emergence of a network of cracks on the corrugation crests, which resemble a combination of irregular headchecks and minor squats. The rail defect is named Belgrospi after being initially observed by German engineers Belz, Grohmann, and Spiegel on a German high-speed line. Belgrospi cracks pose a risk of consequential and substantial damage to rails. Research by Schoech [20] indicates that short-pitch corrugation with a depth of 0.03 mm can significantly elevate dynamic forces, leading to the development of such structural defects.

A visual inspection of the rails on the double-track railway Belgrade - Novi Sad for speeds up to 200 km/h, which was put into regular traffic on March 20, 2022, indicates the presence of RCF rail defects. On this railway line, belgrospi rail defects were observed for the first time in Serbia. Figure 3 shows the development of corrugation and belgrospi defects on the corrugation crests. Figure 4 shows the development of a squat defect in a typical place next to a concrete sleeper due to a change in the vertical stiffness of the switch support. Figures 3 and 4 show the RCF rail defects in the railway section where preventive grinding of new rails was not carried out.

Figure 3. Belgrospi cracks forming on the corrugation peaks in the switch on the Stara Pazova – Novi Sad railway line (Photoby Aleksandar Milutinović in December 2023)

Figure 4. A squat defect developed right next to the concrete sleeper (Photo by Aleksandar Milutinović in Indjija station, December 2023)

It is essential to develop a plan for managing the emergence and progression of RCF defects on railways in Serbia. The first step is to develop regulations for classifying and coding rail defects, as well as mandatory training for professional staff. Following this, non-destructive methods should be chosen for early detection and monitoring of the development of rail defects. Lastly, the rails have to be repaired or removed.

3 Recommended NDT methods for RCF inspection of rail defects on the serbian railway network

The inspection methods for rail defects during the development of railway infrastructure and vehicles undergo cycles of progress and inactivity. Progress is driven by advancements in measurement devices, equipment, acquisition systems, and software for processing and analyzing recorded data (Figure 5). The effectiveness of these processes relies on the knowledge, economic, and management capabilities of the inspection management, as well as the skills of the employees who perform the inspection tasks.

Internal and external factors influencing each railway company's decision on choosing NDT (Non-Destructive Testing) methods for inspecting RCF rail defects can be diverse. Table 2 shows several factors that may impact the decision.

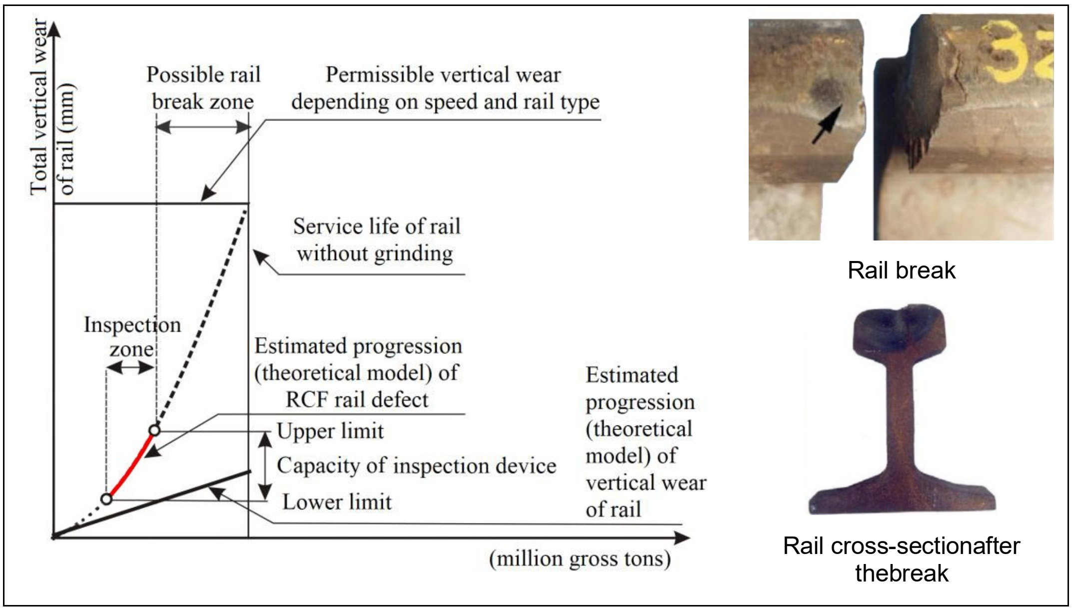

Figure 5. The capacity of inspection devices and their impact on the lifespan of the railway

Table 2. Overall factors influencing a railway company's decision on choosing NDT for inspecting RCF rail defects

Internal factors influencing a railway company's decision	
Financial Resources	The availability of financial resources for implementing a specific NDT method can be a crucial factor. Equipment costs, staff training, and maintenance expenses may limit the options.
Staff Expertise	For a particular NDT method to be successful, staff must be trained in its application. An internal factor includes having experts within the railway company familiar with a specific method.
Resource Availability	Depending on the company's size and capabilities, certain NDT methods may not be practical or feasible. In some cases, implementing specific NDT methods may not be practical or achievable due to limitations in the company's resources or infrastructure.
System Sustainability	Infrastructure and vehicle maintenance, as well as access to accurate system condition data, play a crucial role in selecting an appropriate NDT method.
External factors influencing a railway company's decision	
Regulations	Legal requirements and technical regulations may demand the use of specific NDT methods to ensure safety and compliance with Directives, TSIs, and EN standards.
Technological Advancement	Rapid technological developments in NDT can offer new and more efficient methods that the company may consider to enhance its inspection procedures.
Industry Developments	Changes in the railway transportation industry, such as new types of vehicles or increased speeds, can influence the need for more advanced inspection methods.
Social Responsibility	Increased awareness of environmental protection and accident reduction can affect the decision to use more precise inspection methods to minimise the risk of accidents.

All these factors together can influence the decision-making process regarding the selection of a suitable NDT method for inspecting RCF rail defects. The railway company needs to consider these factors to achieve a balance between efficiency, economic feasibility, and compliance with standards and regulations. Traditionally, Serbian railways use visual and ultrasonic methods to detect rail defects.

Figure 6 shows the different groups of methods available for detecting rail defects along with the methods that IM plans to apply (highlighted in grey in Figure 6). IM will achieve this by purchasing equipment and installing it on inspection or commercial vehicles. It is possible and sometimes preferable to use a combination of multiple testing methods.

Figure 7 shows in detail the specific NDT methods that are already used on the Serbian railways (visual testing and conventional ultrasonic testing), as well as the methods recommended by the authors of this paper, as follows:

- ultrasonic testing using phased array probes,
- conventional eddy current testing, and
- axle box acceleration measurement.

SWOT analysis was used to see if the suggested NDT methods would work on the Serbian railway network to find RCF rail defects. This type of analysis gives a full picture of a thing's strengths, weaknesses, opportunities, and threats (Table 3). Considering these methods' advantages, their high precision in detecting structural changes indicative of RCF defects stands out. Additionally, their effectiveness in identifying defects at the early stages of development enables preventive maintenance, which can significantly reduce costs and enhance overall railway system safety.

However, these methods are not without objective and/or subjective limitations. High implementation costs, particularly the acquisition of specialized equipment and personnel training, are possible weaknesses. Limitations in inspection speed and data analysis complexity may also pose challenges. Opportunities for improvement in these methods may arise from technological advancements and the development of algorithms for rapid and precise result analysis.

Furthermore, the SWOT analysis recognises opportunities for integrating new technologies, such as artificial intelligence (AI) and machine learning, to enhance the efficiency and precision of RCF defect detection. Opportunities also exist for the development of standardised inspection procedures to ensure consistency in the application of these methods globally, with the possibility of combining several NDT methods.

On the other hand, threats may stem from insufficient support for research and the implementation of new technologies, as well as the rapid technical obsolescence of existing equipment. Therefore, despite challenges, the SWOT analysis provides a comprehensive overview to optimize the use of proposed methods for NDT inspection of rail RCF defects, contributing to the improvement of safety and sustainability in railway systems.

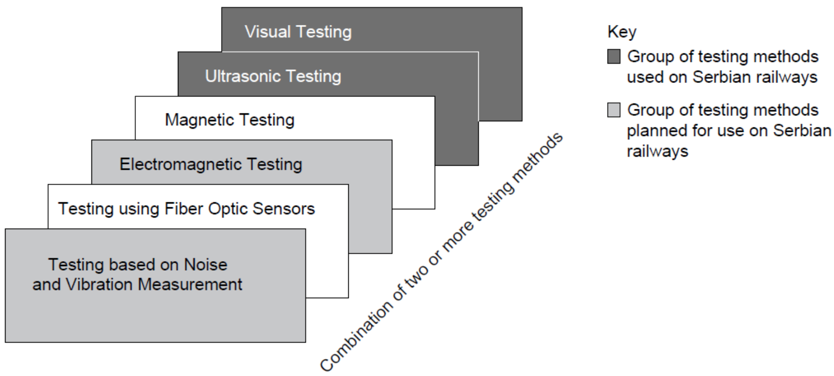

Figure 6. Available, used, and recommended groups of NDT methods for the inspection of RCF rail defects on the Serbian railway network

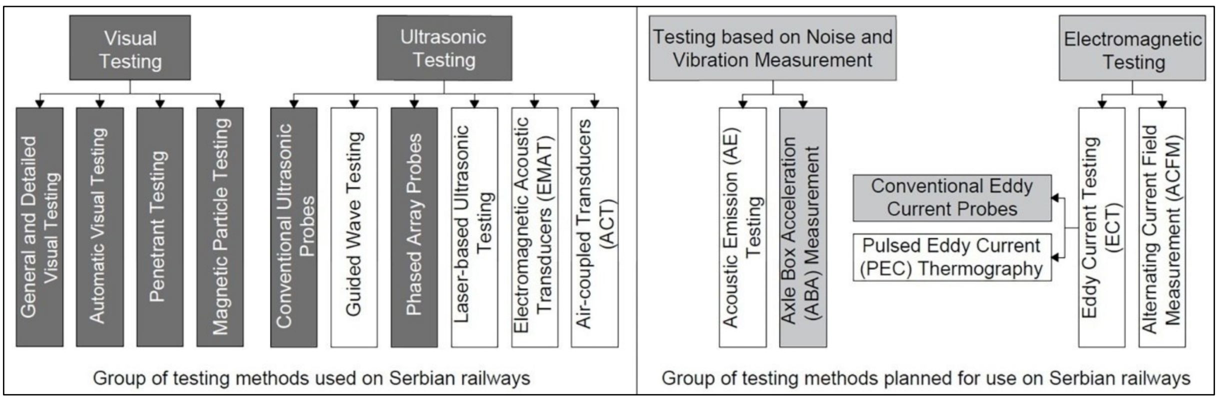

Figure 7. NDTs used (left) and recommended for use(right) on the Serbian railway network

Table 3. SWOT analysis of recommended NDTs for RCF rail defects on the Serbian railway network

INTERNAL FACTORS	
☺STRENGTHS of recommended NDTs	☹WEAKNESSES of recommended NDTs
✓ Possibility of combining the proposed methods (VT, AVT, MT, PT, conventional UT, phased array UT, ECT, ABA). ✓ Possibility of mounting measuring equipment on the SEVER-1435 track recording car (Figure 8) used by Serbian Railways (AVT, phased array UT, ECT, ABA). ✓ Possibility of installing measuring equipment on commercial and inspection vehicles at commercial speed (AVT, ABA). ✓ Detection of defects in the early development stage (phased array UT, ECT, ABA). ✓ Evaluation of defect severity (VT, AVT, ABA). ✓ Accessibility and usability of the inspection method (AVT, MT, conventional UT, phased array UT, ECT, ABA). ✓ Simplicity inthe interpretation of inspection results (VT, AVT, conventional UT, phased array UT, MT, PT, ECT, ABA). ✓ Application ofNDT method on running rails(AVT, conventional UT, phased array UT, ECT, ABA), preferably without track closure. ✓ Mounting of inspection equipment to the inspection trolley for testing specific zones of limited length (AVT, conventional UT, phased array UT, ECT, ABA), preferably without track closure. ✓ Application of non-contact NDT methods (ABA, AVT, ECT).	? Obligation of IM to organize test track sections for calibration of measuring systems mounted on measuring vehicles and training of professional staff (conventional UT, phased array UT, ECT, ABA). ? Inability to apply the method in bad weather conditions (VT, AVT, MT, PT). ? Inability to detect defects undercertain sizes(VT, AVT, conventional UT, phased array UT, ABA). ? Inability to detect defects over acertain size (conventional UT, phased array UT, ECT). ? Inabilityof theNDT method to detect RCF subsurface rail defects (VT, AVT, conventional UT, ABA). ? Inability to assess the severity of RCF defects(MT, PT, conventional UT, phased array UT, ECT). ? Inspectionand measurement of RCF rail defects obscured by other cracks (UT, AVT, ECT). ? The pronounced subjectivity in assessing the type and severity of RCF rail defect (VT, AVT). ? Impossibility to mount to the commercial and/or inspection vehicle (VT, MT, PT). ? Low inspection speed and application of the method on track sections of limited length (VT, MT, PT). ? Safety risk for persons who are conducting inspections (VT, MT, PT, all types of inspections using trolley).
EXTERNAL FACTORS	
☺ OPPORTUNITIESforrecommended NDTs	☹THREATSfor recommended NDTs
± Education of inspection staff and improvement of knowledge in the field of RCF defect developmentthrough professional seminars in Serbia. ± Specialized education for improving the knowledge of engineers for the application of inspection methods and analysis of measurement results with obtaining a certificate. ± Combining the results of several methods to detect with greater probability the exact type (type and severity) and characteristics of defects. ± Further improvement of NDT inspection methods. ± Automated identification and classification of RCF rail defects based on their type and severity using AI. ± Development of machine learning techniques suitable for defect detection. ± Expanding the database of individual defects used for AI training.	! RCF defects are spread over the entire railway network (about 3800 km of railway lines in Serbia). ! Lack of professional knowledge and experience among infrastructure maintenance employees in predicting the development of RCF defects. ! Availability of professional staff training and certification only abroad. ! Lack of professional knowledge and experience in rail maintenance planning (preventive, cyclical and corrective maintenance of running rails in service). ! Reliance on the rail inspection schedule based on railway traffic timetables. ! Possibility to conduct rail inspection within short periods of railway line closure. ! Reluctance of the inspection management to embrace innovative inspection technologies. ! High costs forpurchase and maintenance of inspection equipment.

± Optimizing the number and type of parameters for detecting defects using machine learning. ± Support provided by EN standardisation of NDT inspection method. ± Improving railway transport sustainability and competitiveness in Serbia by ensuring safety, increasing comfort, reducing maintenance costs, andreducing noise and vibration emissions. ± Establishing a laboratory for periodic calibration and checking the characteristics of measuring equipment in Serbia.	! Impossibility to calibrate and verify the operation of the equipment according to the prescribed cycles at test sections/laboratories. ! Undetected RCF rail defects may impact the safety of railway operations. ! Challenges associated with the procurement of equipment from international sources based on the risk of availability of materials and components.
Key: ABA - Axle Box Acceleration, AVT - Automatic Visual Testing ECT - Eddy Current Testing	MT - Magnetic Particle Testing PT - Penetrant Testing UT - Ultrasonic Testing VT - Visual Testing

4 Advantages and limitations of the proposed NDTs

In their previous paper [2], the authors provided a comprehensive overview of modern NDT methods for the inspection of RCF rail defects. Before analysing which methods are suitable for application on the Serbian railway network, the expert team of the Serbian IM should have a good understanding of the procedures and equipment required for implementing these modern NDT methods. This paper highlights the advantages and limitations of each of the proposed methods without delving into the details of the procedures and equipment required for implementing them.

4.1 General and detailed visual testing (VT) and automatic visual testing (AVT)

For years, the Serbian railways relied on maintenance workers to visually inspect tracks in service. Visual examination of rail surface conditions by qualified railway personnel walking along the tracks is the most basic method for general and detailed testing. However, this approach has several drawbacks: it is slow, subsurface and internal defects cannot be observed, it poses safety risks for personnel, and it heavily relies on the knowledge and experience of the railway personnel conducting the inspection [21, 22]. To avoid these issues, the European standard [4] recommends a comprehensive visual testing approach for assessing rail corrugation and other surface rail defects using auxiliary lighting to ensure adequate illumination, enabling a thorough inspection and evaluation of track conditions.

The VT methods provide information on visible surface rail defects. The advantages of this method include its simplicity, which provides a direct insight into the rail surface condition. Moreover, VT can be utilized to control and verify the results from other inspection methods.

Inspection results may be subjective, and a combination of VT and AVT methods is often required for comprehensive analysis. VT has limitations in detecting defects at an early stage of development, and its performance is constrained by the need for walking the track the track, limiting inspection to shorter track sections. Weather conditions and traffic management during rail inspection also influence VT outcomes, and the presence of grinding marks can obscure surface defects in their early stages.

As the speed of commercial trains has increased, reaching up to 200 km/h on the Belgrade-Novi Sad line, and the density of railway traffic has grown, the traditional visual method for detecting irregularities on the rail surface has lost some of its importance. However, automation of visual testing plays a crucial role in quickly and efficiently identifying rail surface irregularities. In Serbia, AVT equipment is mounted on an inspection car (Figure 8). The AVT system includes a device for illumination of running rails, a digital camera, and a device for image processing and defect identification. A specially designed illumination system ensures the preservation of a clear and contrasted image in any weather condition and at any time of the day [23].

AVT is a significant method for detecting surface defects, including squat, HC, belgrospi, and surface corrugation. This method involves various defect parameters, focusing on the precise location, area and length of surface deformation (squat, belgrospi), surface crack length and visibility of subsurface cracks indicated by dark patches on the rail surface (HC), defect orientation, number, and the assessment of defect severity.

The AVT system is an automated inspection system that is user-friendly and simple to operate. The method relies on high-resolution cameras, and its effectiveness is influenced by weather conditions. The AVT method is suitable for real-time monitoring and more detailed determination of defect parameters through image post-processing. However, this method’s outcomes may still be influenced by subjectivity, and the presence of grinding marks can obscure surface defects at an early stage of development. A combination of the VT and AVT methods is often required for comprehensive defect analysis.

Limitations on measurement speeds stem from the impact of higher vehicle speeds on image blurring. Detailed inspections are feasible at lower speeds, while inspections at higher speeds rely on the jump search method [24].

To improve efficient rail inspection, ongoing developments of the AVT method focus on more detailed image processing and real-time inspection using complex algorithms [25-28].

Figure 8. Modern recording car for track inspection on the Serbian railway network

4.2 Magnetic particle testing (MT) and penetrant testing (PT)

MT and PT constitute suitable methods for detecting surface defects, including squat, belgrospi and HC, on short track sections. These methods primarily focus on defect parameters such as location and surface crack length, although the latter is rarely utilized for squat defects.

Noteworthy advantages of these methods include the ability of MT to indicate the presence of shallow subsurface defects, albeit with insufficient reliability [29]. Both MT and PT offer improved visibility of small defects at an early stage of development compared to VT and AVT. Additionally, these methods provide the possibility of recognizing defects below contaminated surfaces, such as those affected by lubricants. However, both MT and PT have inherent disadvantages, as they are not automatic and are time-consuming.

4.3 Ultrasonic testing (UT) using conventional and phased array ultrasonic probes

Calibration of the measuring system for volume defects is described in EN 16729-1 [30]. It defines the methods for calibrating probes and the preparation of the test sections. Furthermore, in [30], the optional and mandatory probe angles for different types of volumetric rail defects, as well as the frequency range of ultrasonic waves (from 2 to 5 MHz), are defined.

In addition, standard EN 16729-3 [4] indicates the possibility of using UT probes for the detection of certain types of RCF defects (HC and squat, excluding corrugation and belgrospi), by defining the probe angle and the way of conducting the inspection (manual or vehicle-mounted equipment).

In general, the conventional UT method may prove incapable or unreliable in detecting surface and shallow subsurface defects due to the "dead-zone" phenomenon. The width of this zone depends on the probe angle concerning the vertical plane defined by [4] and affects the minimum depth at which defects can be detected. Furthermore, the minimum depth of defect detection is different depending on whether manual or vehicle-mounted equipment is used.

To detect squat and HC defects, it is recommended to use a probe angle of 70° to excite subsurface Rayleigh waves in the rail head. Moreover, for measuring the depth of the squat depression, a probe angle of 0° is recommended. However, it is important to note that the measurements may be obscured by other local cracks. For manual UT of HC defects, vertical depth can only be measured from 3 mm. In the case of vehicle-mounted UT equipment for HC defects, vertical depth measurement starts from 5 mm [4].

Instead of conventional UT, the application of phased array probes is increasing. The advantage of these probes lies in the capability of software to adjust the frequency, angle, and penetration depth of ultrasonic waves to specific appearance zones associated with rail defects. It allows for the simultaneous spreading of ultrasonic waves in various directions. One phased array probe can replace seven conventional UT probes, which reduces the amount of contact medium needed for inspection. Phased array systems enable fast signal analysis, and the real-time defect detection algorithms are constantly being improved.

The method's speed limitations stem from the influence of the contact medium and the needed measurement resolution. Modern measuring systems have developed protection for the probes from wear based on different forms of belts and sliding systems. In practice, inspection at speeds up to 80 km/h provides accurate detection of defects. The preferable inspection speed range is from 40km/h to 80 km/h, although some manufacturers provide systems intended for speeds up to 100 km/h.

4.4 Eddy current testing (ECT) using conventional probes

ECT, particularly when employing conventional eddy current probes, represents an efficient and often used method for detecting both surface-originated and subsurface defects like squat, HC, flaking, and spalling [4, 31]. It is a non-contact inspection method and can be optimised for specific types and zones of defect by choosing optimal shapes, characteristics, and arrangements of eddy current probes. This is the standard inspection method implemented both on commercial manual systems and automatic systems mounted on vehicles. The defect parameters that can be detected are precise location, HC pocket length, depth (with limitations on accuracy), and distance between HC cracks. The authors presented a detailed description of this method in their published papers [2, 32].

ECT can be utilized to monitor the performance of rail grinding machines [33] and is suitable for combination with other inspection methods [34].

The disadvantage of this method is the influence of lift-off on the characteristics of eddy current signals [35]. This affects the accuracy of squat defect sizing andthe evaluation of the depth of HC cracks and their distance. Additionally, the depth of penetration of eddy currents is limited by the inspection material and used frequency, so the pocket length of HC defects can be measured up to 10 mm, and their depths are calculated indirectly using an assumed angle and the measured pocket length [4].

When eddy current systems are mounted on the vehicle, the vehicle speed causes an increase in the frequency of induced eddy currents and a change in their penetration depth. The usual measuring speeds are up to 80 km/h.

The accuracy of the method is improved by applying multi-differential eddy current probes and enhancing the signal processing techniques [36-39].

4.5 Tests using axle box acceleration (ABA) measurements

The ABA method uses accelerometers mounted on the axlebox of trains in-service to determine the short- and long-wave unevenness of the rail head surface. This system detects vertical and longitudinal oscillations due to rail surface defects [40]. Signal processing is based on frequency and time domain analysis of ABA signals, including wavelet analysis.

This method represents a significant method for detecting squats and corrugation, and commercial ABA systems are applied worldwide [41]. It focuses on defect parameter evaluation, such as the exact location and length of surface depression. Additionally, this method is suitable for the automatic detection and classification of squat defect severity into four categories (trivial, light, moderate, and severe). Each defect severity category has characteristic amplitude-frequency spectra for ABA signals. Compared to vertical, longitudinal ABA signals are particularly sensitive to detecting light squats [42].

However, hunting, rolling bandwidth, and periodic repetitive vibrations originating from wheel defects influence the measured ABA signal and the probability of defect recognition. Moreover, the ABA signal characteristics of light squat defects are influenced by the speed of inspection vehicles and commercial trains.

5 Conclusion

This paper reports on the results of a case study that analysed the inspection methods used for identifying Rolling Contact Fatigue (RCF) rail defects on the railway network in Serbia, involving the performance of the railway infrastructure, inspection vehicles, and the expertise of the professional staff.

Effective inspection and maintenance of rail defects, particularly RCF rail defects, are crucial for ensuring the safety and reliability of railway networks. The implementation of standardized inspection methods, such as ultrasonic testing (UT), visual testing (VT), automatic visual testing (AVT), eddy current testing (ECT), magnetic particle testing (MT), and penetrant testing (PT), plays a significant role in identifying and monitoring various types of RCF rail defects. Furthermore, the utilization of advanced inspection methods and adherence to reference European standards are essential for enhancing the accuracy and efficiency of defect detection.

The Infrastructure Manager (IM) has to establish a comprehensive Rule book encompassing essential data for successful inspection and maintenance of rail defects, including standardized benchmark photos, detailed descriptions of defect origin and development, recommended inspection methods, and unique numbering codes.

Additionally, collaboration with international research initiatives and adherence to safety guidelines outlined by organizations such as the European Committee for Standardization (CEN) and the International Union of Railways (UIC) is fundamental for promoting best practices in rail defect management. Considering future developments in inspection technologies, it is recommended that the Railways of Serbia continue to invest in research of modern inspection methods for RCF rail defects. This includes exploring the potential of phased array technology, eddy current testing and axle box acceleration measurements for more efficient and comprehensive RCF defect detection. Furthermore, the establishment of a laboratory and test track section for periodic calibration and checking the characteristics of measuring equipment would further enhance the accuracy and reliability of inspection processes in Serbia.

The paper promotes the significance of combining different non-destructive inspection methods to provide reliable and early detection of RCF rail defects within the railway network. By integrating various inspection methods, it becomes possible to comprehensively assess the condition of the rails and identify RCF defects in their early stages. This approach not only contributes to the overall safety and reliability of railway operations but also minimises the potential impact of RCF defects on maintenance costs, noise, and vibration emissions.

By continuously refining inspection techniques and embracing technological advancements, the Railways of Serbia could mitigate the risks associated with RCF rail defects, ultimately ensuring the sustaining of the lifecycle and safety of the railway network for passengers and freight transportation.

Credit authorship contribution statement

Zdenka Popović: Writing – original draft, Conceptualization, Supervision, Writing – review & editing. **Ljiljana Brajović**: Validation, Methodology, Writing – review & editing. **Milica Mićić**: Methodology, Writing – review & editing. **Luka Lazarević**: Supervision, Conceptualization, Writing – review & editing.

Declaration of conflicting interests

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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References

[1] Z. Popović, L. Lazarević, The role of railway in the European transport policy, Izgradnja 67(7-8) (2013) 285-291.

[2] M. Mićić, Lj.Brajović, L. Lazarević, Z.Popović,Inspection of RCF rail defects–Review of NDT methods, Mech. Syst. Signal Pr. 182 (2023)109568.https://doi.org/10.1016/j.ymssp.2022.109568.

[3] International Union of Railways, IRS 70712 Rail Defects, 2018.

[4] CEN, EN 16729-3:2018, Railway applications - Infrastructure - Non-destructive testing on rails in track - Part 3: Requirements for identifying internal and surface rail defects.

[5] CEN, EN 13231-5:2018, Railway applications - Track - Acceptance of works - Part 5: Procedures for rail reprofiling in plain line, switches, crossings and expansion devices.

[6] Z. Popović, L.Lazarević, M.Mićić, Lj.Brajović, Critical analysis of RCF rail defects classification, Transportation Research Procedia 63(2022) 2550-2561. https://doi.org/10.1016/j.trpro.2022.06.294.

[7] International Union of Railways, UIC Code 712 Rail defects, 2002.

[8] International Union of Railways, UIC Code 725 Treatment of rail defects, 2015.

[9] Office of Rail Regulation, Train derailment at Hatfield: A final report by the independent investigation board. https://www.railwaysarchive.co.uk/documents/HSE_HatfieldFinal2006.pdf, 2006 (accessed 10 January 2024).

[10] E. Magel, P. Mutton, A. Ekberg, A. Kapoor, Rolling contact fatigue, wear and broken rail derailments, Wear 366 (2016) 249-257. https://doi.org/10.1016/j.wear.2016.06.009.

[11] Z. Popović, V. Radović, Analysis of cracking on running surface of rails, Gradevinar 65(3) (2013) 251-259. https://doi.org/10.14256/JCE.877.2012.

[12] M. Ishida, Rolling contact fatigue (RCF) defect of rails in Japanese railways and its mitigation strategies, Electron. J. Struct. Eng. 13 (1) (2013) 67–74.https://doi.org/10.56748/ejse.131621.

[13] Z. Popović, Lj. Brajović, L. Lazarević, L. Milosavljević, Rail defects head checking on the Serbian railways, Teh. Vjesn. 21(1) (2014) 147-153. https://hrcak.srce.hr/116587.

[14] R. Heyder, M. Brehmer, Empirical studies of head check propagation on the DB network, Wear 314(1-2) (2014) 36-43. https://doi.org/10.1016/j.wear.2013.11.035.

[15] M. Vilotijević, Lj. Brajović, A. Pustovgar, Methodology for statistical analysis of squat rail defects, in: XVIII Scientific-expert conference on railways-RAILCON 18, Faculty of Mechanical Engineering, Niš, Serbia, 2018, pp. 157-160.

[16] M. Ishida, History of mitigating rolling contact fatigue and corrugation of railway rails in Japan-Review, EPI Int. J. Eng. 1(2) (2018) 13-24.https://doi.org/10.25042/epi-ije.082018.02.

[17] V.V. Krishna, S. Hossein-Nia, C. Casanueva, S. Stichel, Long term rail surface damage considering maintenance interventions, Wear 460–461 (2020) 203462.https://doi.org/10.1016/j.wear.2020.203462.

[18] H. Zhu, H. Li, A. Al-Juboori, D. Wexler, C. Lu, A. McCusker, J. McLeod, S. Pannila, J. Barnes, Understanding and treatment of squat defects in a railway network, Wear 442 (2020) 203139.https://doi.org/10.1016/j.wear.2019.203139.

[19] S.Y. Zhang, M. Spiryagin, H.H. Ding, Q. Wu, J. Guo, Q.Y. Liu, W.J. Wang, Rail rolling contact fatigue formation and evolution with surface defects, Int. J. Fatigue 158 (2022) 106762.https://doi.org/10.1016/j.ijfatigue.2022.106762.

[20] W. Schoech, Rolling contact fatigue mitigation by grinding, in: Proceedings of the Rail Tech Europe Conference, Utrecht, 2007.

[21] Y. Santur, M. Karaköse, E. Akin, Random forest based diagnosis approach for rail fault inspection in railways, in: 2016 National Conference on Electrical, Electronics and Biomedical Engineering (ELECO 2016), Bursa, Turkey, 2016, pp. 745-750.

[22] Z. Popović, V. Radović, L. Lazarević, V. Vukadinović, G. Tepić, Rail inspection of RCF defects, Metalurgija 52(4) (2013) 537-540. https://hrcak.srce.hr/100836.

[23] Tvema. https://tvema.com/640, (accessed 10 January 2024).

[24] F. Marino, A. Distante, P.L. Mazzeo, E. Stella, A real-time visual inspection system for railway maintenance: automatic hexagonal-headed bolts detection, IEEE T. Syst. Man Cy. C 37(3) (2007) 418-428. https://doi.org/10.1109/TSMCC.2007.893278.

[25] Y. Min, B. Xiao, J. Dang, B. Yue, T. Cheng, Real time detection system for rail surface defects based on machine vision, EURASIP J. Image. Vide. 2018 (1) (2018) 3, https://doi.org/10.1186/s13640-017-0241-y.

[26] D. De Becker, J. Dobrzanski, L. Justham, Y. Goh, A laser scanner based approach for identifying rail surface squat defects, P. I. Mech. Eng. F-J. Rai. 235 (6) (2021) 763–773, https://doi.org/10.1177/0954409720962252.

[27] J. Ye, E. Stewart, C. Roberts, Use of a 3D model to improve the performance of laser-based railway track inspection, P. I. Mech. Eng. F-J. Rai. 233 (3) (2019) 337–355, https://doi.org/10.1177/0954409718795714.

[28] Y. Wu, Y. Qin, Z. Wang, L. Jia, A UAV-based visual inspection method for rail surface defects, Appl. Sci. 8 (7) (2018) 1028, https://doi.org/10.3390/app8071028.

[29] N. Pedrosa, M. Pinto, M. Papaelias, INTERAIL - Towards a safer and reliable European Railway, in: Transport Research Arena (TRA) 5th Conference: Transport Solutions from Research to Deployment, Paris, France, 2014, 10 pp.

[30] CEN, EN 16729-1:2016, Railway applications - Infrastructure - Non-destructive testing on rails in track - Part 1: Requirements for ultrasonic inspection and evaluation principles.

[31] CEN, EN 16729-2:2020, Railway applications - Infrastructure - Non-destructive testing on rails in track - Part 2: Eddy current testing of rails in track.

[32] Z. Popović, Lj. Brajović, L. Lazarević, Rail inspection by eddy current method, in: 3rd International Scientific and Professional Conference „CORRIDOR 10 - A sustainable way of integrations“, Belgrade, Serbia, 2012, pp. 238-251.

[33] R. Pohl, R. Krull, R. Meierhofer, A new eddy current instrument in a grinding train, in 9th European Conference on NDT, Berlin, Germany, 2006, pp. 1-7. https://www.ndt.net/article/ecndt2006/doc/P178.pdf

[34] T. Szugs, A. Krüger, G. Jansen, B. Beltman, S. Gao, H. Mühmel, R. Ahlbrink, Combination of ultrasonic and eddy current testing with imaging for characterization of rolling contact fatigue, in: 19th World Conference on Non-Destructive Testing (WCNDT 2016), Munich, Germany, 2016, vol. 2, pp. 1603-1610. https://www.wcndt2016.com/Programme/show/P22.

[35] J. Rajamaki, M. Vippola, A. Nurmikolu, T. Viitala, Limitations of eddy current inspection in railway rail evaluation, P. I. Mech. Eng. F-J. Rai. 232 (1) (2016) 121–129, https://doi.org/10.1177/0954409716657848.

[36] A. Opanasenko, A. Iurchenko, G. Lutsenko, V. Uchanin, Eddy current multi-channel module for in-line high-speed inspection of railroad rails, in: 19th World Conference on Non-Destructive Testing (WCNDT 2016), Munich, Germany, 2016, vol.6, pp. 4478-4484,https://www.wcndt2016.com/Programme/show/P98.

[37] V. Uchanin, New type multidifferencial eddy current probes for surface and subsurface flaw detection, in: ZeszytyproblemoweBadanianieniszczące, Warsaw, Poland, 2001, no. 6, pp. 201-204.

[38] S.G. Kwon, T.G. Lee, S.J. Park, J.W. Park, J.M. Seo, Natural rail surface defect inspection and analysis using 16-channel eddy current system, Appl. Sci. 11 (17) (2021) 8107, https://doi.org/10.3390/app11178107.

[39] J.W. Park, T.G. Lee, I.C. Back, S.J. Park, J.M. Seo, W.J. Choi, S.G. Kwon, Rail surface defect detection and analysis using multi-channel eddy current method based algorithm for defect evaluation, J. Nondestruct. Eval. 40 (2021) 83, https://doi.org/10.1007/s10921-021-00810-9.

[40] M. Molodova, Z. Li, A. Núñez, R. Dollevoet, Automatic detection of squats in railway infrastructure, IEEE T. Intell. Transp. 15 (5) (2014) 1980–1990, https://doi.org/10.1109/TITS.2014.2307955.

[41] H. Cho, J. Park, K. Park, Analysis of axial acceleration for the detection of rail squats in high-speed railways, CivilEng 4(4) (2023), 1143-1156, https://doi.org/10.3390/civileng4040062

[42] Z. Li, M. Molodova, A. Núñez, R. Dollevoet, Improvements in axle box acceleration measurements for the detection of light squats in railway infrastructure, IEEE T. Ind. Electron. 62 (7) (2015) 4385–4397, https://doi.org/10.1109/TIE.2015.2389761.