

Plenary Session



FROM AUTOMATION TO INTELLIGENT TRAIN CONTROL: AI, DIGITAL TWINS AND TRUSTWORTHY AUTONOMY FOR FUTURE RAILWAYS

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Abstract – Railway transport is entering a new phase of digital transformation in which automation, artificial intelligence and advanced communications are expected to support higher capacity, improved energy efficiency, more flexible operations and enhanced safety. Current railway control architectures already provide a mature foundation through Automatic Train Protection, Automatic Train Operation and traffic supervision, with the certified signalling and train-protection layer defining the safety envelope within which trains are allowed to operate. Moving from conventional automation to higher levels of autonomy, however, requires additional intelligence: trains and infrastructure must perceive operational contexts, detect anomalies, support human operators and adapt to degraded or unexpected situations without compromising safety integrity. This keynote presents a vision of Intelligent Train Control as the progressive evolution of automatic train management towards trustworthy autonomous railway systems. The core idea is not to replace the proven principles of railway safety with opaque AI, but to integrate AI-enabled functions around and within existing control paradigms in a way that remains explainable, verifiable and certifiable. Examples include AI-based driving assistance, obstacle and intrusion detection, artificial vision for railway signal recognition, predictive maintenance of railway assets, anomaly detection at level crossings, and decision-support functions for traffic management and supervision. Such functions can enrich the operational picture available to drivers and control centres while supporting the gradual transition towards autonomous and resilient railway operations. A central part of this vision is the combination of trustworthy artificial intelligence with digital twins and autonomic computing. Digital twins can act as run-time predictive models, continuously synchronised with the physical world through sensor data and operational information. Coupled with MAPE-K loops — monitoring, analysis, planning, and execution over a shared knowledge — they can support online diagnosis, prediction, reconfiguration and self-healing strategies. In safety-critical railway contexts, this requires robust sensor fusion, redundancy and diversity, explicit management of uncertainty, and explainable reasoning mechanisms such as probabilistic models and Bayesian networks, so that AI outputs remain understandable to human operators and assessable by safety engineers. The keynote will also discuss open research and engineering challenges that must be addressed before intelligent train control can be widely deployed. These include the availability and sharing of high-quality datasets, the generation of rare and adverse operating conditions, mixed-reality simulation for testing machine-learning components, assurance cases for AI-enabled functions, and the integration of distributed intelligence across edge, fog and cloud layers. Particular emphasis will be placed on preserving human oversight, regulatory compliance and safety certification while exploiting AI to improve perception, prediction and operational decision-making. By framing AI as an enabling technology within a disciplined systems-engineering approach, Intelligent Train Control can contribute to future railways that are safer, more efficient and sustainable, and better prepared for autonomous operation.

Keywords - intelligent train control; autonomous railways; trustworthy AI; digital twins; safe perception; railway automation; safety-critical systems.

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FROM NODE TO NETWORK: HOW TRANSPORT INTERCHANGES DEFINE THE PATHWAYS TO RAILWAY TRANSFORMATION

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Abstract – Railways are increasingly expected to serve as the structural backbone of decarbonised, urbanised and digitally integrated mobility systems. This work argues that the pathway to railway transformation runs through transport interchanges, and that a railway's value is created less at the node than through it. Drawing on network science, we reconceptualise the interchange as a physical, modal, informational and urban junction whose quality is a network variable: transfer friction at a single node propagates into the effective connectivity, resilience and reach of every route passing through it. We propose a six-tier typology of interchanges, from local halts to high-speed international hubs and freight–passenger co-located nodes, with a five-dimension assessment framework covering connectivity, transfer friction, resilience contribution, land-use integration and passenger experience. Comparative evidence from European case studies shows that, despite divergent primary levers, successful schemes share a common narrative: multi-actor governance, friction reduction by design and network-level demand effects. The digital layer, comprising Mobility-as-a-Service, real-time information, station digital twins and fare interoperability, can deliver connectivity gains comparable to civil works at lower cost. Situating the analysis within the 2026 European policy context, including TEN-T requirements for multimodal passenger hubs in 431 urban nodes by 2030 and proposed single-ticket passenger rights contingent on minimum connection times, we present an iterative Diagnose–Design–Integrate–Govern–Evaluate pathway model. We conclude that railway transformation is as much an institutional challenge as an engineering one, demanding appraisal, funding and governance at network scale.

Keywords - transport interchanges; multimodal hubs, railway governance, TEN-T urban nodes, network centrality.

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ENHANCING COMPETITIVENESS OF INTERNATIONAL RAILWAY FREIGHT CORRIDORS THROUGH A COOPERATIVE GAME APPROACH

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Abstract – This research addresses the problem of governance of European rail freight corridors through the formulation of an economic model of intergovernmental cooperation along the corridors, based on the application of cooperative game theory. The main aim of the research is to develop a model demonstrating that a cooperative approach can enhance the efficiency and competitiveness of rail freight corridors in Europe. By applying cooperative games, the research seeks to define a fair and stable mechanism for distributing the benefits that arise from joint governance and coordinated policy implementation along the corridors. The core objectives of the research are to formulate an economic model that integrates a transport demand model with a cooperative game among states, to develop new solution concepts for benefit allocation, and to assess their applicability in the real operating environment of rail freight corridors. Three solution concepts are applied: the Shapley value, as a theoretically grounded and widely accepted approach, and two newly developed concepts specifically tailored to the characteristics of rail corridors termed as the Proportional Rule and the Adjusted Proportional Rule. The applicability of the proposed model is demonstrated through the Alpine–Western Balkan Rail Freight Corridor, which connects Austria, Slovenia, Croatia, Serbia, and Bulgaria. Based on a transport demand model calibrated with real corridor data, it was established that the joint implementation of measures defined through a cooperation strategy could increase freight volume by 43%. The analysis of 32 possible state coalitions showed that the Shapley Value and the Proportional Rule led to stable outcomes in which no country has an incentive to leave the grand coalition, whereas the Adjusted Proportional Rule reveals that, in certain smaller coalitions, some countries may achieve higher individual payoffs. However, given the strategic nature of rail freight corridors, such shortcomings can be overcome through political negotiations and intergovernmental compromises. The findings confirm that cooperative games represent an effective analytical instrument for improving the governance of rail freight corridors, as they provide an objective means of measuring the effects of cooperation and developing equitable benefit-sharing mechanisms. At the same time, the proposed model demonstrates potential for application beyond the European context, particularly on Eurasian corridors connecting China and Europe, where institutional mechanisms of cooperation have not yet been fully established.

Keywords – rail freight corridors; competitiveness; cooperative games; Shapley value; benefit allocation.

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IMPROVING THE RELIABILITY OF RELEVANT RAILWAY SIGNAL DETECTION BY COMBINING ARTIFICIAL INTELLIGENCE AND CLASSICAL COMPUTER VISION METHODS

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Abstract – Transferring visual monitoring tasks from the driver to onboard systems is an important research direction for autonomous railway operation. Reliable recognition of wayside signals could support drivers and, following further development and safety validation, contribute to driverless operation on conventionally signalled routes. This requires more than recognising a light's colour: the system must identify the signal that applies to the train's own track and provide a timely, stable interpretation. The task becomes more difficult when several tracks and signals are visible in the same scene, particularly under varying lighting conditions. This paper presents a hybrid framework combining deep learning, classical computer vision and temporal verification. TEP-Net estimates the train's ego-path, supported by Canny edge detection and Hough-based geometric checks. In the proposed configuration, YOLO detects red, yellow and green signal lights across the full image. The estimated ego-path defines a narrower region of interest for additional candidate detection using histogram of oriented gradients features and logistic regression, and a wider region for assessing signal-to-track association. After candidate matching, local colour and shape checks complement the detector outputs. Signal evidence, track quality and spatial evidence are combined to score each candidate. Candidates are tracked across successive frames before confirmation. When the evidence is insufficient to distinguish between them, the system leaves the choice unresolved rather than selecting a signal solely on the basis of its detection score. Digital infrastructure maps combined with train localisation are considered as a future extension to support verification of the estimated track and association of detected candidates with expected signals. The experimental protocol uses two datasets from railway environments with different infrastructure, terrain, signalling and vegetation. Each includes nested training sets of 500, 1,500 and 3,000 images, a fixed 300-image validation set and separate video test sequences. Planned comparisons between the detector alone and different fusion configurations will assess detection accuracy, incorrect signal-to-track association, missed restrictive signals, temporal stability and decision delay. The intended contribution is a modular framework whose decisions can be examined through individual module outputs, together with a reproducible procedure for evaluating its benefits and limitations.

Keywords - autonomous railways; driver assistance; railway signal detection; ego-path detection; temporal verification.

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Rolling Stock



CALCULATION OF SELECTED PARAMETERS OF A SCREW COUPLER AND BUFFERS OF A LOCOMOTIVE SCALED MODEL

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Abstract – Railway and railway vehicles are often not only a favorite kind of transport, or favorite kind of a transport means, but also a subject of personal hobby of many people. Efforts to be as near as possible to railways force people to develop scaled models of railway vehicles together with the needed infrastructure. The presented study is focused on determination of selected parameters of a chosen components of a scaled model of a shunting locomotive. It is a shunting locomotive of older design, but due to its availability, it was chosen for creating of the scaled model. Performed calculations are based on an analytical approach. The dimensional calculation comes from the strength and plasticity theory. There are calculated parameters of the screw coupler and the buffers. These structural units are important mainly during acceleration and deceleration of the vehicle during operation.

Keywords – calculation, locomotive, scaled model, screw coupler, buffer.

1. INTRODUCTION

Railway modelling is a long-standing activity that combines technology and creativity. It is an activity in which people with a passion for railways strive to create functional, realistic scale models of real railway systems. In addition to the vehicles themselves, their operating environments are also created, such as tracks, landscapes, buildings, station buildings and various infrastructure accessories. According to the National Modelling Association (NMRA), it also includes a lot of work from planning to subgrade construction, electrical installation, environment construction, to the detailed creation of vehicles and their technical elements.

When designing the structural parts of the vehicle, it was necessary to base the design on a real existing locomotive. When making the selection, it was necessary to consider several factors that significantly influence the design solutions when creating the

model. Since it is a 1:8 scale model, the resulting model will be reduced by 8-times compared to the real locomotive. The main criteria are the manufacturability of individual components, economic and efficient production and structural simplicity of the proposed solution, the availability of technical documentation, as well as the possibility of a physical inspection of the locomotive. Based on these input conditions, the shunting locomotive R799 was selected (Fig. 1). Fig. 2 depicts a compositive view to the chosen locomotive.

A screw coupler and buffers device located on the front ends of the main frame serves to connect the individual rail vehicles (i.e. a locomotive and wagons) in a train and to transfer longitudinal forces between the vehicles. With its spring device, it is able to absorb a significant part of the dynamic longitudinal forces that arise during the operation of railway vehicles, especially during starting and braking, and mainly during shunting movement. Most railway vehicles on

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the European standard gauge railway network use a coupling device with separate functions for the transfer of push and pull forces as standard. A screw coupler in the form of a hook and a screw is used to transfer the pull forces, and two buffers mounted symmetrically to transfer the pressure forces [1, 2].



Fig.1. A locomotive R799 class

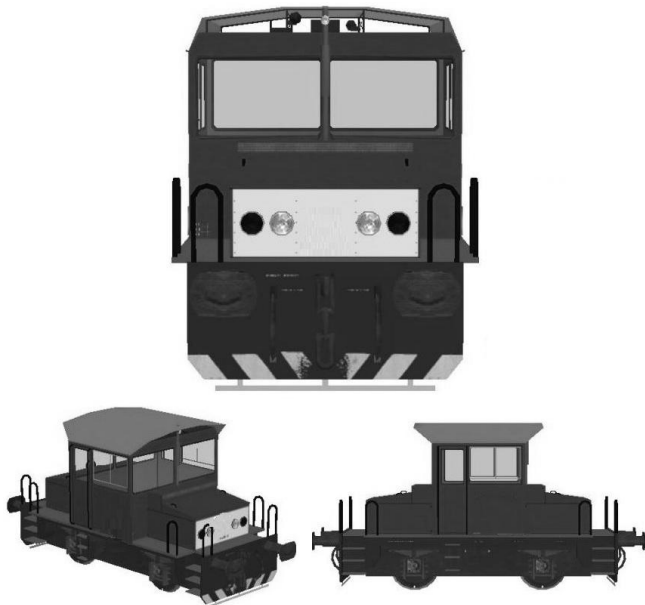


Fig.2. A compositive view of the chosen locomotive

The main objective of the presented work is to calculate the selected parameters of the screw coupler and buffers, which will be mounted on a scaled model of the chosen shunting locomotive.

2. CALCULATION OF PARAMETERS OF THE SCREW COUPLER

The suspension of the screw coupler hook is an important part of the screw coupler of a railway vehicle. Its main function is to reduce the dynamic shocks associated with starting. The elastic element in the screw coupler allows partial deformation of the system when longitudinal forces are applied, thereby absorbing and gradually transferring energy [3]. This reduces the stress on individual structural parts and at the same time improves the operational properties of the vehicles. The calculation of the suspension is

based on the requirements for damping the longitudinal forces acting in the drawbar.

Fig. 3 shows the assembly of the screw coupler. It consists of a hook, guide, pin, tie bolt and a spring-loaded body with an annular spring. The tow hook forms an external functional member for capturing the coupled vehicle. It transfers the load to the internal towing mechanism via the pin. The design is based on the principle of two mutually sliding tubes. The external tube performs the function of supporting and guiding casing, and the internal tube is connected to the moving part of the mechanism. A tie bolt is located in the rear part of the assembly, which serves to connect, adjust and transfer force to the elastic system. The annular spring ensures elastic shock absorption. When the towing force is applied, the internal parts in the guide move longitudinally, the spring is compressed and the load is smoothly transferred. The location of the drawbar hook also allows to be rotated in a horizontal plane, which is especially necessary when passing through curves in the track, when their relative position changes.

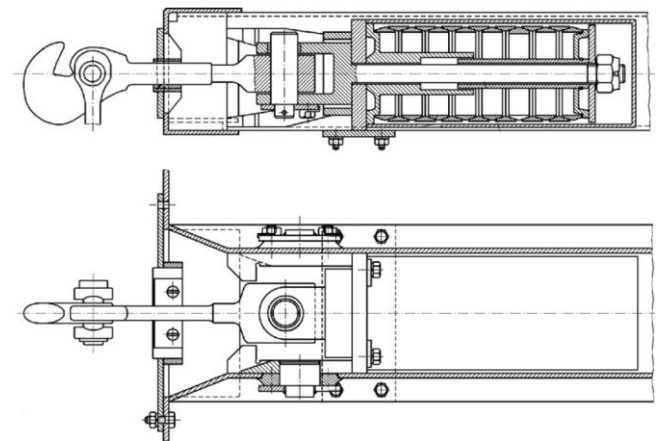


Fig.3. A conceptual view to the screw coupler

The basic assumption for the design of the spring and ensuring its proper operation is the loading force. This force was defined when calculating the resistances, i.e. 79.2 N. It is assumed that a situation may arise where the load increases due to the action of a dynamic shock [4]. Therefore, the dynamic safety coefficient $k_d = 2$ was chosen:

$$F_{pt} = F_o \cdot k_d = 79.2 \cdot 2 = 158.4 \text{ N} \quad (1)$$

Thus, the maximum force F_{pt} that was considered in the calculation is 158.4 N. The maximum stroke considered is 20 mm. After determining these two parameters, it was possible to calculate the required spring stiffness k :

$$k = \frac{F_{pt}}{x} = \frac{158.4}{20} = 7.92 \text{ N} \cdot \text{mm}^{-1} \quad (2)$$

Since the design of the locomotive model is based on the use of standardized components, the screw

coupler spring will also be selected as a standardized element. In the previous section, the required functional parameters of the spring, design force, working stroke and required stiffness were determined by calculation. These values represent the basic criteria for selecting a suitable spring [5]. Other geometric parameters of the spring, such as wire diameter, number of turns, free length, inner and outer diameter, will be selected from the range of standardized springs. In CAD modeling, a specific standardized spring will then be selected, which will satisfy the spatial and geometric conditions in terms of geometry and will also meet the calculated stiffness and working stroke. Fig. 4. shows a 3D model of the designed screw coupler of the locomotive scaled model.

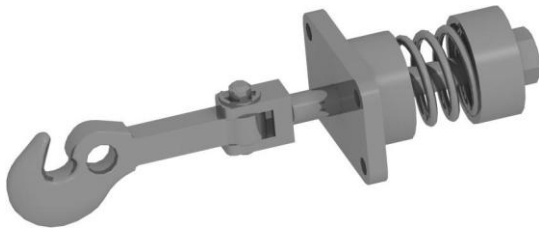


Fig.4. The three-dimensional model of the screw coupler

The concept of the screw coupler was chosen from Fig. 3, which shows the connection of the screw coupler hook to the screw coupler bolt using a pin. The screw coupler hook is rotated around this pin. At the same time, it is subjected to double shear stress during the transfer of forces. Therefore, it was necessary to design its diameter using dimensional calculation [9]:

$$\tau_s = \frac{F}{S} = \frac{F_{pt}}{2 \cdot \frac{\pi \cdot d^2}{4}} = \frac{2 \cdot F_{pt}}{\pi \cdot d^2} \quad (3)$$

Formula (3) shows the basic relationship for shear stress. The area S must be multiplied by 2 because it is a double shear. To calculate the minimum diameter d of the pin, it is necessary to include the material properties in the calculation. C45 steel was chosen as the material.

C45 steel is an unalloyed structural carbon steel with a medium carbon content, which is commonly used to produce machine parts stressed for strength, such as pins and shafts. It is characterized by a good ratio of strength, toughness and is also suitable for heat treatment. The permissible shear stress is stated as 80 to 120 MPa. The average value, i.e. 100 MPa, is taken for the calculation [14]:

$$\tau_D \leq \tau_s \Rightarrow \tau_D \leq \frac{2 \cdot F_{pt}}{\pi \cdot d_{min}^2} \quad (3)$$

Then:

$$d_{min} = \sqrt{\frac{2 \cdot 140}{\pi \cdot 100}} = 0.94 \text{ mm} \quad (4)$$

By expressing the diameter d_{min} from the strength condition, the minimum value of the pin diameter was determined. However, this value cannot be the final value and must be adjusted by the safety factor k_s . The value of the safety factor was chosen to be 3. Therefore, the final value for the pin diameter is calculated as follows:

$$d = d_{min} \cdot k = 0.94 \cdot 3 = 2.82 \text{ mm} \quad (5)$$

Thus, the final value of the pin diameter is of 2.82 mm. The calculated value serves as an indicative basis for the structural design and subsequent CAD modeling of the drawbar. When creating the 3D model, the pin diameter will be adapted to the normalized dimensions and design requirements, while the nearest larger normalized diameter will be selected.

3. CALCULATION OF PARAMETERS OF BUFFERS

Buffers on locomotives serve to absorb impacts during vehicle contact, especially when coupling or when transmitting longitudinal forces during travel. Their role is to reduce the magnitude of impacts, protect the vehicle frame and other parts from damage, and at the same time contribute to a smoother transfer of forces between vehicles [6].

The buffer (Fig. 5) consists of a buffer plate, a base plate for attachment to the vehicle frame, a basket tube and a buffer tube as a guide sleeve. The inner part consists of a rod guided in a flexible member, which is usually in the form of an annular spring. The assembly is supplemented with washers and guide elements, and a screw for adjusting the preload [6].

Forces act on the buffers, just like the screw coupler. The calculation of the buffer spring is based on determining the magnitude of the load acting on the buffer and the required stroke when compressed. For the model under consideration, the load caused by the deceleration of the system, i.e. the braking force, is considered [7]. When braking, the force of the towed system is transferred to the locomotive. This force depends on the mass of the set and the braking deceleration. A 3D model of the designed buffer is shown in Fig. 6.

The braking deceleration considered is $0.15 \text{ m} \cdot \text{s}^{-2}$. That is, the deceleration for normal operation.

$$F_b = m \cdot a_b = 300 \cdot 0.15 = 45 \text{ N} \quad (6)$$

The braking force transmitted to the front of the locomotive is 45 N. This force must be absorbed by the two bumpers that will be mounted on the fronts of the locomotive.

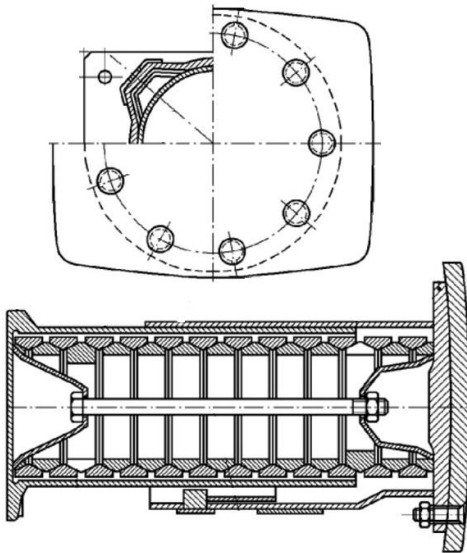


Fig.5. A conceptional view of the buffer

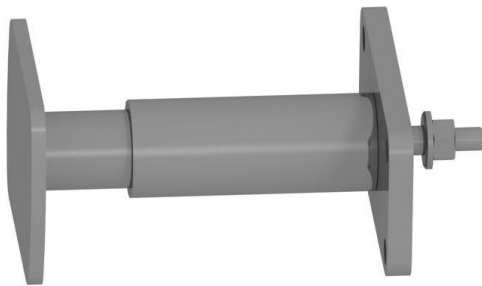


Fig.6. A three-dimensional model of the buffer

As a result, the force is ideally distributed evenly, i.e. 22.5 N per a buffer. Due to the occurrence of dynamic shocks, sudden braking with high intensity, it was necessary to increase this force by a safety margin. Therefore, the load was increased to 35 N per a buffer. The working pressure was determined to be 5 mm:

$$k_b = \frac{F_b}{x} = \frac{35}{5} = 7 \text{ N} \cdot \text{mm}^{-1} \quad (4)$$

Both the screw coupler and the buffers will contain a coiled compression spring. Since this is a standardized part, it will be necessary to choose a spring with the closest parameters. An important parameter will be the closest stiffness while compromising with the dimensional conditions of the frame. Therefore, the buffers are designed primarily as an element for transmitting operating forces with a limited ability to absorb minor impacts, not as a full-fledged system for absorbing kinetic energy in a frontal impact of the entire set.

4. CONCLUSION

The presented research was focused on calculation of the selected parameters of the screw coupler and

buffers, which will be mounted in a scaled mode of the shunting locomotive. These calculations were performed by an analytical approach. There are calculated forces, stiffnesses and deflections of the chosen components. The chapter Conclusion which summarizes the paper is obligatory. The future research will be focused on calculation, analysis and dimensioning all important components of the locomotive, which are necessary to launch the locomotive to a real operation.

ACKNOWLEDGEMENT

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REFERENCES

- [1] Kalinčák, D., *Rail vehicles I* (in Slovak), University of Žilina, Žilina, Slovak Republic, 2008.
- [2] Zošiak, M., *Design of selected structural elements of the travel of a two-axle locomotive in a scale of 1:8* (in Slovak), Qualification thesis, University of Žilina, Žilina, Slovak Republic, 2026.
- [3] Serajian, R., Mohammadi, S., Nasr, A., *Influence of train length on in-train longitudinal forces during brake application*, Vehicle System Dynamics, 57, 2, 192–206, 2019.
- [4] Wu, H., Luo, S., Fu, B., Wang, L., Wang, L., *Research on adaptability of diesel locomotive in plateau railway based on dynamics*, Proceedings of the SPIE conference, Seventh International Conference on Electromechanical Control Technology and Transportation (ICECTT 2022), 123020E, 2022.
- [5] Xu, P., Qu, C., Yao, S., Yang, C., Wang, A., *Numerical optimization for the impact performance of a rubber ring buffer of a train coupler*, Energies, 9, 10, 225, 2021.
- [6] Zhang, Z., Chu, G., Lv, K., Wang, F., Zhang, Y., *Experimental investigation on the dynamic performance of a heavy haul locomotive and its coupler and buffer system under longitudinal forces*, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 240, 4, 465–476, 2026.
- [7] Musayev, J., Zhauyt, A., Solonenko, V., Alipbayev, K., Kaliyeva, N., Smailova, G., Kurmangaliyeva, N., *Modeling the interaction of the rolling stock and the track in the emergency braking mode of a passenger train*, Engineered Science, 40, 2026.



A STUDY OF THE STRENGTH OF THE LOAD-BEARING STRUCTURE OF A BOX WAGON WITH CORRUGATED CLADDING SHEETS

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Abstract – The study is based on the assumption that the strength of the load-bearing structure of a box wagon can be improved by using corrugated sheets. It can reduce the tare of the load-bearing structure of the box wagon in comparison with that of the typical design by 2.3%. To substantiate the proposed improvement, the strength of the load-bearing structure of the box wagon is calculated using the finite element method. A spatial model of the load-bearing structure of the box wagon is constructed in SolidWorks. The von Mises criterion is used as the design criterion in the calculations. The results demonstrate that the proposed solution reduces stresses in the cladding by 8.6% compared to the typical design. The conducted studies will help improve the strength of the load-bearing structures of a box wagon and reduce its maintenance cost.

Keywords – box wagon, design improvements, corrugated cladding sheets, structural strength, railway transport.

1. INTRODUCTION

Rail transport is the most important sector of the transport system, which is responsible for transporting passengers and freight, including goods of strategic importance. Railways carry a wide and varied range of goods, among which are those that require protection from the elements, which are transported primarily in box wagons.

The box wagon walls are usually made of stamped metal sheets that may have various types of damage (deformations, cracks, tears, etc.) caused by the operational load conditions. Such damage requires unscheduled repairs to the wagons, and, consequently, incurs maintenance costs. Furthermore, the train that includes a wagon with such damage can pose a threat to the rail operation safety. It is therefore necessary to improve the cladding of a box wagon in order to enhance their operational efficiency.

In order to study the current state of the research into the improvements of load-bearing structures in box wagons, a review of recent scientific publications has been carried out. In [1], it is proposed that the tare weight of a box wagon can be reduced by improving its roof through constructing it as a triangular arch.

This solution reduces the tare weight of the wagon body by 1.8% compared with that of the typical design. The calculations of the dynamic and strength characteristics of the proposed wagon body with the roof confirm the effectiveness of this solution. However, the authors do not consider the issue of improving the cladding of such a wagon.

The design improvements to the body of the BCNHL box wagon are described in [2]. The authors propose changes to the door opening geometry in order to facilitate loading/unloading operations by using mechanised equipment. However, limited attention has been given to enhancing the structural strength of the wagon body cladding during operation.

In [3], the strength of a box wagon's body walls is improved through the use of sandwich panels, comprising two smooth metal sheets with an energy-absorbing material core. The strength calculations demonstrate the feasibility of this solution. However, efficiency can be improved by modifying the configuration of the sheets within the sandwich panel.

A similar shortcoming is also found in [4, 5], where the strength of the cladding of a wagon is improved by using materials with better strength and

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mass characteristics. Although such materials offer several advantages over steel, they require significant capital investment and the availability of the necessary technical infrastructure for wagon repair and maintenance.

The analysis of scientific publications has shown that at present the issue of improving the cladding of box wagons has yet to be addressed, which requires therefore relevant research in this area.

The purpose of the study is to substantiate the use of corrugated sheets for cladding for the box wagon body. To achieve this purpose, the following tasks were set:

- to construct a three-dimensional model of the load-bearing structure of a box wagon with corrugated

cladding sheets, and

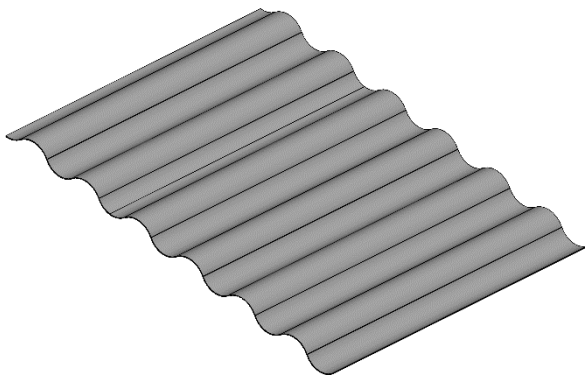
- to calculate the strength of the load-bearing structure of a box wagon.

2. MATERIALS AND METHODS OF RESEARCH

The box wagon is intended for transporting goods that need protection from the elements.

There is a range of specialised wagons on the basis of the general-purpose wagons.

It was proposed to improve the strength of the box wagon by using corrugated sheets as its cladding (Fig. 1).



a)



b)

Fig.1. The damage to the cladding of a box wagon: a) deformation of the third cladding sheet from the corner post; b) deformation of the outermost cladding sheet from the corner post

A corrugated sheet has a number of advantages over a smooth sheet. Thus, it provides higher structural strength due to the wavy layers which divide the material into several parts, thus reducing the probability of tearing. Corrugated sheets also possess shock-absorbing properties, which protect the packaged cargo from vibration loads. Furthermore, their use reduces the overall structural weight.

To confirm this hypothesis, a spatial model of the box wagon body was developed, featuring cladding made of corrugated sheets. The spatial model was constructed in SolidWorks (Fig. 2), and the strength was calculated in SolidWorks Simulation.

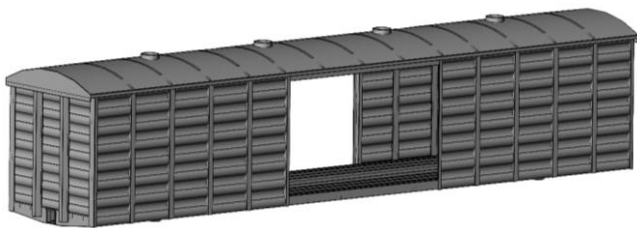


Fig.2. The spatial model of the load-bearing structure of the box wagon

The spatial model of the load-bearing structure of the box wagon included the elements rigidly interacted with each other. Since the double-leaf doors had hinged interaction with the body, they were not included in the model.

The thickness of the cladding sheet was assumed to be 2 mm. It was determined by the optimization model developed in the previous studies of the authors. Importantly, the use of corrugated sheets can also reduce the tare of the load-bearing structure of the box wagon compared to that of the typical design by 2.3%.

The strength of the load-bearing structure of the box wagon was calculated using the finite element method. As far as the load-bearing structure of the wagon was made of low-alloy steel 09G2S, the von Mises criterion was used in the calculations. For this steel grade, the permissible stresses are 310.5 MPa for design mode I and 210 MPa for design mode III of wagon operation [6].

The finite-element model of the load-bearing structure of the box wagon was formed by tetrahedra (Fig. 3). The number of elements was determined graphically and analytically by performing a mesh sensitivity analysis. Thus, the model had 222,372 elements, and 72,316 nodes. The maximum size of the

element in the model was 12.5 mm, and the minimum size was 0.625 mm. The mesh was refined in the areas of rounding using the software package options.

The structural design scheme of the load-bearing structure of the box wagon included the effect of the vertical load P_v (Fig. 4).

The walls of the body were subject to the pressure P_p from the bulk cargo (grain). The longitudinal force P_l , which was equal to 3.5 MN, was applied to the rear draft lugs. This force was balanced by the reaction R applied on the opposite side of the wagon. The support of the body on the bogies was represented by rigid elements placed at the centre plates.

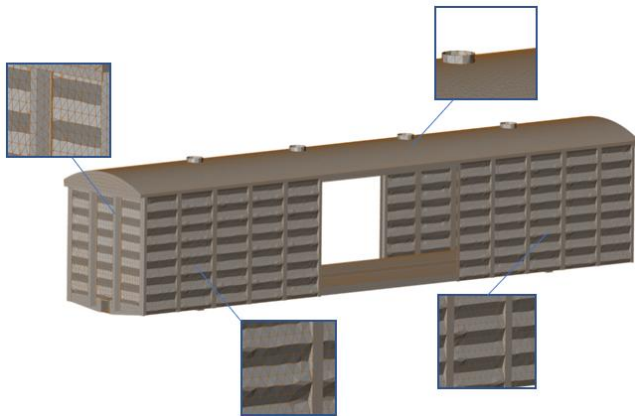


Fig. 3. The finite element model of the load-bearing structure of the box wagon

The pressure from the bulk cargo P_p was calculated by the formula

$$P_p = \gamma \cdot g \cdot H \cdot tg^2 \left(\frac{\pi}{4} - \frac{\varphi}{2} \right), \quad (1)$$

where γ is the density of bulk cargo, t/m^3 ; H is the height of the side wall, m; φ is the critical angle of repose of the cargo, rad; g is the free fall acceleration, m/s^2 .

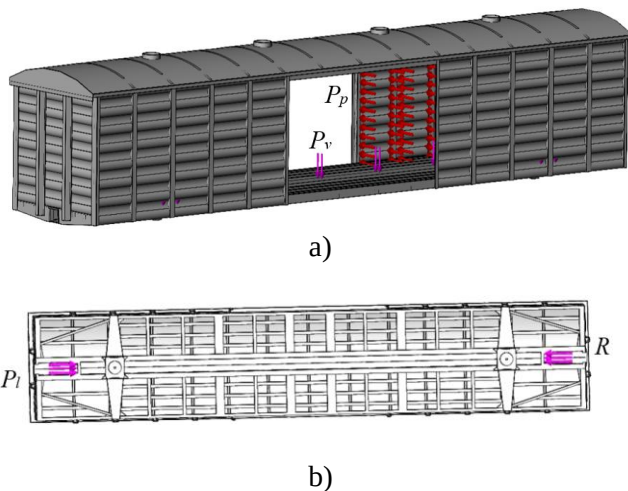


Fig. 4. The structural design scheme of the load-bearing structure of the box wagon: a) vertical and transverse forces; b) longitudinal forces

3. RESULTS AND DISCUSSION

The design model built was used to calculate the strength of the load-bearing structure of the box wagon. The results are shown in Fig. 5 – 7. The maximum stresses were recorded in the centre sill of the frame between centre plates and bolsters (Fig. 5). These stresses amounted to 304.4 MPa (Fig. 6) and were lower than permissible. In the cladding, the maximum stresses were 128.3 MPa; they were 8.6% lower than those emerging in the cladding of the typical design.

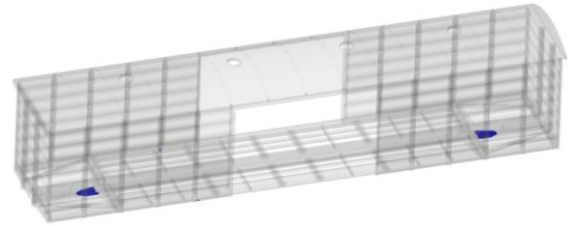


Fig. 5. The zones with highest stresses

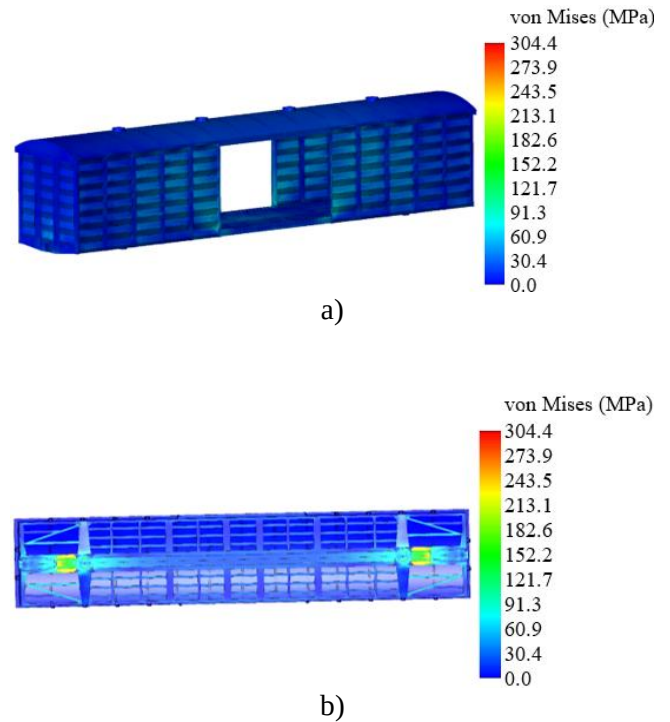


Fig. 6. The stress state of the load-bearing structure of the box wagon: a) view 1; b) view 2

The maximum displacements occurred in the middle part of the box wagon frame; they were 3.4 mm (Fig. 7).

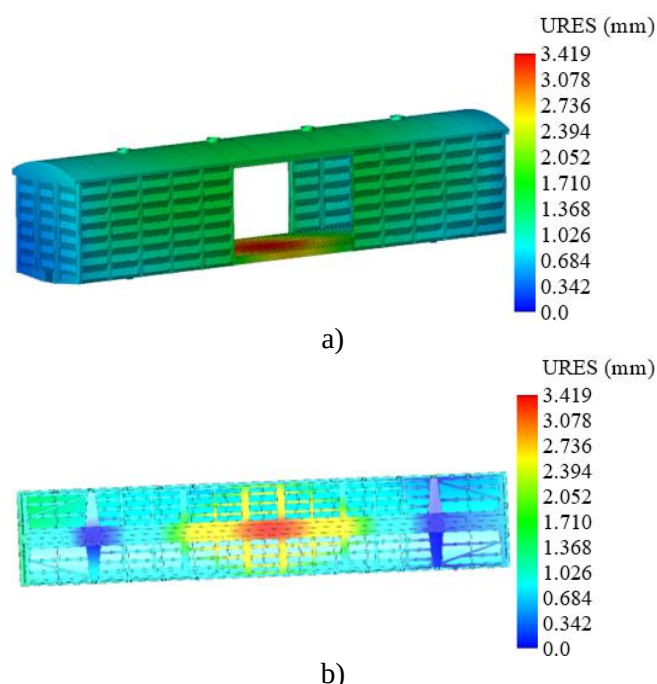


Fig. 7. The displacements in the units of the load-bearing structure of the box wagon:
a) view 1; b) view 2

The proposed solution is effective in reducing the load on the box wagon's cladding sheets and is suitable for both new designs and the modernization of existing rolling stock.

A further area of the research in the field can be the fatigue strength of the load-bearing structure of a box wagon with corrugated cladding sheets. Optimizing the geometry of cladding sheets (corrugation pitch, width, length, etc.) is also of high importance, as well as exploring the possibility of using sandwich panels with corrugated sheets for wagon wall cladding. All these issues will be considered in further research.

The research conducted will help improve the strength of the load-bearing structures of box wagons and reduce their maintenance cost.

4. CONCLUSION

In order to substantiate the use of corrugated sheets as cladding for the box wagon body, a three-dimensional model of the wagon has been developed

and a strength analysis has been carried out. The peculiarity of the model built is that it includes only structural elements rigidly interacted with each other.

The strength of the load-bearing structure of the box wagon has been calculated. The highest stresses are concentrated in the centre sill, namely, in the area between the centre plates and the bolsters. The stresses amount to 304.4 MPa, which does not exceed the permissible values. The maximum stresses in the cladding are 128.3 MPa; they are 8.6% lower than those in the typical design. The maximum displacements (3.4 mm) are in the box wagon frame. The strength calculations have demonstrated the effectiveness of the proposed solution.

ACKNOWLEDGEMENT

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REFERENCES

- [1] Lovska, A., Stanovska, I., Prokopovych, I., Sydorenko, I., Muradian, A., *Determining patterns of the vertical load on a covered wagon roof with a frame in the form of a triangular arch*, Eastern-European Journal of Enterprise Technologies, №4/7 (130), P. 6 – 13, 2024.
- [2] Chandra Prakash Shukla, Bharti P. K., *Study and Analysis of Doors of BCNHL Wagons*, International Journal of Engineering Research & Technology (IJERT), Vol. 4, Issue 04, P. 1195–1200, 2015.
- [3] Panchenko, S., Gerlici, J., Lovska, A., Vatulja, G., Rybin, A., *Determination of the transverse load of the box wagon body with sandwich panel walls*, AIP Conf. Proc., 3129, 060002, 2024.
- [4] Galimova, F., Khurmatov, Y., Abdulloev, M., Jumabekov, B., Sultonaliyev, D., Ergeshova, D., *Modern Gondola with Lightweight Body*, Lecture Notes in Networks and Systems, Vol. 247. P. 1043 – 1050, 2021.
- [5] Tang, J., Zhou, Z., Chen, H., Wang, S., Gutiérrez, A., *Research on the lightweight design of GFRP fabric pultrusion panels for railway vehicle*, Compos. Struct., Vol. 286, 115221, 2022.
- [6] DSTU 7598:2014. *Freight cars. General requirements for calculations and design of new and modernized wagons of 1520 mm gauge (non-self-propelled)*. Kyiv, 2015. 162 p. (In Ukrainian)



ANALYSIS OF FRICTION COEFFICIENTS OF CERTIFIED COMPOSITE BRAKE BLOCKS IN FREIGHT RAILWAY WAGONS

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Abstract – Due to the increasing public demand for reducing railway noise emissions, the implementation of composite brake blocks for freight wagons has intensified over the past twenty years. Consequently, composite brake blocks have become mandatory for newly manufactured freight wagons operating in international railway traffic. However, only a relatively small number of manufacturers have successfully certified this type of brake block in accordance with the applicable European standards. These standards specify a set of performance requirements that must be verified through type testing performed on certified brake test benches and in exploitation. Despite the extensive laboratory testing procedures, it is also essential to evaluate the braking performance on the specific freight wagon equipped with the tested composite brake blocks. These tests reveal the operational characteristics of individual brake block types under realistic service conditions. This paper presents and analyses selected results obtained from braking performance tests carried out on a freight wagon equipped with three different types of certified composite brake blocks.

Keywords – composite brake block, slip brake test, friction coefficient, deceleration.

1. INTRODUCTION

In 2003, the former International Union of Railways (UIC) officially approved the use of K-type composite brake blocks in international railway transport [1]. Since then, conventional grey cast-iron brake blocks installed on existing freight wagons have gradually been replaced by LL-type composite brake blocks, while L-type brake blocks have been introduced to a lesser extent.

The requirements governing the design, dimensions, performance, and testing of composite brake blocks are specified in UIC and EN standards [2, 3]. These standards define the functional requirements for brake blocks acting on the wheel tread within tread braking systems, as well as the interface requirements between the brake block and the railway vehicle.

Furthermore, the standards establish testing procedures for verifying compliance with safety and interoperability requirements, material quality control procedures to ensure product reliability and conformity, and requirements related to environmental protection.

The introduction of composite brake blocks has significantly contributed to reducing railway noise

while maintaining the required braking performance. Nevertheless, the braking characteristics of composite materials differ considerably from those of conventional cast-iron brake blocks. Their friction coefficient depends on several operating parameters, including braking force, vehicle speed, contact pressure, wheel temperature, and environmental conditions. Consequently, each type of composite brake block exhibits distinct braking characteristics that must be evaluated through laboratory and vehicle tests before being approved for service.

The objective of this paper is to analyse the braking performance of a freight wagon equipped with three different types of composite brake blocks by comparing stopping distance, mean deceleration, and the variation of the friction coefficient during braking.

2. ADVANTAGES AND DISADVANTAGES OF COMPOSITE BRAKE BLOCKS

The application of composite brake blocks in tread brake systems, as well as composite inserts in disc brake systems, provides significantly lower variation in braking force throughout the braking process. As a result, the braking force remains more uniform over the

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entire speed range separated from the available wheel–rail adhesion, representing one of the principal advantages of composite friction materials.

Owing to their more stable friction characteristics, composite brake blocks with a higher nominal friction coefficient can be employed without increasing the risk of wheel locking at low speeds, which is a common drawback of conventional grey cast-iron brake blocks. This constitutes another important advantage of composite materials, as the required braking force can be achieved with a lower brake block contact force due to the higher friction coefficient.

The reduced contact force enables the use of lighter brake rigging components while maintaining the same braking performance. Furthermore, the required brake cylinder force is lower, allowing the installation of smaller brake cylinders. Consequently, the overall mass of the mechanical braking system can be reduced, contributing to lower vehicle weight and improved operational efficiency.

An additional benefit of composite brake blocks is the substantial reduction in rolling and braking noise. According to published studies, the replacement of cast-iron brake blocks with composite materials can reduce rolling noise by more than 8 dB, which represents a significant improvement in terms of environmental protection and passenger comfort.

Despite these advantages, several operational challenges remain. One of the primary concerns is the increased wheel tread wear associated with certain composite materials, which requires more frequent wheel reprofiling and consequently increases maintenance costs.



Fig.1. Composite brake block

3. TYPE TESTS

To verify the performance characteristics described above, each type of composite brake block shall successfully complete a comprehensive type testing procedure before being approved for operational use.

Type testing includes the assessment of the following characteristics:

- brake block design and geometry;
- instantaneous and mean friction coefficient;
- static friction coefficient;
- performance under wet friction conditions;
- tendency to collect metallic particles and the formation of surface deposits ("stickers");
- behaviour under wheel-slide or wheel-locking

conditions;

- wear characteristics of both the brake block and the wheel under different axle loads and braking conditions;
- friction performance under winter operating conditions;
- influence on railway signalling systems (electromagnetic interference and related effects);
- material properties and quality characteristics of the brake block.

Certification requires a multi-stage approval pathway [4] comprising laboratory dynamometer bench testing, full-scale slip brake vehicle testing under dry and winter conditions, and a 12-month operational monitoring phase in revenue service.

Because the certification procedure is extensive, technically demanding, and time-consuming, only a limited number of manufacturers have obtained approval for composite brake blocks intended for international railway traffic. The list of approved brake blocks is maintained by the European Union Agency for Railways (ERA) and UIC.

4. SLIP BRAKE TEST

Following the installation of an approved type of composite brake block on a freight wagon, the braking performance of the complete braking system must be verified. If the measured braking characteristics satisfy the requirements specified by the applicable standards [6, 7], the corresponding brake block type is approved for use on that vehicle, and its designation is marked on the wagon.

Whenever the brake block manufacturer or brake block type is changed, the wagon must undergo a new series of brake performance tests.

This paper analyses the results obtained from brake performance tests carried out on an Sgnss 60' container flat wagon equipped with three different types of composite brake blocks in a 2×Bg brake configuration. The tested brake blocks are designated as Type A, Type B, and Type C.

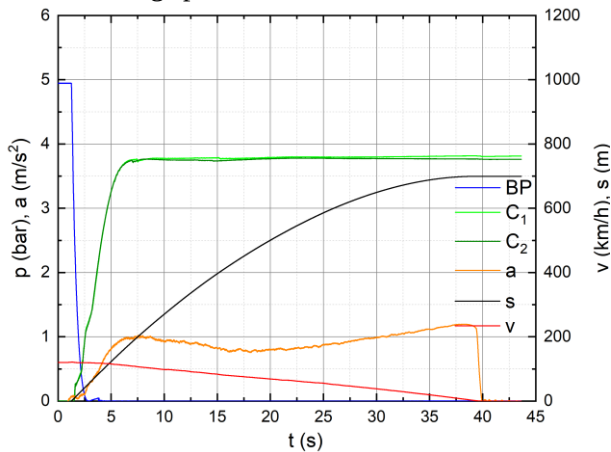
All tests were conducted in full accordance with the methodology specified in [6] without any irregularities [8]. Before testing, all brake blocks were properly bedded-in until a contact pattern exceeding 85% was achieved, thereby ensuring stable friction conditions during the measurements.

4.1. Test results

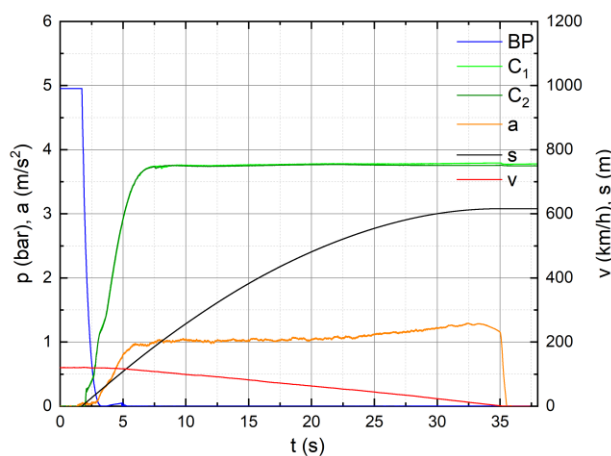
Figure 1 presents representative results obtained during the brake performance tests. The following symbols are used: BP – brake pipe pressure, C - brake cylinder pressure, v – speed, s – stopping distance, a – deceleration.

The results presented in Figure 1 correspond to tests performed with a wagon axle load of 18 t/axle and an

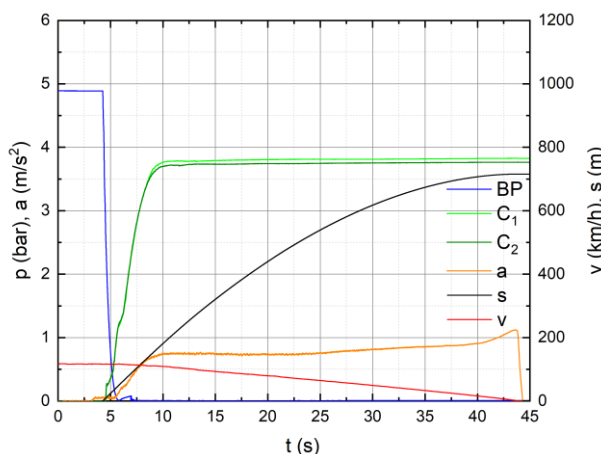
initial braking speed of 120 km/h.



a) Brake blok type A



b) Brake blok type B



c) Brake blok type C

Fig.1. Braking diagrams

Table 1 summarizes the corrected test results for the loaded wagon, including the stopping distance (s), brake mass percentage (λ), mean deceleration (a_m), and mean friction coefficient (μ) for all three tested brake block types. [9, 10, 11].

Tab. 1. Measured corrected test results-loaded wagon

Brake block	m	V	p _{nom}	λ	S	a _m	μ
	[t]	[km/h]	[bar]	[%]	[m]	[m/s ²]	[-]
A	72 t	100	3.80	105	460	0.95	0.263
		120		110	648	0.96	0.264
B		100		100	480	0.91	0.251
		120		101	697	0.88	0.243
C		100		86	553	0.78	0.214
		120		91	760	0.80	0.221

The results clearly indicate that the stopping distances differ among the tested brake block types. Consequently, the corresponding brake mass percentages are not identical and, for some brake block types, deviate from the acceptance range prescribed by the applicable standard ($\lambda=100-105\%$) [2, 7]. These differences indicate that the effective friction coefficients of the tested brake blocks are not equivalent under identical operating conditions.

Tab. 2. Measured corrected test results- empty wagon

Brake block	m	V	p _{nom}	λ	s	a _m	μ
	[t]	[km/h]	[bar]	[%]	[m]	[m/s ²]	[-]
A	19.2 t	100	1.30	109	444	0.99	0.259
		120		114	629	0.99	0.269
B		100		112	433	1.02	0.277
		120		118	610	1.02	0.279
C		100		92	516	0.84	0.242
		120		97	721	0.85	0.245

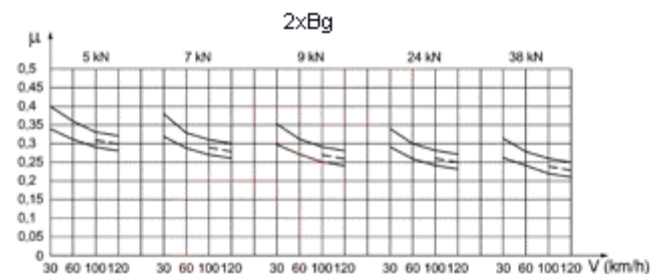


Fig.2. Permissible values of the friction coefficient of for K brake block [2]

In these tests, where the brake block force acting on the wheel is approximately 18 kN, the prescribed mean friction coefficient specified in UIC Leaflet 541-4 should be within the following limits:

- 0.245–0.285 at 100 km/h;
- 0.235–0.275 at 120 km/h

Furthermore, the deceleration curves shown in Figure 1 demonstrate that the braking behaviour varies throughout the braking process. Since the braking force is directly related to the friction coefficient, the observed variation in deceleration indicates continuous changes in the friction characteristics during braking.

This behaviour is mainly caused by the reduction in vehicle speed and the increase in brake block temperature resulting from frictional heating.

For Brake Block Type A, the deceleration initially increases to a maximum value, then decreases before increasing again as the wagon approaches a stopping. This behaviour indicates a more pronounced variation in the friction coefficient during braking.

In contrast, Brake Block Types B and C exhibit considerably more stable deceleration value, indicating more consistent friction characteristics throughout the braking process.

Table 2 presents the corrected test results obtained for the empty wagon.

Comparison of the results obtained for the loaded and empty wagon shown that the friction behaviour of the tested brake block types is influenced by the wagon load. For the empty wagon, Brake Block Type A exhibits a lower mean friction coefficient than Brake Block Type B, whereas the opposite trend is observed for the loaded wagon.

These differences can be attributed to the different chemical compositions and mechanical properties of the composite friction materials used by the manufacturers. As a result, each brake block type exhibits distinct friction characteristics, which directly influence the braking performance of the freight wagon.

5. CONCLUSION

The analysis of the brake performance test results demonstrates that different types of composite brake blocks exhibit significantly different braking characteristics, even when tested under identical operating conditions.

The measured stopping distances, mean deceleration values, and friction coefficients varied among the tested brake block types, confirming that the friction behaviour of composite materials depends on their composition and operating conditions.

These differences make it difficult or even impossible to replace one approved brake block type with another on the same freight wagon while maintaining compliance with the braking performance requirements specified in the applicable standards. Consequently, wagon owners and operators cannot simply substitute brake blocks with more readily available or less expensive alternatives without additional tests.

Whenever a different brake block type is introduced, brake performance tests must be performed. Depending on the test results, modifications to the braking system may be required to ensure compliance with the prescribed braking performance.

The brake blocks shown in this paper are based on organic composite materials. In addition to these

materials, sintered metallic composite blocks offer superior thermal endurance compared to organic matrix blocks. However, sintered blocks require significantly longer bedding-in distances to reach 85% contact area and exhibit higher aggressiveness toward wheel steel.

Experience from railway operation and published UIC technical reports indicates that, despite their environmental advantages and substantial noise reduction, composite brake blocks continue to present several operational challenges, and further research is required to optimize their characteristics.

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REFERENCES

- [1] Technical and Research Platform, SET 07, "Braking", Design rules for composite brake blocks (K), 1. August 2013.
- [2] UIC Leaflet 541-4, Brakes - Composite brake blocks - General conditions for certification and use, 6th edition, November 2020.
- [3] European standard EN 16452+A1 Railway applications – Braking – Brake blocks, March 2019.
- [4] International Railway Solution IRS 50548: Brakes - Requirements of friction test benches for the international certification of brake pads and brake blocks, 2nd edition, October 2022.
- [5] International Railway Solution IRS 50544-1: Brakes - Braking performance, 1st edition, March 2025.
- [6] European standard EN 16834 Railway applications – Braking – Brake performance, April 2019.
- [7] European standard EN 14198 Railway applications – Braking – Requirements for the brake system of trains hauled by locomotives, March 2026.
- [8] Saša Radulović, Dragan Milković, Milan Raković, Goran Simić, Aleksandra Kostić, Influence of the Head Wind on Determining Braking Performance of Zacs Tank Wagon, Acta Polytechnica Hungarica, Óbuda University, Budapest, Hungary, 19/6, 2022.
- [9] Report of Brake performance test of Sgnss wagon, No. LSV-I-3/25, University of Belgrade, Faculty of Mechanical Engineering, Laboratory of rail vehicles, Belgrade 2025.
- [10] Report of Brake performance test of Sgnss wagon, No. LSV-I-31/25, University of Belgrade, Faculty of Mechanical Engineering, Laboratory of rail vehicles, Belgrade 2025.
- [11] Report of Brake performance test of Sgnss wagon, No. LSV-I-32/25, University of Belgrade, Faculty of Mechanical Engineering, Laboratory of rail vehicles, Belgrade 2025.

CONCEPTUAL SOLUTION OF A TEST STAND FOR CALIBRATION OF MEASURING RAILWAY WHEELSETS FOR DIFFERENT TRACK GAUGES

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Abstract – The paper presents a conceptual solution of a test stand for calibration of measuring railway wheelsets. Unlike existing test stands that are designed for a single, fixed track gauge (1435 mm), the proposed conceptual solution enables testing and calibration of measuring wheelsets for different track gauges – 1435 mm and 1676 mm. The test stand is equipped with a linear platform for moving the contact point and a rotary platform for simulating the wheel angle of attack (angle up to 2.5°). The paper provides the basic concept, a description of the main functional units and technical specifications. The proposed solution is modular and adaptable, and can serve as a basis for further development and fabrication of the test stand.

Keywords – Test stand; Calibration of measuring wheelsets; Track gauge, Wheel-rail contact.

1. INTRODUCTION

The assessment of dynamic behavior of railway vehicles in terms of running safety is based on the measurement of lateral force Y and vertical force Q in wheel-rail contact, as well as their ratio Y/Q . These parameters are key indicators of running stability and the risk of derailment, especially when passing through curves. These measurements are defined by international standards that prescribe procedures for the acceptance of dynamic behavior of railway vehicles [1, 2].

For reliable measurement of forces Y and Q under operating conditions, measuring wheelsets are used, which are installed on the tested vehicle. These assemblies are equipped with sensors (most commonly strain gauges) that measure wheel deformations, based on which the required forces are determined indirectly by applying an appropriate algorithm. An important aspect of the application of measuring wheelsets is their adequate calibration in order to ensure appropriate measurement accuracy [3]. For this purpose, special test stands have been developed that enable calibration of measuring wheelsets under laboratory conditions. One solution of such a test stand is described in [4], where a test stand for calibration of measuring wheelsets is presented, which enables operation in static and dynamic modes, with independent application of

vertical and lateral forces in wheel-rail contact (Fig. 1). A detailed theoretical and experimental basis for the development of similar test stands is given in [5], where the influential parameters in wheel-rail interaction on the running stability of railway vehicles are analyzed, as well as methods for experimental determination of forces using measuring wheelsets.



Fig.1. Test stand for testing and calibration of measuring wheelsets [4, 5]

However, most existing test stand solutions are designed for a single, fixed track gauge. In modern railway practice, there is a need for calibration of measuring wheelsets used on vehicles intended for different track gauges. In addition to the standard gauge (1435 mm), other significant gauges include 1676 mm (broad gauge, present in India, Pakistan,

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Spain), 1520 mm (Russia, Finland, former USSR countries), as well as 1668 mm (Portugal). Different track gauges require an appropriate geometry of the test stand, i.e., the possibility of adjusting the distance between the left and right wheel-rail contact pair. Some contemporary test stand solutions are based on the use of dynamic rollers and rotary platforms, which enable simulation of more realistic loading conditions, including the simulation of the wheel angle of attack [6–9]. However, these solutions are often designed for specific conditions and rarely offer the possibility of track gauge adjustment.

The aim of this paper is to propose a conceptual solution of a new test stand for calibration of measuring wheelsets, which enables testing and calibration for different track gauges (1435 mm and 1676 mm), linear movement of the contact point along the wheel profile, as well as simulation of the wheel angle of attack using a rotary platform (rotation angle up to 2.5°). The paper provides the basic concept, a description of the main functional units and technical specifications of the proposed test stand, which is modular and adaptable, and can serve as a basis for further detailed design and fabrication.

2. PROBLEM FORMULATION

The basic purpose of a test stand for calibration of measuring wheelsets is to enable simulation of loading conditions to which the measuring wheelset is exposed during actual movement of a railway vehicle. The simulation should be as realistic as possible, in order to establish, through calibration, a reliable relationship between the deformations recorded on the wheel and the forces causing these deformations.

In wheel-rail interaction, the key parameters to be determined are the vertical force Q and the lateral force Y (Fig. 2). The force Q represents the load transmitted by the wheel to the rail, originating from the weight of the vehicle and cargo. It is dominant under normal running conditions and directly affects the stresses in wheel-rail contact. The force Y arises as a consequence of centrifugal force when negotiating curves and vehicle guidance. Its value depends on running speed, curve radius, bogie design, etc.

The ratio Y/Q is the main indicator of running safety against derailment. When this ratio exceeds limit values (according to UIC 518 and EN 14363 standards, the limit is 0.8 for large radius curves, i.e. 1.2 for small radius curves), the wheel flange climbs onto the rail head and derailment occurs, which can have catastrophic consequences. Therefore, precise measurement and calibration of forces Y and Q is of crucial importance for railway safety.

In addition to forces Q and Y , the wheel angle of attack is also a significant parameter for analyzing vehicle behavior in curves, as it directly affects the

intensity of lateral forces and profile wear.

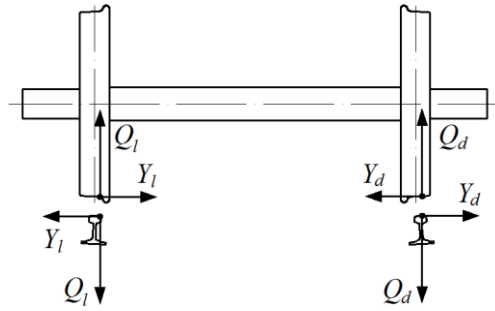


Fig.2. Forces in wheel-rail contact

Considering the above, the task of the test stand is to enable the following functions under laboratory conditions: independent application of force Q and force Y over a wide range; change of the contact point position along the wheel profile (from the rolling surface to the flange); simulation of wheel attack at a certain angle; operation in static mode (loading without rotation) and dynamic mode (loading during wheel rotation). In this way, the test stand should enable calibration of measuring wheelsets for different loading conditions corresponding to actual operation.

Existing test stand solutions are designed for a fixed track gauge – most commonly the standard gauge of 1435 mm. However, in some cases there is also a need for calibration of measuring wheelsets of larger track gauge. Namely, several standard track gauges exist on world railways. In addition to the standard gauge (1435 mm), broad gauges also exist – 1520 mm (Russia, Finland, former USSR countries), 1600 mm (Ireland), 1668 mm (Portugal, Spain) and 1676 mm (India, Pakistan, Bangladesh, Argentina, Chile). Based on the above, a requirement has been formulated for the development of a conceptual solution of a test stand for calibration of measuring wheelsets for different track gauges (1435 mm and 1676 mm). The test stand should enable linear movement of the contact point along the wheel profile, simulation of the wheel angle of attack, and independent application of Q and Y forces on the left and right wheels. Solving such a problem requires the synthesis of several engineering disciplines from the fields of railway engineering, mechanical structures, hydraulic and electrical systems, as well as control engineering.

3. CONCEPTUAL SOLUTION OF THE NEW TEST STAND

Starting with the defined problem, a conceptual solution of the new test stand has been developed, which is shown in Fig. 3. Unlike existing solutions, which are designed for a fixed track gauge, the proposed test stand enables operation with measuring wheelsets for two different track gauges – 1435 mm and 1676 mm. The difference is only in the universal

bracket with housing that is fitted onto the axle journal of the measuring wheelset being calibrated or tested. A telescopic type bracket is envisaged to enable removal of the wheelset from the supporting columns of the test stand. More precisely, two types of brackets are envisaged – one bracket for accommodating measuring wheelsets for 1435 mm gauge, and the other bracket for 1676 mm gauge.

Installation and removal of the measuring wheelset into the test stand is envisaged from the side of the test stand, using special rails and an additional structure with a roller system. In this process, after removing the load cell and with an appropriate attachment, the lifting function of the measuring wheelset is performed by the hydraulic cylinders for applying the vertical force. Guidance of the measuring wheelset bracket within the columns of the test stand

supporting structure is provided by a bearing system. In this way, handling is facilitated and the risk of damage to sensitive sensors (strain gauges) during installation and removal is reduced.

The function of changing the contact point position between the wheel and the rail imitation is envisaged by means of a linear platform that moves on a roller system. This platform is envisaged to be fixed onto the rotary platform, and its movement should enable positioning of the wheel-rail contact point in very fine intervals with an accuracy of ± 0.5 mm. Hydraulic cylinders with electric control are envisaged for moving the linear platform. The operation of the hydraulic cylinders on the left and right sides of the measuring wheelset should be synchronized, and the contact point position should be monitored using appropriate position sensors with electric readout.

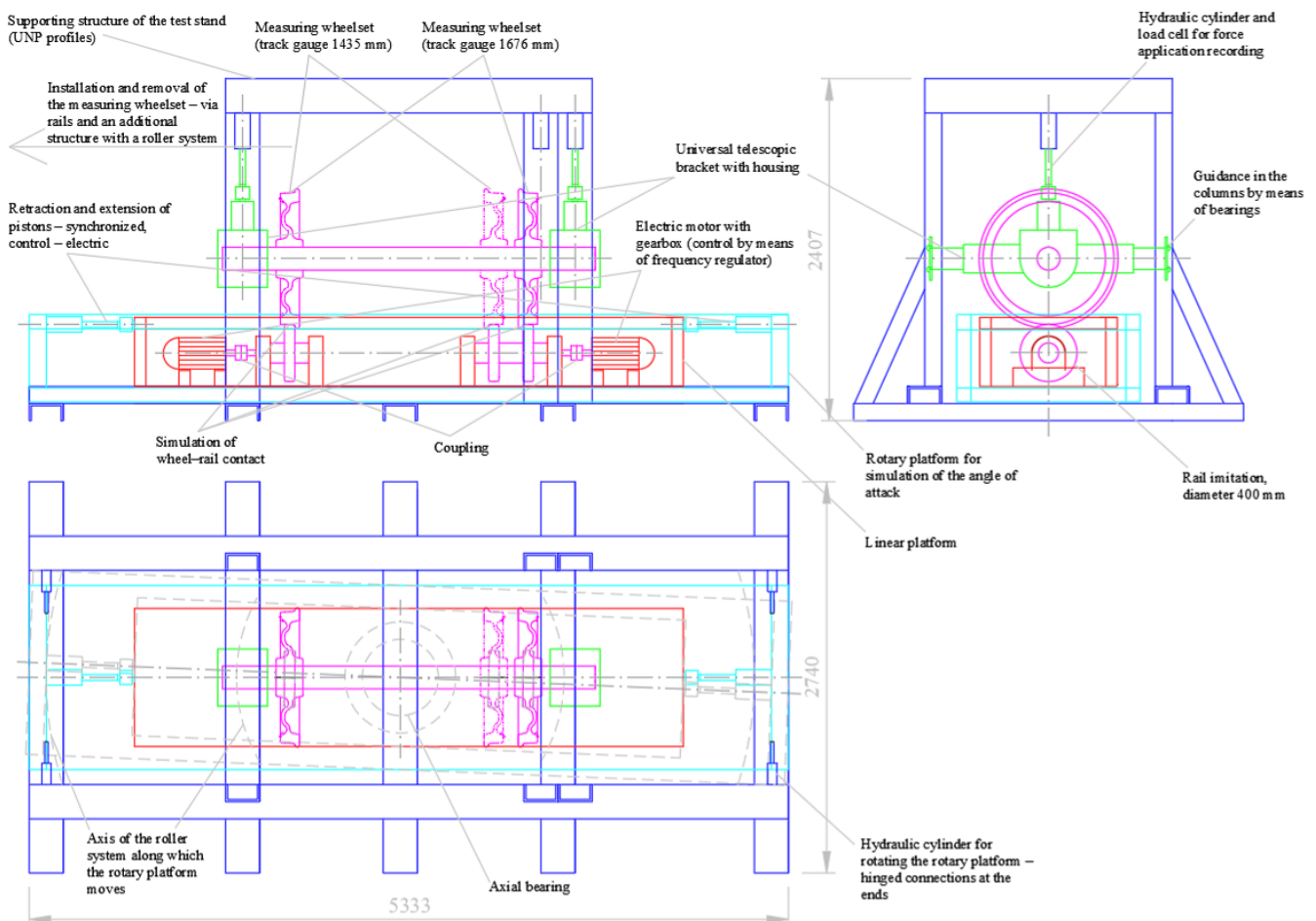


Fig.3. Conceptual solution of the test stand for different track gauges

Simulation of the wheel attack under a certain angle is envisaged by means of a rotary platform. The platform is envisaged to be rotated using four hinged hydraulic cylinders, with a maximum rotation angle of 2.5° . Movement of the platform is envisaged via a special roller system fixed to the test stand supporting structure. Rotation of the platform is envisaged via a large-diameter axial bearing (similar to solutions used on excavators). As already mentioned, the linear platform

would be supported onto this rotary platform via a roller system, thus enabling independent movement along both axes. Control of the hydraulic cylinders for platform rotation is envisaged to be electric, with the possibility of fine adjustment of the wheel-rail angle of attack.

Simulation of wheel-rail contact is envisaged by means of a lower pair of wheels which are specially machined so that their profile imitates the rail head. The diameter of these wheels should be 400 mm. Rotation of

this lower pair of wheels is envisaged via two drive electric motors with gearboxes and cardan shafts, which also enables rotation of the tested measuring wheelset. Control of the electric motors is envisaged using frequency regulators, and the rotation speed can be finely adjusted in accordance with the calibration requirements of the measuring wheelset (the maximum rotation speed should correspond to a linear speed of approximately 70 km/h). For more efficient and simpler calibration of both wheels of the measuring wheelset, it is envisaged that both drive electric motors are connected to the lower pair of wheels via couplings. In this way, during calibration, simple connection and disconnection of the drive is enabled – when one coupling is engaged, the other should be disengaged, and vice versa.

Application of the force Q in the contact between the calibrated wheel and the rail head imitation is envisaged via hydraulic cylinders acting on the vertically movable bracket of the upper wheelset. Application of the force Y is envisaged by moving the linear platform, also via the previously mentioned hydraulic cylinders. It should be possible to apply these forces independently of each other, both in static and dynamic mode (loading during rotation). The test stand should enable application of force Q up to 160 kN and force Y up to 100 kN per wheel being calibrated. Application of forces Q and Y must be possible in steps of 1.0 kN, with an accuracy of approximately 0.1 kN. For recording the values of the applied forces, appropriate load cells connected directly to the test stand control module are envisaged.

The control module of the test stand should enable efficient and integrated control of all the aforementioned functions – positioning of the linear and rotary platforms, application of forces, control of the electric motor rotation speed, as well as monitoring of the safety systems. The supporting structure of the test stand is envisaged from steel UNP profiles, with additional stiffeners providing the required rigidity under maximum loads. The overall dimensions of the test stand are approximately: length 5.3 m, width 2.8 m, height 2.4 m. The test stand should be equipped with all necessary safety systems – an electronic curtain, an emergency stop button, etc. All rotating elements of the test stand should be painted red, linearly movable elements blue, and stationary elements yellow, or other colors as desired.

4. CONCLUSION

The paper presents a conceptual solution of a test stand for calibration of measuring railway wheelsets for different track gauges. Unlike existing test stands, which are designed for a single, fixed track gauge (1435 mm), the proposed solution enables calibration of measuring wheelsets for two different track gauges – 1435 mm and 1676 mm. The test stand is envisaged with a linear

platform for precise positioning of the contact point along the wheel profile (with an accuracy of ± 0.5 mm) and a rotary platform for simulation of the wheel angle of attack (up to 2.5°). Independent application of vertical force Q (up to 160 kN) and lateral force Y (up to 100 kN) is envisaged, with a force step of 1 kN and an accuracy of approximately 0.1 kN. The test stand is envisaged to operate in both static and dynamic modes, with a maximum rotation speed corresponding to a linear speed of 70 km/h. The proposed solution is modular, adaptable and can serve as a basis for further detailed design and fabrication. Future work should focus on detailed structural analysis, selection of specific commercial components, and experimental validation of the proposed test stand.

ACKNOWLEDGEMENT

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REFERENCES

- [1] UIC CODE 518 OR, Testing and approval of railway vehicles from the point of view of their dynamic behavior – Safety – Track fatigue – Running behavior, 4th edition, Int. Union of Railways – UIC, 2009.
- [2] EN 14363, Railway applications – Testing for the acceptance of running characteristics of railway vehicles – Testing of running behavior and stationary tests, Eur. Comm. for Standardization – CEN, 2005.
- [3] Petrović, D., Babić, A., Bižić, M., Djelošević, M. (2010). Measuring systems for testing the safety and security of railway vehicles. Proceedings of RAILCON 2010, Niš, pp. 177-181.
- [4] Bižić, M., Tomić, M., Djinović, Z., Petrović, D. (2011). Test stand for calibration of measurement railway wheelsets. Proceedings of IRMES 2011, Zlatibor, pp. 419-424.
- [5] Bižić, M. (2015). Istraživanje uticajnih parametara u interakciji točak-šina na stabilnost kretanja železničkih vozila. Doktorska disertacija, Univerzitet u Kragujevcu., (in Serbian).
- [6] Bracciali, A., Macherelli, M., Boccolini, L. (2016). Design of an Innovative Test Bench to Calibrate Instrumented Wheelsets. Proceedings of the third international conference on railway technology: research, development and maintenance, 4.4.2016-8.4.2016.
- [7] Jin, X. (2020). A measurement and evaluation method for wheel-rail contact forces and axle stresses of high-speed train. Measurement, Volume 149, 106983.
- [8] Jin, X. (2020). Evaluation and analysis approach of wheel-rail contact force measurements through a high-speed instrumented wheelset and related considerations. Vehicle System Dynamics, Volume 58, Issue 8, pp. 1189-1211, 23 pp.
- [9] Kothari, K. (2018). Accurate Wheel-rail Dynamic Measurement using a Scaled Roller Rig. Masters Theses, Virginia Tech.



PASS-BY NOISE ASSESSMENT OF CONTEMPORARY AND LEGACY RAIL VEHICLES ON SERBIAN RAILWAYS

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Abstract – Pass-by noise represents one of the key environmental criteria in the approval and operation of modern railway vehicles. In addition to vehicle design, the condition of the track and braking technology significantly influence the measured noise levels. During the type testing of a diesel track inspection vehicle on the upgraded Belgrade–Novi Sad railway line, pass-by noise measurements were conducted on various passenger and freight trains under identical, controlled experimental conditions. This setup enabled a direct acoustic comparison between contemporary and legacy rolling stock, including electric multiple units (EMUs), freight trains with different braking systems, and multiple generations of electric locomotives. All measurements complied with the EN ISO 3095:2025 standard, with track acoustic characteristics validated through rail roughness and track decay rate (TDR) assessments. The obtained results demonstrate substantial differences in environmental noise emission between older and modern rolling stock. Notably, freight wagons equipped with cast iron brake blocks generated approximately 9 dB higher pass-by noise than wagons fitted with composite brake blocks. Furthermore, modern electric locomotives exhibited significantly lower noise emissions than their legacy counterparts. These findings underscore the critical role of advanced braking technologies in mitigating railway noise and highlight the environmental benefits of fleet modernization in achieving compliance with current European Technical Specifications for Interoperability (TSI).

Keywords – Railway acoustics; pass-by noise; freight wagons; composite brake blocks; EN ISO 3095:2025.

1. INTRODUCTION

Environmental noise generated by railway traffic has become an increasingly important aspect of railway system development due to stricter European environmental regulations and the continuous modernization of railway infrastructure. Among the different sources of railway noise, rolling noise generated at the wheel–rail interface dominates at medium and high operating speeds and is strongly affected by wheel and rail surface conditions, vehicle design, and braking technology.

Pass-by noise measurements are therefore an essential part of the type approval procedure for new railway vehicles and are standardized by EN ISO 3095:2025. Reliable comparison of vehicle noise performance requires measurements under controlled

acoustic and track conditions, including verification of rail roughness and track decay rate to ensure that the measured noise originates primarily from the vehicle rather than the infrastructure.

The reconstruction of the Belgrade–Novi Sad railway line created suitable conditions for conducting standardized pass-by noise measurements. During the type testing of a diesel track inspection vehicle, additional measurements were performed on passenger trains, freight trains, and electric locomotives operating over the same test section. Since all measurements were carried out under identical environmental and track conditions, the collected data enabled a direct comparison of noise emissions from contemporary and legacy rolling stock.

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Particular attention is devoted to freight trains, where braking technology has a pronounced influence on rolling noise. The comparison between wagons equipped with conventional cast iron brake blocks and those fitted with composite brake blocks provides a practical illustration of the benefits achieved through modern braking systems and supports current European requirements for quieter railway operation.

2. MEASUREMENT CONDITIONS

The pass-by noise measurements were performed on the upgraded Belgrade–Novi Sad railway line during the type approval testing of the diesel track inspection vehicle DV GPK. The test campaign provided an opportunity to measure the pass-by noise of several passenger and freight trains operating over the same track section under identical environmental and infrastructure conditions.

Measurements were carried out in accordance with the requirements of EN ISO 3095:2025. The selected test site was located at km 61+960 of the railway line, where the track fulfilled the acoustic requirements prescribed for standardized pass-by noise measurements. Weather conditions during testing complied with the standard, including the absence of precipitation, low wind speed and sufficiently low background noise.

Since the acoustic characteristics of the track have a significant influence on measured pass-by noise, the test section was characterized before vehicle testing. Rail acoustic roughness was measured in accordance with SRPS EN 15610:2025 using the Müller-BBM *m|rail trolley* system. The measured roughness spectra remained within the permissible limits specified by the standard, ensuring that the rail surface did not introduce excessive rolling noise.

The dynamic acoustic behaviour of the track was additionally verified through track decay rate measurements performed according to EN 15461. Frequency response functions were obtained using an instrumented hammer and rail-mounted accelerometers in both vertical and lateral directions. The measured decay rates satisfied the prescribed acceptance criteria, confirming the suitability of the selected track section for comparable pass-by noise measurements.

During each vehicle passage, the A-weighted sound pressure level was continuously recorded using a calibrated microphone positioned 7.5 m from the track centreline and 1.2 m above the top of the rail. An optical sensor installed at the microphone section detected the wheel passages and enabled accurate determination of vehicle speed together with the beginning and end of the measuring interval.

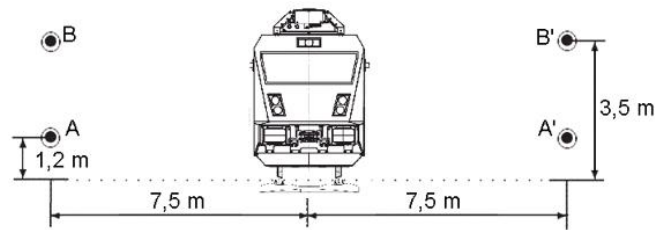


Fig. 1. Standard microphone positions for pass-by noise measurements according to EN ISO 3095:2025

Measured equivalent sound pressure levels were corrected to the reference speed of 80 km/h in accordance with EN ISO 3095:2025, allowing direct comparison of different vehicle types. The investigated rolling stock included contemporary electric multiple units (Stadler KISS and Stadler FLIRT), freight trains equipped with both composite and cast iron brake blocks, an older series 441 electric locomotive, a Siemens Vectron locomotive, and the diesel inspection vehicle subjected to type approval testing.

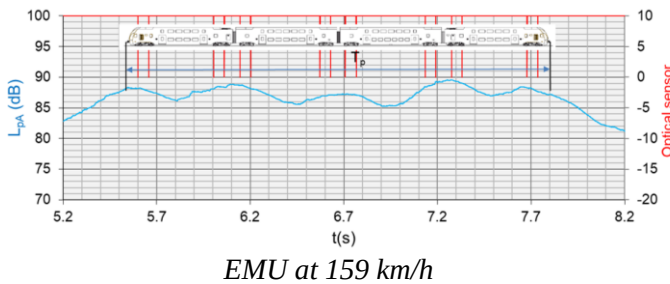
3. RESULTS AND DISCUSSION

The measurement campaign included six pass-by tests of contemporary electric multiple units, three freight trains with different braking technologies, one Siemens Vectron electric locomotive, and the diesel track inspection vehicle undergoing type approval testing.

3.1 Passenger trains

Figure 2 presents the sound pressure level recorded during the passage of a Stadler KISS electric multiple unit at a speed of approximately 159 km/h. The characteristic variation of the sound pressure level clearly indicates the passage of individual bogies, while the optical sensor pulses enable accurate determination of the measuring interval used for calculating the equivalent pass-by noise level.

Table 1 summarizes the pass-by noise results obtained for the tested electric multiple units. After correction to the reference speed of 80 km/h, all measured values satisfy the limit specified by EN ISO 3095:2025. The corrected equivalent sound pressure levels ranged between 74 dB and 80 dB, confirming the excellent acoustic performance of contemporary passenger rolling stock operating on Serbian Railways.



EMU at 159 km/h

Tab. 1. Pass-by noise results for EMUs

Test No	EMU series	V _{test} [km/h]	L _{pAeq,Tp} (v _{test}) [dB]	L _{pAeq,Tp} (80 km/h) [dB]	Limit Value [dB]
1	Stadler Kiss	146.6	82.00	75	80
2	Stadler Kiss	142.3	86.16	78	
3	Stadler Kiss	146.7	87.48	79	
4	Stadler Flirt	159.3	83.69	74	
5	Stadler Flirt	158.9	87.15	79	
6	Stadler Flirt	159.4	87.78	80	

The relatively small variation between repeated measurements demonstrates the good repeatability of the test procedure and indicates stable operating conditions during the measurement campaign. The results further confirm that modern vehicle design, improved suspension systems and disc braking technology contribute significantly to the reduction of rolling noise.

3.2 Freight trains and locomotives

Unlike passenger vehicles, freight trains exhibited considerably larger differences in pass-by noise depending on braking technology.

Figure 3 shows the sound pressure level recorded during the passage of a freight train consisting of a Class 441 electric locomotive and Sggn container wagons equipped with composite K brake blocks.

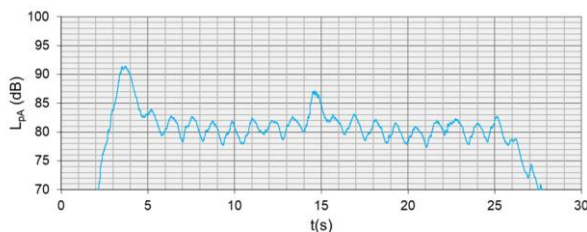


Fig. 3. Pass-by sound pressure level of freight train with composite brake blocks

In contrast, the freight train equipped with conventional cast iron brake blocks produced consistently high sound pressure levels along the entire train length, as illustrated in Figure 4.

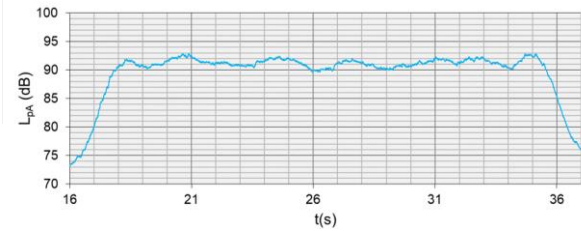


Fig. 4. Pass-by sound pressure level of freight train with cast iron brake blocks

The difference between the two braking technologies is clearly visible. While wagons equipped with composite brake blocks satisfy current European noise requirements, wagons fitted with cast iron brake blocks exceed the allowable limit by approximately 9 dB.

Table 2 summarizes the measured pass-by noise levels for freight trains, locomotives and the diesel inspection vehicle.

Tab. 2. Pass-by noise results for freight trains, locomotives and inspection vehicle

Train composition/ vehicle type	V _{test} [km/h]	L _{pAeq,Tp} (v _{test}) [dB]	L _{pAeq,Tp} (80 km/h) [dB]	Limit value [dB]
Loc. 441 + Sggn wagons with K brake blocks	81.0	82.32	82	83
Loc. 441 + different container transport wagons with K brake blocks	80.9	82.43	82	83
Loc. 441 + Eas wagons with cast iron brake blocks	77.7	91.31	92	83
Vectron locomotive	79.7	81.92	82	84
Diesel inspection car with disc brakes	80.3	81.66	81.6	
	80.8	80.91	80.8	
	81.1	83.20	83.0	
	158.4	87.42	78.5	
	156.2	87.47	78.8	
	161.1	88.21	79.1	
Average rounded to nearest decibel			80	85

The locomotive represents the dominant noise source, producing sound pressure levels close to 90 dB, whereas the container wagons generate substantially lower noise levels that remain within the prescribed limits for freight rolling stock.

The measurements also demonstrate the influence of locomotive design. The Siemens Vectron locomotive achieved a corrected pass-by noise level of approximately 82 dB, remaining well below the applicable limit. In comparison, the older Class 441

locomotive produced substantially higher sound pressure levels, primarily due to older traction equipment and conventional tread braking.

The diesel inspection vehicle fulfilled all requirements prescribed for type approval testing. The average corrected equivalent sound pressure level remained below the applicable limit value, confirming compliance with current European interoperability requirements.

Overall, the obtained results clearly demonstrate that brake block technology represents one of the dominant factors influencing pass-by noise of freight trains. Replacing cast iron brake blocks with composite friction materials reduces rolling noise by approximately 9 dB under identical operating conditions. Considering the logarithmic nature of the decibel scale, this reduction represents a significant improvement in environmental acoustic performance and highlights the importance of fleet modernization for achieving compliance with contemporary railway noise regulations.

4. CONCLUSION

Pass-by noise measurements performed on the upgraded Belgrade–Novi Sad railway line enabled a direct comparison of the acoustic performance of contemporary and legacy railway vehicles under identical test conditions.

The results confirmed that modern passenger rolling stock equipped with disc brakes satisfies the pass-by noise limits prescribed by EN ISO 3095:2025 with a comfortable margin. Similarly, the Siemens Vectron locomotive and freight wagons equipped with composite brake blocks demonstrated significantly lower noise emissions than older vehicle designs.

The most pronounced difference was observed between freight wagons fitted with composite and cast iron brake blocks. Under comparable operating conditions, freight wagons equipped with cast iron brake blocks generated approximately 9 dB higher pass-by noise than wagons using composite brake blocks. Considering the logarithmic nature of the decibel scale, this represents a substantial reduction in environmental noise emission and confirms that braking technology remains one of the dominant factors influencing rolling noise.

The study also confirms the importance of standardized measurement procedures and controlled track characteristics for obtaining reliable and

comparable pass-by noise results. Compliance with the requirements for rail roughness and track decay rate ensures that the measured noise levels primarily reflect vehicle characteristics rather than infrastructure effects.

The presented results support the continued modernization of railway fleets through the replacement of conventional cast iron brake blocks with composite friction materials, contributing to compliance with current European interoperability requirements and to the reduction of environmental noise along railway corridors.

ACKNOWLEDGEMENT

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REFERENCES

- [1] EN ISO 3095:2025, *Acoustics – Railway applications – Measurement of noise emitted by railbound vehicles*.
- [2] EN ISO 3381:2021, *Railway applications – Acoustics – Noise measurement inside railbound vehicles*.
- [3] EN 15153-2:2020, *Railway applications – External visible and audible warning devices – Warning horns for heavy rail systems*.
- [4] EN 15153-4:2020, *Railway applications – External visible and audible warning devices – Audible warning devices for urban rail systems*.
- [5] EN 15610:2025, *Railway applications – Acoustics – Rail and wheel roughness measurement related to noise generation*.
- [6] *Pass-by Noise Test of Track Geometry Railcar DV GPK*, Test Report No. LSV-I-12/23, Laboratory of Rail Vehicles, Faculty of Mechanical Engineering, University of Belgrade, September 2023.
- [7] EN 15461:2008+A1:2010, *Railway applications – Noise emission – Characterisation of the dynamic properties of track sections for pass-by noise measurements*.
- [8] Commission Regulation (EU) No. 1304/2014 on the Technical Specification for Interoperability relating to the subsystem "Rolling Stock – Noise", together with subsequent amendments.
- [9] Directive 2002/49/EC of the European Parliament and of the Council relating to the assessment and management of environmental noise.

MODELING AND PREDICTION OF STOCHASTIC VIBRATIONS IN TRAIN OPTICAL DETECTION SYSTEMS

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Abstract This paper presents a stochastic modeling approach for optical detection systems employing viscoelastic stabilizers. In order to develop an adequate vibration model, experimental results obtained from dynamic testing of a viscoelastic optical detection system mounted on a railway vehicle were used. The conducted tests evaluated the effectiveness of viscoelastic vibration suppression in a railway optical detection system whose primary objective is to stabilize the captured image and reduce potential errors in system decision-making. The tested viscoelastic stabilizer is represented using the Voigt–Kelvin model, whose parameters are optimized based on experimental measurements obtained under real-time operating conditions of the optical detection system. The system response is further analyzed under a real noise stochastic process used to represent the external excitation load.

Keywords – Stochastic model, viscoelastic suppression, Voigt-Kelvin model, railway optical detection system, real noise process.

1. INTRODUCTION

The stabilization of optical systems is essential in applications such as astronomy, optical communications, laser systems, and medical imaging, where image quality must be preserved under vibrations, thermal variations, and other environmental disturbances. Numerous studies have addressed this challenge using advanced modeling and control approaches, including modern design methodologies for mitigating turbulence, structural vibrations, and thermal effects [1], as well as adaptive filtering techniques, such as Kalman-based algorithms, for reducing noise and improving image correction performance [2].

Among available solutions, viscoelastic stabilization represents an effective passive approach for vibration suppression. The incorporation of viscoelastic layers between optical components and their supporting structure reduces resonant amplitudes and enhances overall dynamic stability [3-5]. Within the H2020 SMART project [6], an optical detection system (ODS) for freight vehicles was developed, incorporating a dedicated passive isolation system to attenuate vibrations induced by vehicle motion. The dynamic behavior of such systems has been further investigated in [7].

2. OBSERVED SYSTEM

The optical detection system (ODS) is installed on a freight locomotive and comprises three RGB cameras, a thermal imaging camera, a night-vision camera, and a 3D laser scanner (LiDAR). All sensing components are integrated within a specially designed protective enclosure. The enclosure is mounted on a structural plate rigidly attached to the locomotive (Fig.1) carbody beneath the front headlights, resulting in direct structural coupling with the vehicle.



Fig. 1. The SMART ODS prototype mounted on

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locomotive

Due to the rigid connection between the mounting plate and the locomotive structure, dynamic loads arising from wheel-rail interaction, track irregularities, and structural vibrations are directly transmitted to the enclosure and the embedded vision sensors. To reduce vibration transmissibility and mitigate the effects of broadband stochastic excitations and transient shocks, a passive vibration isolation system based on viscoelastic elements was designed and implemented, as shown in Fig. 2.



Fig. 2. Viscoelastic elements for vibration suppression

Vibration responses were recorded using two triaxial inertial measurement units (IMUs), installed on the mounting plate and inside the ODS enclosure (Fig. 3) presents viscoelastic system for which the Voigt-Kelvin vibration model is suggested.

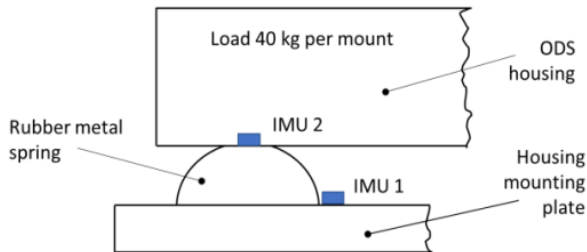


Fig. 3. Positioning of IMU's on the housing mounting plate and inside the ODS housing

The performance of the isolation system was evaluated during operational train runs at speeds ranging from 20 to 80 km/h on a straight track section. Acceleration measurements were conducted in the vertical direction at two locations: on the mounting plate rigidly attached to the carbody and inside the sensor enclosure. This direction was treated as the most important one, since the largest disturbance levels and the most pronounced dynamic effects were observed in the vertical axis. For this reason, the vertical response was taken as the primary indicator of the effectiveness of the proposed isolation concept. Based on the measured vertical accelerations shown in Fig. 4, the stochastic force acting on the ODS was

recalculated and used as the input for further dynamic optimization.

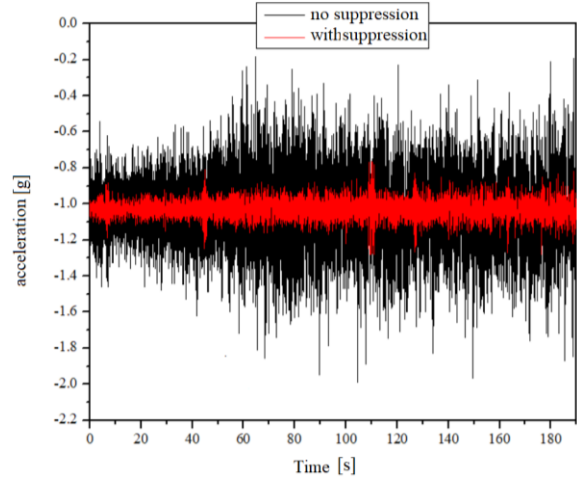


Fig. 3. Experimental measurements in vertical direction

This approach made it possible to evaluate the transmissibility of vibrations through the mounting structure and to assess how efficiently the viscoelastic elements reduce the excitation transferred to the optical detection system under realistic operating conditions.

3. VIBRATION MODEL OPTIMIZATION

According to the viscoelastic system described for stabilising the ODS system in the previous section, the viscoelastic Voigt-Kelvin model [8] is applied to model and analyse camera stochastic vibrations. This model is one of the basic linear approaches for describing materials that simultaneously exhibit elastic and viscous properties, with an elastic spring and a viscous damper connected in parallel to represent the stress-strain relationship.

$$F(t) = c \cdot x(t) + b \cdot dx(t)/dt + m \cdot d^2x(t)/dt^2, \quad (1)$$

where c is the spring stiffness, b is damping coefficient, m is the mass of analyzed system.

For the initial Voigt-Kelvin model parameter identification the global optimization method Differential Evolution was employed.

The parameters b and c of the Voigt model were optimized by defining an objective function aimed at minimizing the deviation between the experimentally measured output acceleration and the corresponding model response. Initially, the optimization procedure was based on direct fitting of the complete time-domain signal. However, this approach did not provide a satisfactory correlation between the experimental data and the simulated response, particularly in terms of accurately reproducing the dynamic characteristics of the measured signal over the entire observation interval.

To improve the robustness of the parameter identification process, the optimization criterion was

further modified so that the model primarily reproduces the amplitude range of the response. In this context, special emphasis was placed on matching the minimum and maximum acceleration values, as well as the standard deviation of the experimental signal, which was used as an indicator of the overall variability and energy content of the response. Such an approach enabled a more stable and physically meaningful identification of the model parameters, despite the simplicity of the employed constitutive representation. Figure 5 shows that the optimized Voigt-Kelvin model provides a good agreement with the experimentally observed accelerations amplitudes by matching both the minimum and maximum response levels of the system, which indicates that the identified stiffness and damping parameters capture the dominant dynamic behavior of the viscoelastic mount under service conditions.

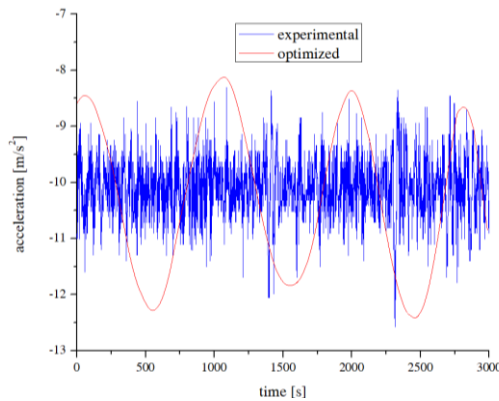


Fig. 5. Optimization results: $c=9.02$ N/m and $b=0.096$ Ns/m

4. STOCHASTIC RESPONSE UNDER REAL NOISE EXCITATION

According to Voigt-Kelvin model given with expression (1) the adequate simulation scheme is constructed (Fig 6).

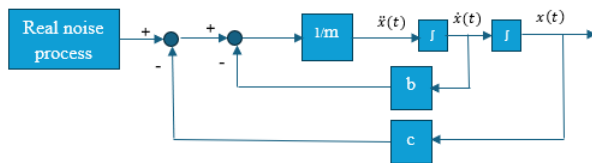


Fig. 6. Simulation scheme of Voigt-Kelvin model given by expression (1)

Now, the system response is tested when input stochastic force in simulation is modeled by real noise process.

The real noise process is given by the one-dimensional Itô-type stochastic differential equation

$$dX(t) = \alpha * X(t) * dt + \sigma * dW(t), \quad (2)$$

where α and σ are constants and $W(t)$ is the standard Wiener process.

Real noise process is a random signal characterized by broadband, irregular fluctuations with statistical

properties derived from measured or observed data, making it more complex than idealized noise models such as white or colored noise. In system analysis, it is often used to model actual environmental or operational forces acting on a structure, such as the vibration induced forces on an optical detection system mounted on a moving vehicle. By representing the force as a stochastic real noise process, researchers can more accurately simulate the system's dynamic response under realistic, unpredictable excitations and evaluate the effectiveness of stabilization or damping strategies, such as viscoelastic isolation, under real world conditions. Modeling and simulation of this process using MATLAB software is detailedly presented in previous authors work [9].

Figures 7 and 8 illustrate how the Voigt-Kelvin model responds under a real noise excitation when the model parameters are varied, showing that both stiffness and damping coefficient significantly influence the amplitude and character of the predicted vibration response.

In Figure 7, changes in the damping coefficient mainly affect the rate of energy dissipation, with higher damping reducing oscillation intensity and producing a more stable response, which confirms the expected role of viscous resistance in limiting vibration transmission.

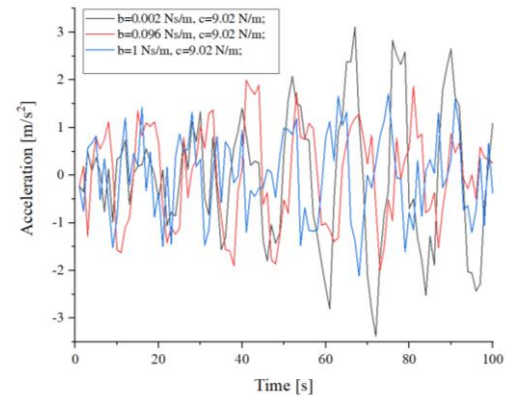


Fig. 7. Voigt-Kelvin model response for different values of damping coefficient b under real noise process

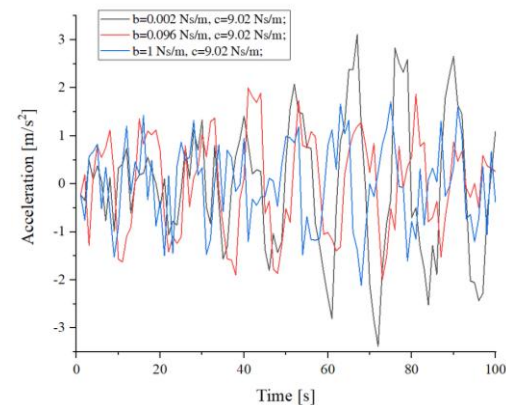


Fig. 8. Voigt-Kelvin model response for different values of spring stiffness c under real noise process

In Figure 8, variation of the spring stiffness alters the overall rigidity of the system, so that higher stiffness tends to increase the transmitted dynamic force and reduce the isolation effect, while lower stiffness improves vibration attenuation but may also lead to a softer system response. Taken together, the two figures demonstrate that the optimized model is sensitive to parameter selection and that a balanced combination of stiffness and damping is necessary to achieve effective stabilization under stochastic excitation.

5. CONCLUSION

The performed analysis confirms that the passive vibration isolation system effectively reduces the transmission of railway induced vibrations to the optical detection system mounted on the train body. Experimental results demonstrate that the selected rubber-metal mounts provide substantial attenuation of vibrations in vertical direction, thereby improving the operational stability of the sensor housing under real service conditions.

In addition to the experimentally confirmed isolation performance, the Voigt-Kelvin viscoelastic model proved to be a useful simplified analytical representation of the stabilized system. After parameter optimization based on measured acceleration data, the model offers a physically meaningful description of the spring-damper behavior and can be efficiently applied for preliminary evaluation of system response, sensitivity analysis, and design refinement.

Further testing of the optimized model under real stochastic excitation shows that it can also be employed as a force-input representation of the acting noise process for different levels of disturbance and model parameters. In this way, the model supports the analysis of stabilization effectiveness under realistic non-deterministic loading and provides a practical framework for assessing the robustness of the optical detection system.

Although the Voigt-Kelvin model does not fully reproduce the measured dynamic response with the accuracy of more complex viscoelastic formulations, its simplicity, interpretability, and computational efficiency make it valuable for stabilization oriented design and optimization. It is therefore suitable as an intermediate modeling tool between experimental assessment and higher order constitutive analysis. Overall, the combined experimental and numerical results confirm that the proposed isolation concept

improves the dynamic conditions required for reliable optical sensing in railway applications. The optimized Voigt-Kelvin model adds further value by enabling fast evaluation of stabilization performance under stochastic excitation and by supporting future development of vibration isolated vision based systems.

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REFERENCES

- [1] R. K. Tyson, *Principles of Adaptive Optics*, 4th ed. Boca Raton, FL, USA: CRC Press, 2015. doi: 10.1201/b19712.
- [2] L. A. Poyneer and J.-P. Véran, "Kalman filtering to suppress spurious signals in adaptive optics control," *J. Opt. Soc. Am. A*, vol. 27, no. 11, pp. A223–A234, 2010, doi: 10.1364/JOSAA.27.00A223..
- [3] M. Wang, J. Xiong, S. Fu, J. Ding, Y. Sun, Y. Peng, S. Xie, J. Luo, H. Pu and S. Shao, "An active vibration isolation and compensation system for improving optical image quality: Modeling and Experiment," *Micromachines*, vol. 14, no. 7, 1387, 2023, doi: 10.3390/mi14071387.
- [4] Z.-W. Hu, Z.-D. Xu, Y. Tian, Z.-H. Chen, J.-X. He, J. Dai, Q.-S. Miao i X.-L. Du, "Test, modeling, and vibration control of a novel viscoelastic multi-dimensional isolation and mitigation device," *Actuators*, vol. 13, no. 12, p. 481, 2024.
- [5] G. L. Hermsdorf, S. A. Szilagyi, S. Rösch, i E. Schäffer, "High performance passive vibration isolation system for optical tables using six degree-of-freedom viscous damping combined with steel springs," *Rev. Sci. Instrum.*, vol. 90, no. 1, Art. no. 015113, Jan. 2019, doi: 10.1063/1.5060707.
- [6] Smart Automation of Rail Transport - SMART, <https://cordis.europa.eu/project/id/730836>
- [7] M. Banić, I. R. Pavlović, A. Miltenović, M. Simonović, M. Mladenović, D. Jovanović, and M. Rackov, "Prediction of Dynamic Response of Vibration Isolated Railway Obstacle Detection System," *Acta Polytechnica Hungarica*, vol. 19, no. 3, pp. 51–70, 2022. [22] I. Pavlović and D. Milić, "Modeling and simulation of stochastic processes," *Innovative Mechanical Engineering*, vol. 1, no. 2, pp. 153–162, 2022.
- [8] W. N. Findley, J. S. Lai, and K. Onaran, *Creep and Relaxation of Nonlinear Viscoelastic Materials*, 1976.
- [9] I. Pavlović and D. Milić, "Modeling and simulation of stochastic processes," *Innovative Mechanical Engineering*, vol. 1, no. 2, pp. 153–162, 2022.

EXPERIMENTAL RESEARCH OF CHARACTERISTICS OF RIGID POLYURETHANE FOAM FOR KINETIC COLLISION ABSORPTION SYSTEMS - OGDEN MATERIAL MODEL

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Abstract – Rigid polyurethane (PU) foam was investigated as a filling material for a tube collision energy-absorbing component intended for railway vehicle crashworthiness applications. Quasi-static uniaxial compression tests were performed on cubic specimens extracted from a cylindrical PU foam block with a nominal density of 175 kg/m³ in order to characterize its compressive behavior and obtain material parameters for finite element analysis (FEA). The experimental stress-strain curves exhibited the characteristic nonlinear response of cellular material. An Ogden foam constitutive model was subsequently calibrated in Ansys using experimental compression data and implemented in numerical simulations of energy absorber designs. The numerical study evaluated the force-displacement behavior and energy absorption capability of each configuration under quasi-static axial compression applied through a conical bushing. For a compression stroke of 60 mm, the fully foam-filled tube demonstrated a 16% increase in absorbed energy compared with the empty tube, while the configuration incorporating the concentric steel core achieved an improvement of 9.5%. The findings confirm that the incorporation of rigid PU foam enhances the quasi-static energy absorption performance of tubular railway crash absorbers.

Keywords – Collision Energy Absorber, Rigid PU foam, Ogden foam model, Experimental investigation, Numerical simulation.

1. INTRODUCTION

Increasing train operating speeds require more efficient crash-energy management systems to improve passenger safety and protect vehicle structures during collisions [1]. Owing to its low density, low cost, and high energy absorption capability under compressive loading, rigid polyurethane (PU) foam has attracted considerable attention as a potential filler material for energy absorbers [2]. Its cellular structure enables efficient dissipation of impact energy through compression, making it suitable for railway crashworthiness applications. In modern railway vehicles, crash energy is primarily dissipated through deformable structural components such as crush tubes and anti-climbing devices. The concept investigated in this study consists of a steel tube filled with rigid PU foam that is compressed by passing through a conical bushing, Figure 1.

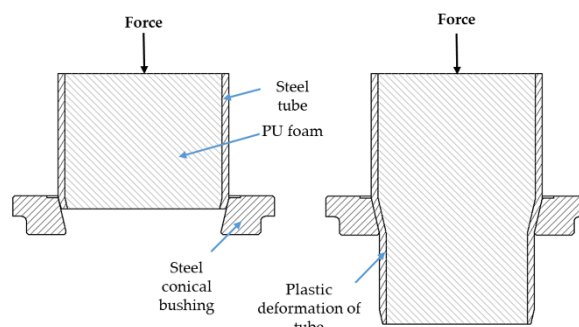


Fig.1. Collision absorber diagram (a) at start of force application (b) post force application.

During deformation, both the steel tube and the foam core contribute to energy dissipation through plastic deformation, foam compression, and friction, providing an effective mechanism for impact energy absorption. Accurate numerical modelling of foam-filled energy absorbers requires an appropriate constitutive model capable of reproducing the compressible nonlinear behavior of rigid PU foam.

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Previous studies have shown that rigid PU foam exhibits characteristics between elastomeric materials and cellular foams, making conventional incompressible hyperelastic models unsuitable [3]. Among available material models, the Ogden foam formulation has been identified as suitable for reproducing PU foam behavior in Ansys simulations [4], although accurate calibration requires reliable experimental data.

The present study investigates rigid PU foam as a filler material for a tube railway vehicle collision absorber consisting of a foam-filled steel tube compressed through a conical bushing. Experimental compression tests were performed on foam specimens extracted from different regions of a cylindrical sample, and the obtained data were used to calibrate an Ogden foam model in Ansys. The validated model was then applied to compare the performance of three absorber configurations: an empty tube, a fully foam-filled tube, and a foam-filled tube reinforced with a concentric steel core. Such a model enables preliminary assessment of absorber performance under quasi-static loading conditions before further crashworthiness evaluation.

1.1. Hyperelastic models and Ogden foam model

Hyperelastic models are widely used in finite element analysis to describe the nonlinear elastic behaviour and large deformations of materials such as rubbers and elastomeric foams, whose response cannot be accurately represented by conventional elastic parameters.

The Ogden foam model, also known as the hyperfoam model, uses a modified Ogden [5] form of strain energy potential function for compressible foams. The function is given by [6]:

$$W = \sum_{n=1}^N \frac{\mu_n}{\alpha_n} \left(J_{cl}^{\alpha_n/3} (\bar{\lambda}_1^{\alpha_n} + \bar{\lambda}_2^{\alpha_n} + \bar{\lambda}_3^{\alpha_n}) - 3 \right) + \sum_{n=1}^N \frac{\mu_n}{\alpha_n \beta_n} (J_{cl}^{-\alpha_n \beta_n} - 1)$$

where: μ_n , α_n are material constants, β_n is the compressibility parameter, $J_{cl} = J$ is the determinant of the elastic deformation gradient, $\bar{\lambda}_i$, the principal stretch ratios due to tensile/compressive strain and N is the order of fitting. The parameter β_n governs the compressibility of the material and is related to Poisson's ratio ν_n :

$$\beta_n = \frac{\nu_n}{1 - 2\nu_n}$$

Poisson's ratio can be determined experimentally by measuring the lateral strain during the compression test.

2. EXPERIMENTAL RESERACH

2.1. Material

PU foam is created by reacting a liquid isocyanate

with two or more isocyanate groups per molecule with liquid polyol, an organic compound containing multiple hydroxyl groups per molecule in the presence of a catalyst [7]. In this research, the PU foam was produced in circular tubes of diameter 85 mm and length 200 mm, with a density of 175 kg/m³. A 100 mm length of the foam cylinder was initially cut into twenty cubic 20 mm samples, Figure 2.

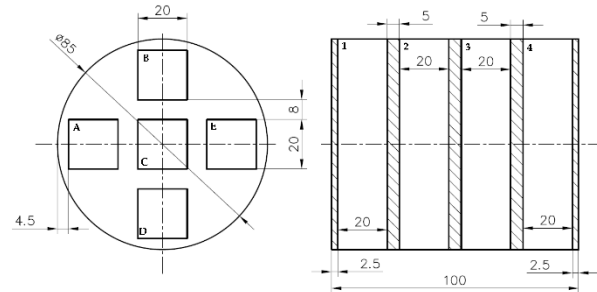


Fig. 2. (a) Cutting pattern from cylindrical sample. (b) Cubic samples cut from one 100 mm column.

This configuration was chosen to test whether cubic samples taken from the centre (C) exhibit different material properties to samples taken from other locations in the cylinder (A,B,D,E).

2.2. Testing

Uniaxial compression tests were performed on cubic samples using a Shimadzu tensile test frame with a 10 kN load cell, Figure 3. Tests were conducted at room temperature with a constant crosshead speed of 25 mm/min. until the predefined stroke was reached. Samples labeled as type 1 were compressed to 2 mm, type 2 to 4 mm, type 3 to 8 mm, and type 4 to 12 mm, corresponding to approximately 60% strain. A preload of about 1 N was applied before each test, and force, stress, strain, and stroke data were recorded at 0.01 s intervals.

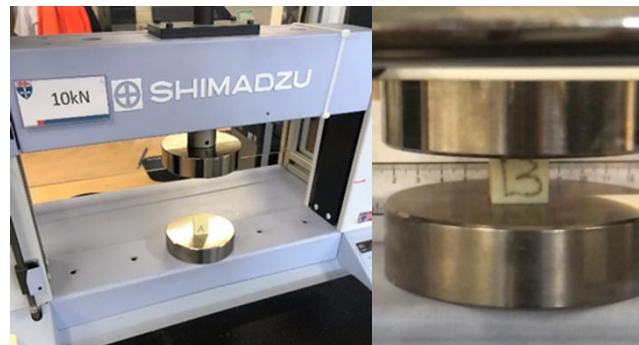


Fig. 3. Mechanical testing using Shimadzu 10 kN load cell.

3. EXPERIMENTAL RESULTS

Figure 4 shows the compression curves obtained from testing, with each graph containing four curves

labeled A to E. The curves show similar trends, except for sample C. All specimens exhibit linear elastic behavior up to approximately 8% strain, but the lines do not pass through the origin, likely due to the low preload. Therefore, arbitrary offsets will be applied when determining the Ogden foam model constants. For the 12 mm stroke tests, excluding sample C, the maximum difference between samples is 0.7 MPa at approximately 10% strain. Curve D shows the largest scatter, with the 12 mm specimen differing by 0.71 MPa, compared with 0.10, 0.19, and 0.09 MPa for cases A, B, and E, respectively.

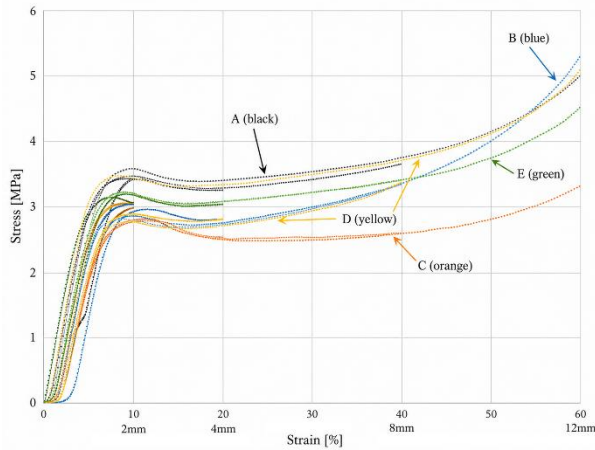


Fig. 4. Compressive stress-strain curves for all cubic samples.

Stress-strain curves up to 60% strain show the typical hyperelastic response, with linear, plateau, and densification regions. A representative curve was extrapolated from cubic sample B, Figure 5. The three regions represent distinct deformation mechanisms: linear elastic cell-wall bending, plateau-stage cell collapse, and densification through cell-wall compression, with the response influenced by the foam's anisotropy.

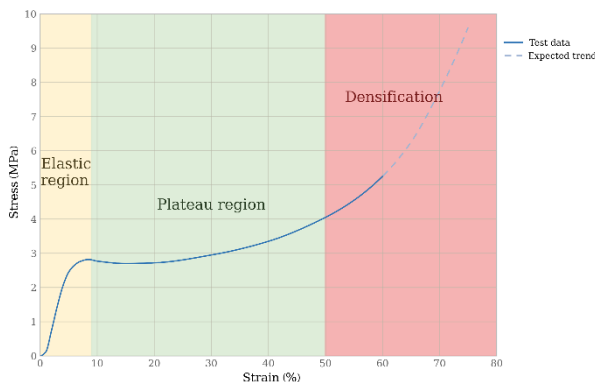


Fig. 5. Stress-strain curves of cubic sample B.

4. NUMERICAL SIMULATIONS

FEA was performed in ANSYS Mechanical 2019 R3 using a third-order Ogden foam model to replicate the compression tests and assess the absorber's energy

absorption [6]. Although hyperelastic models assume reversible, nearly incompressible deformation, the tested foam samples showed clear irreversible deformation after compression, Figure 6. The irreversible collapse of the foam complicates accurate hyperelastic modelling, but a model can be calibrated to reproduce the force response within the strain range relevant to the single-use collision absorber.



Fig. 6. Cubic samples B1 and B4 post-testing.

The measured engineering stress and strain were converted to true values for FEA, Figure 7.

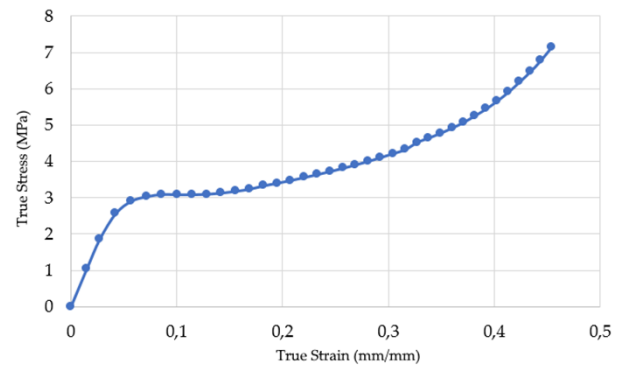


Fig. 7. True Stress vs Strain curve.

The compressibility parameters β_n were derived from experimental data, and the material constants were refined iteratively:

$$\begin{aligned} \mu_1 &= 4.4 \times 10^6 & \alpha_1 &= 20 & \beta_1 &= 0.452 \\ \mu_2 &= 4.4 \times 10^6 & \alpha_2 &= -10 & \beta_2 &= 0.542 \\ \mu_3 &= 9.9 \times 10^6 & \alpha_3 &= 0.45 & \beta_3 &= 1.082 \end{aligned}$$

One-eighth of the cube was modelled with three frictionless supports and displacement loading, using 22 elements along the loading direction and 18 perpendicular, with 31977 nodes, Figure 8. The reaction force was recorded throughout the stroke.

These tests showed that the first-order foam model is sufficient for strains up to 11%, while higher-order modelling is unnecessary. Figure 9 shows the curve fit of the 1st order model to be accurate up to a stroke of 2 mm on a 20 mm cubic sample, equivalent to 10% strain.

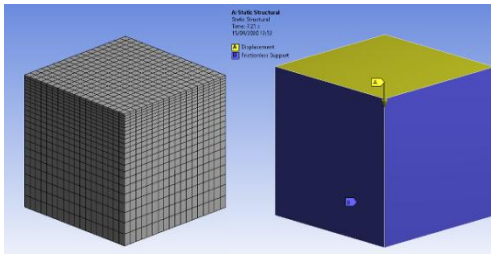


Fig. 8. Boundary conditions and mesh for eighth cubic sample.

The constants used in the material model for the foam in the collision absorber are:

$$\mu_1 = 14 \times 10^6 \quad \alpha_1 = 10 \quad \beta_1 = 0.5$$

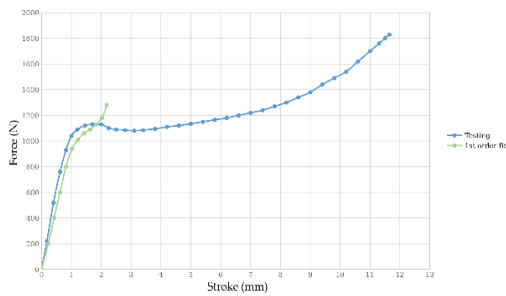


Fig. 9. 1st order model fit for strains up to 11% in cubic sample.

Using the validated PU foam model, three absorber configurations were analysed. A quarter-symmetry model with frictional tube–bushing contact ($\mu = 0.15$) was used, with mesh refinement optimized for convergence, Figure 10.

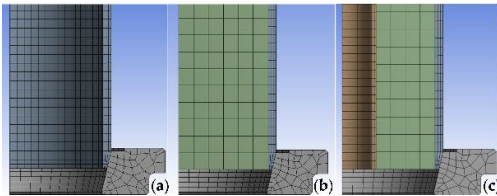


Fig. 10. Collision absorber meshes. (a) Empty tube. (b) Foam filled tube. (c) Concentric filled tube.

Figure 11 shows the force vs stroke for the three different energy absorber models up to a stroke of 60 mm.

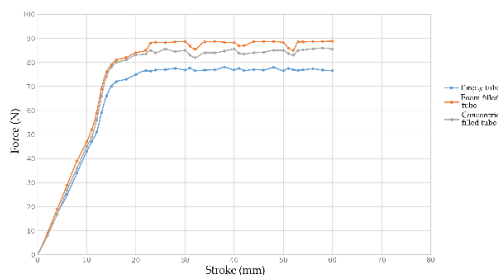


Fig. 11. 1st order model fit for strains up to 11% in cubic sample.

As shown, both foam-filled absorbers exhibited higher quasi-static energy absorption than the empty

tube, by approximately 16% for the fully filled and 9.5% for the concentric configuration.

5. CONCLUSION

This study demonstrated that rigid PU foam can enhance the quasi-static energy absorption of tubular railway collision absorbers. Compression tests confirmed the nonlinear foam response and some cross-sectional property variation, while the Ogden model adequately reproduced the experimental behavior; considering the predicted maximum strain of $\sim 11\%$, a first-order model was adopted for the final simulations. Among the three investigated configurations, the fully foam-filled absorber showed the highest energy absorption (4.61 kJ), representing an increase of $\sim 16\%$ over the empty tube (3.96 kJ), while the concentric-core configuration absorbed 4.38 kJ ($\sim 9.5\%$ increase). Further work should address dynamic foam testing, transverse strain measurement, mesh/contact sensitivity and experimental validation, including the effects of foam density, absorber geometry, tube dimensions and installation constraints.

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REFERENCES

- [1] EN 15227:2020+A1:2024. Railway Applications Crashworthiness Requirements for Rail Vehicles; European Committee for Standardization: Brussels, Belgium, 2024.
- [2] Xiao, Y.; Yin, J.; Zhang, X.; An, X.; Xiong, Y.; Sun, Y. Mechanical performance and cushioning energy absorption characteristics of rigid polyurethane foam at low and high strain rates. *Polym. Test.* 2022, 112, 107531.
- [3] Kim, S.; Shin, H.; Rhim, S.; Rhee, K. Y. Calibration of hyperelastic and hyperfoam constitutive models for an indentation event of rigid polyurethane foam. *Compos. Part B: Eng.* 2019, 163, 297–302.
- [4] Petre, M.T.; Erdemir, A.; Cavanagh, P.R. Determination of elastomeric foam parameters for simulations of complex loading. *Comput. Methods Biomech. Biomed. Eng.* 2006, 9(4), 231–242.
- [5] Ogden, R.W. Large deformation isotropic elasticity—On the correlation of theory and experiment for incompressible rubberlike solids. *Proc. R. Soc. Lond. A Math. Phys. Sci.* 1972, 326(1567), 565–584.
- [6] ANSYS Workbench Mechanical, Release 2019 R3 and Release 2025 R2.
- [7] Seymour, R.B.; Kauffman, G.B. Polyurethanes: A class of modern versatile materials. *J. Chem. Educ.* 1992, 69(11), 909–910.



BATTERY POWERED TRAINS FOR CROATIAN RAILWAYS

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Abstract – KONČAR - Electric Vehicles have designed and produced two prototypes of battery powered trains, Battery Electric Multiple Unit (BEMU) and Battery Multiple Unit (BMU). Alongside these trains, six stationary battery chargers are delivered and installed in six cities in Croatia: Bjelovar, Virovitica, Osijek, Varaždin, Split and Pula. The paper describes the overall system concept, including traction architecture, battery integration, control strategies, and charging infrastructure. Special attention is given to battery management functions, energy flow control between catenary, traction system, and onboard batteries, as well as the implementation of fast DC charging stations. In addition, the paper presents real operational data obtained from passenger service. Measured specific energy consumption ranges from approximately 2.4 to 3.7 kWh/km, depending on ambient temperature and route characteristics. Based on the defined state-of-charge operating window, the achievable range is estimated at 100–150 km for BEMU and 140–200 km for BMU under beginning-of-life conditions. The results confirm the technical feasibility and energy efficiency of battery-electric trains for regional transport applications, demonstrating their suitability as a replacement for diesel multiple units on partially or fully non-electrified railway networks.

Keywords – battery powered trains, 6211, 6012, NMC batteries, Croatian railways, traction converter, traction transformer, passenger trains, charging station, energy consumption, battery functions, range, kwh.

1. INTRODUCTION

Almost 60% of Croatian railway is non-electrified. In the continental part of Croatia there is a certain mix of electrified and non-electrified network, where there are local non-electrified branches of electrified mainline track. On the contrary, in the southern part of Croatia, starting from city of Ogulin, railway network is completely non-electrified, running all the way to city of Split. In Istria region there is also almost 100 kilometers of completely non-electrified rail network. Recent technological advances in battery storage systems have introduced a new type of rail vehicles, battery powered trains and locomotives. The paper is structured as follows: Section II presents the system concept, Section III describes the powertrain architecture, Sections IV and V address control and battery management functions, Section VI introduces the charging infrastructure, while Section VII presents operational results, followed by conclusions in Section VIII.

Battery-electric trains offer railway operators a clean, quiet and cost-effective way to decarbonise regional passenger services without the expense and disruption of full-line electrification. By replacing

diesel multiple units with zero local-emission traction, they cut greenhouse gas emissions and air pollution directly at the point of use, contributing to national and European climate goals. Powered largely by electricity drawn from the grid and, increasingly, from renewable sources such as on-site photovoltaic generation, these trains bring the environmental benefits of electrified rail to lines where wiring the whole route would otherwise be impractical. As demonstrated by the BEMU and BMU fleet presented in this paper, battery power is a mature, field-proven technology that lets Croatia extend sustainable, green mobility to every corner of its rail network, today rather than decades from now.

2. SYSTEM CONCEPT

KONČAR - Electric Vehicles have designed and produced two prototypes of battery powered trains; battery electric multiple unit (BEMU) and battery multiple unit (BMU). Alongside these trains, six stationary battery chargers are delivered and installed in six cities in Croatia: Bjelovar, Virovitica, Osijek, Varaždin, Split and Pula.

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2.1. BEMU 6211

BEMU Class 6211 is a 3-car train designed to run on both electrified and non-electrified tracks. It combines pantograph and traction transformer for 25 kV_{AC} line and traction batteries for non-electrified operation, making it a bi-modal train. It holds 146 seating and 158 standing passengers, being able to carry 304 passengers in total (in “normal payload working order” according to [1]). It uses a total 1,2 MVA power from 25 kV_{AC} catenary line in “electric mode” or 800 kW power from traction batteries in “battery mode”. In electric mode BEMU’s top speed is 160 kph, while in battery mode it is 120 kph. Batteries can be charged from overhead catenary line while driving or standing still, from every braking cycle by traction motors working as generators and from stationary battery chargers.

2.2. BMU 6012

BMU Class 6012 is a 2-car train designed to run on non-electrified tracks, using traction batteries. It holds 102 seating and 114 standing passengers, being able to carry 216 passengers in total (in “normal payload working order” according to [1]). It uses 800 kW power from traction batteries in “battery mode”, allowing it to run with a top speed of 120 kph. Batteries can be charged from every braking cycle by traction motors working as generators and from stationary battery chargers.

2.3. Charging stations

Six charging stations are produced, installed and put into operation in six cities in Croatia: Bjelovar, Virovitica, Osijek, Varaždin, Split and Pula. Each charging station is identical. Charging station is a standalone power converter designed to be able to charge traction batteries of battery powered trains, namely 6211 and 6012 Class. Input voltage of charging station is 10(20) kV_{AC} while output is regulated DC voltage in range of $650 \div 1010$ V_{DC} with nominal output current of 695 ADC. It can charge two battery groups simultaneously, each with 500 kW of power. Station is comprised of two major elements, a six meter container housing all necessary power equipment and a connection cabinet which is located near the tracks and stores charging cables, one for each battery group, used to make connection with the train.

3. POWERTRAIN ARCHITECTURE

Both trains share all major components of the powertrain, expect for traction transformer and affiliated medium-voltage gear (pantograph, main circuit breaker, instrument transformer and disconnect switch) which are used only on BEMU train. Therefore, following components are used: traction transformer

and affiliated medium-voltage gear (only on BEMU train), battery strings connected in two individual groups, traction and auxiliary converter, traction motors and gearbox.

3.1. Traction transformer

Traction transformer is a roof-mounted medium-voltage transformer made for nominal voltage of 25 kV_{AC}. It consists of a steel core with one primary winding and four secondary windings and two resonant filter chokes stored inside the same container. Secondary windings have nominal voltage of 420 V_{AC} and nominal power of 300 kVA. Filter chokes are actually part of the 100 Hz resonant filter used by the converter DC-link but are stored inside the traction transformer housing sharing the same cooling system (oil cooled by heat exchanger) as primary and secondary windings. Traction transformer is designed and built inside KONČAR Group.

3.2. Batteries

Traction Li-Ion batteries are intended for powering the main and auxiliary drives of the vehicle when it is operating on non-electrified sections of the railway. The batteries can be charged from the overhead line, from a stationary vehicle charging station located along the track, or during regenerative braking. Traction batteries enable vehicle operation on non-electrified railway lines. The traction battery system consists of three main components: battery packs, an electrical control cabinet, and a cooling unit. The battery packs contain battery cells (NMC type), connected in series and/or parallel combinations into a single unit and housed in an enclosure with integrated systems for regulating the temperature of the cells. Additionally, the enclosure includes electronic equipment for monitoring and controlling battery operation (BMS – Battery Management System) as well as power components for connecting all battery units.

The traction batteries are located on the roof of the vehicle and are divided into two groups. On the BEMU, each battery group consists of six packs (a total of twelve per train), while on the BMU, each group consists of seven packs (a total of fourteen per train). Each battery pack has nominal energy of 53 kWh, with voltage range of $720 \div 1000$ V_{DC}. This means that BEMU train has 636 kWh of available energy while BMU’s batteries hold 742 kWh of available energy.

Each battery group on the BEMU is connected to one main converter, while on the BMU, the configuration is different: both battery groups are connected to the same main converter, but to different battery converters integrated within the main converter of the BMU. This setup ensures redundancy on both types of trains, allowing continued operation at reduced power using the second battery group in case one group

fails.

The cooling unit (BTMS – Battery Thermal Management System) is responsible for maintaining the optimal temperature of the batteries. Each battery group has its own cooling unit, which independently manages the temperature of the battery coolant, separate from the other battery group.

3.3. Converter

The main drive of the BEMU consists of two main converters, each installed in one end module, sharing a common main transformer located in the middle module of the train. Each main converter includes two traction motor converters that control two asynchronous traction motors (mounted on the powered bogie), line converters, and a DC/DC converter for connection to the traction batteries. Inside the housing of the main converter, there are also two inverters for powering the auxiliary systems of the vehicle, connected to the DC-link of the main drive, and a battery charger for the control system batteries (24 VDC).

The main drive of the BMU also consists of two main converters; however, in this case, each converter controls one traction motor. Additionally, each main converter includes one DC/DC converter for the traction batteries and one inverter for the auxiliary power supply. One of the two main converters include a battery charger for the control system batteries.

The cooling of the main converter is achieved through forced circulation of coolant, which is air-cooled in a heat exchanger located on the roof of the vehicle. The drive system also includes electrodynamic braking, where the regenerated energy is primarily used to supply auxiliary systems, charge traction batteries (both BMU and BEMU), and/or return energy to the overhead catenary line (BEMU). Braking resistors or voltage limiters for the DC-link are mounted on the roof of the vehicle. Each main converter contains embedded computers that monitor the drive system's status (processing data and measuring current, voltage, and axle speed signals), act in the event of wheel slip, and communicate with the vehicle's main computer.

Converter is designed and built inside KONČAR Group

3.4 Traction motor and gearbox

Traction motor is a squirrel cage asynchronous three phase motor, designed to be powered by frequency inveter and housed inside powered bogie of a railway vehicle. It is a self-ventilated type and is equipped with temperature and speed sensors. Nominal ratings in S1 are as follows: voltage 540 V_{AC}, current 376 A_{AC}, power 300 kW and torque 1069 Nm. During vehicle starting, maximum allowable current is 690 A_{AC}.

Gearbox is a two stage gearbox with gear ratio of

1:4.822 and nominal power of 401 kW. Maximum design speed is 5772 rpm which enables the train to run up to 176 km/h.

Both train types use identical traction motors and gearboxes. BEMU has two powered bogies, each containing two powered axles with motor and gearbox set. This means tha in total BEMU has four traction motors and gearboxes. BMU however, has only one powered bogie, meaning in total it only has two traction motors and gearboxes.

3.5. Traction motor and gearbox

The control system of the KONČAR BEMU 6211 and BMU 6012 is centered around the Vehicle Control Unit (VCU), which supervises and coordinates all traction and energy-related functions of the train. The VCU collects real-time signals from propulsion equipment, converters, batteries, and driver inputs, and manages traction power, braking effort, and energy flow across the vehicle. It interfaces directly with the main propulsion system and ensures coordinated operation of all energy sources under both catenary and battery supply modes.

Traction control is implemented through dedicated microprocessor-based control systems integrated into each motor converter. Each traction converter independently regulates the associated asynchronous motor, controlling torque, speed, and adhesion conditions based on continuous measurement of current, voltage, and axle speed. These control units also implement anti-slip and anti-skid functionality, ensuring optimal traction utilization under varying adhesion conditions. Additionally, they provide built-in protection, diagnostics, and fault recording functions, while maintaining communication with the VCU.

A key element of the control concept is the management of energy flow between the catenary, traction converters, and onboard lithium-ion batteries. The control system dynamically switches between power supply sources and optimises energy usage depending on operating mode. During braking, the traction control system operates the motors in regenerative mode, and the recovered energy is either stored in the traction batteries or, when operating under overhead line and battery capacity is saturated, fed back into the catenary network.

4. BATTERY MANAGEMENT FUNCTIONS

The battery-electric multiple units BEMU 6211 and BMU 6012 are equipped with advanced battery management functions that are fully integrated into the overall traction and energy control system. The battery management system (BMS), in coordination with the vehicle control unit (VCU) and DC/DC converters, ensures safe, efficient, and lifetime-optimized

operation of the lithium-ion traction batteries under all operating conditions.

4.1. State-of-charge window operation

A key element of the battery management strategy is the controlled limitation of the battery state-of-charge (SoC) operating window. During normal operation, charging is typically limited to approximately 85–90% SoC, while discharge is restricted to around 20% SoC. This approach significantly reduces battery degradation and extends service life. In addition, the system enables a dedicated range extension mode, in which controlled discharge to approximately 10% SoC is permitted under predefined conditions, such as missed charging opportunities or degraded infrastructure availability, thereby ensuring operational flexibility and safe return capability. During this extended operation mode, VCU performs automatic traction power deration based on BMS current and voltage limits. Below 10% SoC, traction power is cut-off and batteries are disconnected.

4.2. Charging strategy

The battery charging process is actively managed to accommodate various operating scenarios, with particular emphasis on operation under overhead contact line. When the BEMU operates on electrified sections, its traction system enables continuous charging of the onboard batteries directly from the catenary. In driving mode, the control system automatically manages the energy flow from the overhead line, distributing power between traction motors, auxiliary inverters, and battery charging in accordance with the current driving profile and operational requirements. Depending on the instantaneous power demand, the system can supply traction directly while simultaneously charging the batteries, or prioritize one function over the other. In this way, combined operating modes are possible, where part of the energy is used for propulsion and onboard systems, while the remaining portion is directed to battery charging. In stationary mode under the catenary, the available power can be utilised more efficiently for charging purposes, as only auxiliary systems represent the remaining onboard load. As a result, higher charging power levels can be achieved compared to driving conditions, enabling faster replenishment of battery energy. In addition to catenary-based charging, the system also supports energy recovery through regenerative braking and charging from stationary charging infrastructure. All charging processes are continuously monitored and adjusted in accordance with battery condition, temperature, and operating constraints, ensuring efficient energy transfer while preserving battery lifetime.

4.3. Battery pack connection and system formation

At vehicle start-up, a dedicated battery system initialization sequence is executed in order to form a unified traction battery system. Individual battery packs are first checked with respect to voltage levels, general status, and insulation conditions. Subsequently, the packs are connected via controlled switching devices using pre-charge circuits, allowing gradual voltage equalisation and preventing inrush currents. Through this process, multiple battery packs are safely connected in parallel and combined into a single functional battery system. This connection algorithm ensures reliable energization, balanced load sharing, and provides the capability to isolate individual packs in the event of a fault

5. CHARGING STATIONS

Alongside the BEMU and BMU trains, six charging stations were built, in the cities of Bjelovar, Vinkovci, Varaždin, Osijek, Pula and Split.

5.1. Concept

These charging stations are based on the KONČAR KonCharge 1000 concept, designed as high-power stationary energy conversion units enabling efficient charging of battery-powered rolling stock. Each charging unit converts medium-voltage grid supply (10 or 20 kV) into a controlled DC output suitable for direct battery charging, using IGBT-based power converters with integrated transformer and switching equipment. The system allows parallel charging via two physical DC charging cables, each connected to an independent charging output rated up to 500 kW, enabling flexible and high-power charging operation adapted to timetable requirements.

5.2. Charging interface and handshake

The charging interface between the train and the station is designed to ensure both electrical and functional compatibility, including dedicated pilot connections for safety verification, controlled energisation sequences, and communication channels for real-time data exchange. Establishment of the charging process follows a structured handshake protocol between the vehicle and charging station. This process includes user authorization, selection of charging sequence, initialization of the converter, and physical connection of the charging cables. Once the connection is established, communication between the onboard control system and the charging station verifies readiness for charging, including confirmation of battery status, insulation conditions, and system availability. Only after successful validation are the power contactors closed and charging enabled,

ensuring safe and controlled energy transfer.

During the charging sequence, continuous data exchange is maintained, including parameters such as state of charge, voltage, current, and temperature, enabling adaptive control of the charging process. Upon completion, a controlled disconnection sequence is executed, in which charging current is reduced to zero, power contactors are opened, and the interfaces are safely disconnected following operator confirmation. This structured protocol ensures a high level of operational safety, prevents improper connection or disconnection, and enables reliable integration of the charging infrastructure with the battery-electric train fleet.

6. OPERATIONAL EXPERIENCE

The BEMU and BMU trains represent the first battery-electric passenger trains introduced in Croatia and the broader region. During the initial design phase, extensive simulations were conducted using telemetry data and mission profiles from Class 7023 diesel trains operating on non-electrified routes—the same lines where the BEMU and BMU units are expected to be deployed. These simulations played a key role in estimating energy consumption, operating range, and charging requirements under real-world conditions. Once the battery trains entered passenger service, operational data became available and provided insight into real energy consumption, operational efficiency, and achievable autonomy under different environmental and operational conditions.

For the BEMU platform, measurements were conducted on regional routes such as Zagreb – Bjelovar. Under low ambient temperature conditions (approximately 5 °C), the recorded energy consumption was around 108 kWh over a distance of 30 km, corresponding to a specific consumption of 3.6 kWh/km. Under milder conditions (approximately 20 °C), the energy consumption decreased to approximately 86 kWh over 32 km, yielding a specific consumption of 2.7 kWh/km. Under high temperatures, recorded energy consumption was around 114 kWh over a distance of 31 km, yielding a specific consumption of 3.7 kWh/km. These results clearly indicate the influence of ambient conditions, particularly HVAC demand, on overall energy consumption.

For the BMU platform, operational measurements were carried out on the Split – Kaštel Stari route. At an ambient temperature of approximately 4 °C, the recorded energy consumption was asymmetric depending on the driving direction, with 90 kWh for one direction and 43 kWh for the return trip over the same distance of 18 km, resulting in an average consumption of approximately 3.7 kWh/km. At higher temperatures (approximately 15 °C), the energy

consumption decreased significantly, with measured values of 66 kWh and 22 kWh respectively, corresponding to an average specific consumption of approximately 2.4 kWh/km. The difference between directions is primarily attributed to track gradient and operational conditions, demonstrating the sensitivity of energy consumption to route characteristics.

Based on the available battery capacity and defined state-of-charge operating window (approximately 85% to 20%), the usable energy for traction amounts to approximately 412 kWh at the beginning of life (BoL) for BEMU and 478 kWh for BMU, with reduced values at end-of-life conditions. Consequently, the achievable operational autonomy is estimated in the range of 100 to 150 km for BEMU and 140 to 200 km for BMU under BoL conditions, with corresponding reductions over the vehicle lifecycle.

Given the diversity of routes across the network—each with varying topography, stopping patterns, and climate conditions—battery consumption varies significantly between missions. It will therefore be essential to compare the simulation results with real-world performance data on all track to validate the initial assumptions regarding range and energy efficiency.

7. CONCLUSION

The development and deployment of the BEMU 6211 and BMU 6012 units, supported by a dedicated network of high-power charging stations, represent a significant step toward the modernization and decarbonisation of regional railway transport in Croatia. Together, the battery-electric rolling stock and charging infrastructure form a fully integrated system enabling reliable operation on mixed electrified and non-electrified railway networks.

The analysis of operational data obtained from passenger service confirms that the achieved performance is consistent with design expectations. Measured specific energy consumption in the range of 2.4 to 3.7 kWh/km reflects the influence of ambient temperature, route characteristics, and operational conditions, with particularly strong impact of HVAC demand and track gradients. Based on the defined battery operating window and available energy, the achieved and projected operating ranges of 100–150 km for BEMU and 140–200 km for BMU at beginning-of-life conditions validate the suitability of the concept for regional services.

The deployed charging stations, capable of high-power DC charging via dual connections, play a key role in enabling practical operation of battery-electric trains. Their integration with the onboard control and battery management systems ensures safe, efficient, and flexible charging both in scheduled and operationally constrained conditions. The combination

of stationary charging infrastructure, catenary-based charging (for BEMU), and regenerative braking provides a robust and adaptable energy supply concept.

Overall, the presented experience confirms that battery-electric trains, supported by appropriately dimensioned charging infrastructure, are a technically viable and energy-efficient alternative to diesel-powered units on partially or fully non-electrified railway networks. Future work will focus on further optimisation of energy consumption, refinement of

charging strategies, expansion of the charging network, and continued validation of long-term operational performance.

REFERENCES

- [1] EN 15663:2017, Railway applications - Vehicle reference masses
- [2] G48712d_TO_BMV_Izvedbeni
- [3] G48711a_TO_BEMV_Izvedbeni

Traffic and Transport



ASSESSMENT OF RESIDUAL CAPACITY OF SINGLE-TRACK LINES FROM SIMULATION USING UIC 406 COMPRESSION

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Abstract – How many additional trains a line can accommodate is a recurring question in timetable planning and infrastructure management. This paper presents a computational procedure that derives line-capacity indicators directly from the output of the microscopic simulator OpenTrack. The existing timetable is first adapted for import into OpenTrack; the simulator then generates, for each train, a blocking time stairway, which is converted into section occupancy intervals and compressed according to the UIC 406 method (greedy left-shifting with backward propagation and an optional overlap policy for single-track operation). From the compressed diagram, the bottleneck, infrastructure occupancy and a free-capacity indicator are determined. A residual-capacity estimate “in the tail of the day” is proposed: instead of counting gaps between existing trains, additional homogeneous paths are packed into the interval after the last compressed train, using speed profiles by official train categories. The compressed timetable is exported in an OpenTrack-compatible format for re-simulation. The procedure is demonstrated on a single-track section of main line M202 Zagreb – Rijeka in Croatia for a representative working day, quantifying the bottleneck, its utilisation and the number of additional paths by category and direction.

Keywords – Line capacity; UIC 406; infrastructure occupancy; blocking-time compression; microscopic simulation.

1. INTRODUCTION

The capacity of a railway line is not a single value but the result of the interaction between infrastructure, timetable and operating rules [1], [2]. As demand grows on regional and single-track lines, planners increasingly need a fast and defensible answer to the question: how much room remains alongside the existing timetable, and for which type of traffic? An accepted framework is provided by leaflet UIC 406 [3]: the timetable is compressed without adding time until trains are as close as signalling and running times permit, and the resulting infrastructure occupancy is compared with the available time. The theoretical basis is the analysis of blocking times (the blocking-time stairway), described in [1] and [2].

For realistic running and occupancy times, microscopic simulation is routinely used; in this work OpenTrack [4] serves as a complement, generating blocking time stairways. The analytical part — construction of blocking intervals, UIC 406 compression, bottleneck identification, utilisation and residual-capacity estimation — is carried out in the Etiris RailPrep environment (see Sec. 2). Method reviews [5], [6] distinguish analytical, optimisation and simulation

approaches; here simulation (OpenTrack) and an analytical procedure (RailPrep) are combined.

The contribution is twofold: (i) a reproducible procedure that builds occupancy intervals from blocking time stairways and compresses them according to UIC 406, and (ii) a residual-capacity estimate that quantifies the number of additional trains in the interval after the last compressed train, resolved by train category. Both steps are implemented in the Etiris RailPrep module; the paper focuses on method and results rather than implementation.

2. ETIRIS RAILPREP AND DATA

For this research, Etiris RailPrep was used — an auxiliary software module for the preparation, validation and harmonisation of input data and for line-capacity analysis. The module supports editing of timetable and infrastructure data, their export in OpenTrack-compatible formats and — after simulation — import of blocking time stairways, construction of blocking intervals, UIC 406 compression, bottleneck identification, utilisation and residual-capacity estimation. OpenTrack is used solely as a complement for microscopic simulation and for checking proposed

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timetable changes.

2.1. Courses and their editing

In OpenTrack, each individual train run is described by the notion of a course. A course links three data sets: rolling stock (traction/resistance characteristics and running dynamics), an itinerary (the path through the infrastructure model) and times (arrivals, departures and dwells at stations). For an existing timetable to be simulated faithfully, its courses are prepared and aligned with this structure.

In the RailPrep module, courses are imported, edited and exported in a format compatible with OpenTrack's Courses data. In this way courses can be modified and adjusted before simulation — for example correcting station labels (stationSign), arrival and departure times (arrTime, depTime), dwell times (dwell) or assigning a suitable itinerary — and then exported to OpenTrack. This ensures consistency between the original timetable and the simulation input, while allowing timetable variants to be created easily.

2.2. Timetable

The complete timetable is prepared in the RailPrep module in OpenTrack's text format OT_tt_ie (.txt). Files are stored with a date and name, and on export they retain the original header and footer, preserving version traceability and re-import compatibility with OpenTrack. It is a tab-separated file with one row per course and operating point, with the following columns:

Tab. 1. Columns of Timetable

Column	Description
courseID	Train (course) identifier
intervalCourseID	Interval identifier of the course (if any)
timeToIntervalReference	Reference to the course interval
stationIndex	Sequential number of the operating point along the course route (0, 1, 2, ...)
stationSign	Operating-point label
trackName	Track label (if specified)
arrTimeDayOffset	Day offset for the arrival time (0 = simulation day)
arrTime	Arrival time (HH:MM:SS)
depTimeDayOffset	Day offset for the departure time
depTime	Departure time (HH:MM:SS)
useDepTime	Whether the prescribed departure time applies (1/0)
dwell	Minimum dwell time [s]
stopAtStation	Scheduled stop at the station (1/0)
meanDelay	Mean delay [s]
Distribution	Delay distribution
deltaMass	Train mass correction

Courses prepared in this way, together with the infrastructure model and rolling stock, form the complete input for microscopic simulation.

2.3. Infrastructure data (XML)

The infrastructure model is edited in the RailPrep module in an XML format compatible with OpenTrack's infrastructure data. Several files may be open simultaneously, and on export the original file structure is retained. From these data the operating points and their order are derived, defining a sequence of sections (resources) onto which blocking intervals are later mapped.

2.4. Simulation in OpenTrack and .step2 import into RailPrep

The prepared data (courses, timetable, infrastructure) are loaded into OpenTrack, which performs the microscopic simulation. For each train the simulator exports a blocking time stairways (begin and end). In OpenTrack terminology, the .step1 export gives the distance of the reserved section as a function of time, and the .step2 export the distance of the released section as a function of time. This work uses the .step2 export (release): a piecewise-constant time–distance curve that, at each instant, shows how far along its itinerary a train has released the infrastructure behind it — the trailing edge of the blocking-time stairway. The RailPrep module imports the .step2 files and converts them into blocking intervals (see below).

The line is described by operating points and their order, defining a set of consecutive sections (resources). For each train, the local path from the .step2 curve is mapped onto the line order, and the running direction is recognised from the itinerary header. For a section r , the occupancy interval is obtained as the union of the blocking intervals $[a_i, b_i]$ of all trains using it, which avoids double-counting of overlaps:

$$t_{0ii}(r) = |U_i[a_i, b_i]| \quad (1)$$

The result is a set of blocking intervals (train, section, start a_i , end b_i , direction). Station dwells and shunting are naturally contained in the curves; an optional limit on the stationary “tail” at the terminal station prevents shunting from artificially inflating section occupancy. Using release times (rather than nominal departure/arrival times) keeps occupancy consistent with the simulator's signalling behaviour [2].

3. COMPRESSION ACCORDING TO UIC 406

In the RailPrep module the blocking intervals are compressed according to UIC 406. Compression places the intervals as early as possible, respecting two constraints: the order of sections within each train and conflicts on shared sections [1], [3]. Two overlap

policies are supported. The strict policy allows no overlap on a section (classic UIC 406). The conservative policy (UIC 406+) allows overlap on a section only if the same pair of trains was already overlapping in the original timetable, and never more than the original amount; this accommodates single-track lines where simultaneous occupancy is a consequence of data granularity rather than an actual conflict. A backward-propagation pass then delays the earlier sections of each train so that it arrives “just in time”, removing artificial intermediate dwells.

The span of the compressed timetable T_{comp} is defined by the extreme instants of all intervals:

$$t_{comp} = \max_i b_i - \min_i a_i \quad (2)$$

According to UIC 406, the infrastructure occupancy (consumed capacity) k is the ratio of total occupancy on the governing (critical) section r^* to the chosen time window T_{period} [3], [7]:

$$k = T_{occ}(r^*) / T_{period} \quad (3)$$

The value of k is compared with the recommended UIC limit values: if it is higher, the section is considered congested; if lower, free capacity remains. In addition, the share of the window covered by the compressed timetable is tracked through the ratio T_{comp} / T_{period} , as a measure of the temporal distribution of traffic over the day.

The compressed timetable and the added paths (Sec. 5) are exported by RailPrep in an OpenTrack-compatible format; the proposed increase can be re-loaded into the simulator to check feasibility and delays. Quantitative validation — comparing the analytical estimate with re-simulated delays — is the subject of ongoing work and is not covered here.

4. BOTTLENECK IDENTIFICATION

For each section, the utilisation U_r is computed as the ratio of its occupancy $t_{occ}(r)$ to its compressed span $T_{comp}(r)$:

$$U_r = t_{occ}(r) / T_{period}(r) \quad (4)$$

Besides utilisation, the average spacing between consecutive trains is tracked for each section — the mean buffer time between adjacent blocking intervals. Each section is scored by a weighted combination of utilisation, total occupancy, average spacing and the share of the compressed span it covers. The highest-scoring section is reported as the bottleneck, together with the number of trains, occupancy, compressed span, utilisation and average spacing. The bottleneck defines the governing limit for any capacity addition [1], [6].

In the analysed data the governing section is also the longest and slowest inter-station section and has the highest occupancy and utilisation; the choice is therefore

robust — the same section is identified as the bottleneck over a sensible range of weights. On single-track lines, UIC 406 requires the compression (measurement) points to be placed at crossing stations [7], [8], because the section between two crossings belongs at any instant to a single train of one direction.

5. RESIDUAL-CAPACITY ESTIMATION (“TAIL OF THE DAY”)

Counting the empty gaps that remain between trains after compression overestimates the usable capacity, because these gaps are fragmented and often shorter than a feasible path. Residual capacity is therefore estimated only in the “tail of the day” — the interval on the governing section that follows the last compressed train, up to the end of the analysis horizon.

For each train category, a homogeneous running-time profile is derived from the observed section running times, parameterised by a speed factor that linearly interpolates between the shortest and longest observed time of each section. Additional paths of a given category are packed into the “tail” in turn, each departing only once the previous one has cleared the governing section; the number of paths that fit, by category and direction, represents the residual capacity of that category.

For comparison, the theoretical homogeneous maximum at a target utilisation ρ (e.g. 60%, 75%, 100%) on the bottleneck block time t_{block} (the minimum headway, i.e. the mean blocking time per train on the governing section) is [3]:

$$N_{max} = \lceil (\rho \cdot T_{period}) / t_{block} \rceil \quad (5)$$

N_{max} serves as a theoretical reference for the total homogeneous capacity of the governing section over the whole horizon, as opposed to the number of additional “tail-of-day” paths (Tab. 3), which refers only to the remaining interval. Because the categories share the same “tail”, the per-category values are upper bounds for each category alone and are not additive; mixed addition is obtained by greedily packing compatible paths across categories. In the case study the categories follow from OpenTrack’s speed profiles (fast passenger, regional passenger, freight), derived from the observed section running times.

6. CASE STUDY

The procedure is demonstrated on the single-track section Ogulin–Moravice (main line M202 Zagreb–Rijeka, regional in character; about 29.8 km, six stations: Ogulin, Hreljin Ogulinski, Ljeskovac Bosiljevski, Gomirje, Vrbovsko, Moravice). The input consists of 65 .step2 exports from microscopic simulation for a

representative working day. The section Moravice–Vrbovsko (MOR–VRB) was identified as the bottleneck, occupied for a total of 07:48:49 (Tab. 2). Over a 24-hour horizon this gives an infrastructure occupancy $k = 32.6\%$, below the recommended UIC 406 daily limit for mixed traffic (about 60%) [3], [7] — the section is not congested. The compressed timetable covers $T_{\text{comp}} = 16:27:27$, i.e. 68.6% of 24 h; within the compressed span the section utilisation is 47.5%.

Tab. 2. Bottleneck indicators (section MOR–VRB)

Item	Value
Bottleneck section	MOR–VRB
Number of trains	65
Occupancy (union of block times)	07:48:49
Infrastructure occupancy k (24 h)	32.6%
Compressed span	16:27:27
Section utilisation	47.5%
Average spacing	12.1 min

Tab. 2. Additional paths in the “tail of the day”, by direction and train category

Direction	InterCity	Commuter	Freight
Ogulin → Moravice	+25	+22	+12
Moravice → Ogulin	+23	+21	+11

Categories follow OpenTrack speed profiles (IC/fast, regional, freight). The values are upper bounds per direction, computed without explicit crossing scheduling (see Sec. 7).

The results show that, although the corridor is busy during the active part of the day, the governing section is occupied for less than half of its compressed span, and a substantial number of additional paths — strongly dependent on train category — can be scheduled after the last train. The additional paths in Tab. 3 were not re-simulated; checking their feasibility by re-simulation is the subject of ongoing work (see Sec. 7).

7. DISCUSSION

The obtained indicators are in line with expectations for single-track regional lines, where train headways are relatively large and the load is concentrated in part of the day [5], [6], [8]. The value of the “tail of the day”, relative to classic gap counting, is that it yields feasible, non-fragmented paths, so the result is directly usable in planning. Equations (1)–(5) are definitional, in accordance with UIC 406; the contribution is the reproducible procedure and the “tail-of-day” logic, not a new theory.

Several limitations should be noted. First, the 24-hour horizon includes night hours that on regional lines are routinely reserved for line closures and maintenance; with a representative service window (e.g. 05–23 h) the occupancy rises to $k \approx 43\%$, still below the UIC limit, but part of the “tail” falls into the night, so the practically usable residual capacity is smaller than in Tab. 3.

Second, on a single-track line the directions are not independent: every added path in one direction consumes crossing capacity for the opposite one, so the values in Tab. 3 are upper bounds without explicit crossing scheduling. Third, the result depends on the quality and calibration of the simulation model [4] and on the simplification by a homogeneous speed profile.

Closing the loop — exporting from the RailPrep module to OpenTrack and re-simulating — enables validation; a quantitative comparison of the analytical estimate with re-simulated delays is the subject of ongoing work.

8. CONCLUSION

A reproducible procedure has been presented that converts the output of microscopic simulation into capacity indicators according to UIC 406 and, additionally, into a residual-capacity estimate based on the logic of packing paths “in the tail of the day”, resolved by train category. The approach gives planners a clear answer to the question “how many more trains, and of which type”, and it identifies the bottleneck section that sets this limit. Future work includes extending to mixed category sequences with explicit crossing constraints and validating the estimates against realised timetables.

REFERENCES

- [1] I. A. Hansen, J. Pachl (eds.), *Railway Timetabling & Operations: Analysis, Modelling, Optimisation, Simulation, Performance Evaluation*, 2nd ed., Eurailpress, Hamburg, 2014. ISBN 978-3-7771-0462-1.
- [2] J. Pachl, *Railway Operation and Control*, 4th ed., VTD Rail Publishing, Mountlake Terrace, WA, USA, 2018. ISBN 978-0-9719915-9-0.
- [3] International Union of Railways (UIC), *UIC Code 406 – Capacity*, 2nd ed., UIC, Paris, 2013. ISBN 978-2-7461-2159-1.
- [4] N. Hürlimann, A. Nash, *OpenTrack – Simulation of Railway Networks, Users Manual Version 1.9*, Zürich, Switzerland
- [5] M. Abril, F. Barber, L. Ingolotti, M. A. Salido, P. Tormos, A. Lova, *An assessment of railway capacity*, Transportation Research Part E, vol. 44, no. 5, 2008, pp. 774–806.
- [6] T. Lindner, *Applicability of the analytical UIC Code 406 compression method for evaluating line and station capacity*, Journal of Rail Transport Planning & Management, vol. 1, no. 1, 2011, pp. 49–57.
- [7] T. Lindner, J. Pachl, *Recommendations for Enhancing UIC Code 406 Method to Evaluate Railroad Infrastructure Capacity*, Transportation Research Board 89th Annual Meeting, Washington, D.C., 2010.
- [8] A. Landex, *Evaluation of Railway Networks with Single Track Operation Using the UIC 406 Capacity Method*, Networks and Spatial Economics, vol. 9, no. 1, 2009, pp. 7–23.



COST-MINIMIZING TRAIN PATH MANAGEMENT: CURRENT AND PROPOSED CALCULATION METHOD

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Abstract – Serbian railway access charges for unused reserved capacity are being reformed. This paper develops a cost-minimization model for freight operators selecting train paths under both current (train-count-based) and proposed (train-km-based) penalty calculation method. Three long-term path types are analyzed — Regular (R), Regular on designated days (Rd), and Facultative (F) — together with ad hoc (A) path type. We derive closed-form crossover thresholds, prove that F paths dominate R paths in the deterministic scenario, and expose a systematic distortion in the current method for Rd paths: identical integer thresholds for different numbers of designated days produce disproportionate penalties. The proposed calculation method corrects this by penalizing proportionally to reserved train-km. A numerical example illustrates the magnitude of the distortion.

Keywords – train path allocation, access charges, cost minimisation, unused reserved capacity

1. INTRODUCTION

Infrastructure of Serbian railways (ISR) is transitioning to a new methodology for charging unused reserved train-path capacity. The current regulation penalises railway undertakings (RUs) for unrealised train departures at the origin of the allocated path, while the proposed calculation method, effective from the 2027 Network Statement, imposes penalties based on unrealised train-kilometres. Although the parameter values remain similar, the shift from a departure-count to a distance-based metric changes the economic calculus for every path category.

The change is especially significant for two scenarios common within rail Serbian freight operations: (i) trains that run only part of the reserved route (e.g., a loco path covering 60 % of the full route length), and (ii) Rd paths reserved for specific days of the week, whose occurrence count varies by month. The current regulation does not differentiate between these cases and full-route operations, whereas the new regulation does.

This paper formulates a unified cost-minimisation model, derives analytical solutions and threshold conditions for all four access strategies (R, Rd, F, A), and quantifies the distortion introduced by the old Rd penalty through a concrete numerical example.

2. PROBLEM DESCRIPTION

A freight operator plans capacity for a single route (length $L[km]$) over one month (d_m calendar days, $n_m = d_m/7$ weeks). Four different access strategies are available:

- R — Regular path: reserved every day, charged $d_m \cdot CP_i$ per month (where CP_i denotes requested path price).
- Rd — Regular on designated days: reserved only for d_m^d specified days (e.g., Tuesdays), charged $d_m^d \cdot CP_i$.
- F — Facultative path: reserved with weekly flexibility (any day), charged $n_m \cdot CP_i$.
- A — Ad hoc path: no advance reservation; surcharge $\delta \cdot CP_i$ per departure.

Here $CP_i = c \cdot L$ is the unit-route access charge (c [€/train-km]). Key parameters: $\alpha = 0.35$ (utilisation threshold for R and Rd), $\beta = 0.10$ (threshold for F), $\gamma = 0.20$ (penalty rate), $\delta = 0.10$ (ad hoc surcharge). The RU's total demand is V [train-km/month], deterministic.

3. MATHEMATICAL FORMULATION

3.1 Proposed model — train-km based penalties

Let $x^R, x^{Rd}, x^F \in \{0, 1\}$ indicate which path types are reserved, and $v^R, v^{Rd}, v^F \in \mathbb{R}^+$ denote realised train-km for each path type. Variable $q_0 \geq 0$ captures ad hoc

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train-km. Penalty thresholds: $ad_m L$ (R), $ad_m L$ (Rd), $\beta n_m L$ (F).

$$\begin{aligned} \min Z^{new} = & \gamma c \cdot \max(0, x^R ad_m L - v^R) \\ & + \gamma c \cdot \max(0, x^{Rd} ad_m L - v^{Rd}) \\ & + \gamma c \cdot \max(0, x^f \beta n_m L - v^f) \\ & + \delta c \cdot q_0 \end{aligned} \quad (1)$$

s.t.:

$$\begin{aligned} v^R + v^{Rd} + v^f + q_0 & \geq V \\ v^R & \leq x^R d_m L \\ v^{Rd} & \leq x^{Rd} d_m L \\ v^f & \leq x^f d_m L \end{aligned}$$

3.2 Current model — train based penalties

Let q^R , q^{Rd} , $q^f \in \mathbb{Z}^+$ be departure counts. Integer thresholds: $\tau^R = \lceil ad_m \rceil = 11$, $\tau^{Rd} = \lceil ad_m \rceil$, $\tau^f = \lceil \beta n_m \rceil = 1$.

$$\begin{aligned} \min Z^{old} = & \gamma CP_1 \cdot \max(0, x^R \tau^R - q^R) \\ & + \gamma CP_1 \cdot \max(0, x^{Rd} \tau^{Rd} - q^{Rd}) \\ & + \gamma CP_1 \cdot \max(0, x^f \tau^f - q^f) \\ & + \delta CP_1 \cdot q_0 \end{aligned} \quad (2)$$

s.t.:

$$\begin{aligned} q^R + q^{Rd} + q^f + q_0 & \geq V/L \\ q^R & \leq x^R d_m \\ q^{Rd} & \leq x^{Rd} d_m \\ q^f & \leq x^f d_m \end{aligned}$$

The key structural difference: the proposed model captures partial-route operation through continuous train-km (a train covering $K < L$ km contributes only K , not L). The current model counts departures regardless of distance run, creating the distortions analysed in Section 4.

4. ANALYTICAL RESULTS

4.1 R and F path optimality

Greedy allocation lemma: it is always cost-optimal to fill long-term path capacity before resorting to ad hoc access, in both models. Equating the penalty under one R path with the total ad hoc cost for Q full-route trains gives the crossover threshold:

$$Q_a^R = \lceil \gamma \alpha / (\gamma + \delta) \rceil \cdot d_m \approx 7 \text{ trains/month} \quad (3)$$

Below Q_a^R , ad hoc access costs less than carrying the R -path penalty. The current-model crossover uses $\tau^R = \lceil ad_m \rceil = 11$ instead of $ad_m = 10.5$, giving $Q_a^{old} \approx 7.33$ — slightly higher due to ceiling rounding. For F paths, the threshold is $\beta n_m L \approx 0.43L$ train-km (for proposed calculating method) or $\tau^f = 1$ departure (according to current calculation method): a single entire-route departure eliminates the F -path penalty in both models. Since F costs $n_m \cdot CP_1$ against $d_m \cdot CP_1$ for R (and $n_m < d_m$), F paths dominate R in the deterministic scenario for all $\beta < 7/d_m \approx 0.23$.

Figure 1 shows that with $Q = 11$ trains, even a 1% shortfall in route completion immediately generates a penalty with proposed calculation method, while implementing current method charges nothing.

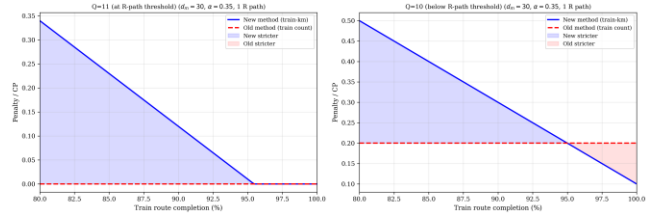


Figure 1. Partial-route penalty for $Q = 11$ (left) and $Q = 10$ (right), R path ($d_m = 30$, $\alpha = 0.35$). Proposed calc method (blue) is continuous; current method (red dashed) is a step function.

The divergence is larger below the threshold (right panel), as the current method gives a fixed step penalty, while the proposed one grades it smoothly with actual km shortfall.

4.2 Rd paths — cost boundary and distortion

For a Rd path with d_m^d designated days, the monthly reservation cost is $d_m^d \cdot CP_1$, vs. $n_m \cdot CP_1$ for F path type. The two are equal at the critical boundary:

$$d^{*d}_m = n_m = d_m / 7 \quad (4)$$

Below d^{*d}_m , the Rd path is cheaper than F but offers slots only on specified days. Above d^{*d}_m , F is both cheaper and more flexible. For January ($d_m = 31$, $n_m \approx 4.43$): Rd within months with five Tuesdays costs more than F ; Rd within months with three or four Tuesdays costs less than F . The ad hoc crossover for Rd paths in the proposed calculation method equals:

$$Q^{RdR}_a = \lceil \gamma \alpha / (\gamma + \delta) \rceil \cdot d_m^d = \rho_a^R \cdot d_m^d \quad (5)$$

This scales continuously with d_m^d . In the current calculation method $Q^{RdR}_{old} = \gamma \tau^{Rd} / (\gamma + \delta)$ scales only with $\tau^{Rd} = \lceil ad_m^d \rceil$, which equals 2 for all $d_m^d \in \{3, 4, 5\}$ for a threshold $\alpha = 0.35$. The current calculation method therefore assigns the same crossover threshold and the same penalties to three operationally different Rd paths. This is the distortion the proposed regulation corrects.

4.3 Numerical example

January ($d_m = 31$) may have 4 or 5 Tuesdays. A RU with one Rd path ("Tuesdays only") and Q complete departures faces the following costs. Penalty thresholds: according the proposed method — $1.40L$ (for 4 Tuesdays month) and $1.75L$ (for 5 Tuesdays month), while current method gives $\tau^{Rd} = 2$ in both cases.

Table 1. Rd penalties: January, 4 vs. 5 Tuesdays ($d_m = 31$, $\alpha = 0.35$, $\gamma = 0.20$, $\delta = 0.10$) and fixed path price

Q	Z^{new} , 4 Tue	Z^{old} , 4 Tue	Z^{new} , 5 Tue	Z^{old} , 5 Tue
0	0.28 CP_1	0.40 CP_1	0.35 CP_1	0.40 CP_1
1	0.08 CP_1	0.20 CP_1	0.15 CP_1	0.20 CP_1
2	0	0	0	0
Ad hoc ($Q=1$)	—	0.10 CP_1	—	0.10 CP_1

Table 1 shows three key findings. First, the current calculation method is completely blind to the difference between 4 and 5 Tuesdays: at $Q=0$ it charges $0.40 CP_1$ in both cases; at $Q=1$ it charges

0.20 CP_i in both cases. The RU pays the same whether the month had fewer or more reserved slots. Second, the proposed calculation method at $Q=1$ charges 0.08 CP_i for 4 Tuesdays — less than the ad hoc surcharge of 0.10 CP_i , so the Rd reservation is cost-effective. For 5 Tuesdays the proposed penalty is 0.15 CP_i , exceeding ad hoc, so the rational choice shifts to not reserving. Third, $Q=2$ clears the threshold and gives zero penalty in all cases.

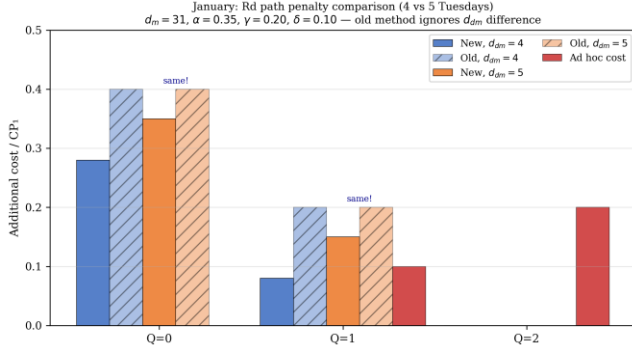


Figure 2. Rd penalty: 4 vs. 5 Tuesdays in January. Hatched bars (current method) are identical for both months at $Q = 0, 1$; solid bars (proposed method) correctly reflect the d_m difference.

5. COST COMPARISON AND SENSITIVITY

Figure 3 overlays the total additional cost against the number of trains Q for one path of each type R , Rd ($d_m = 5$), F , and ad hoc, under both calculation methods. Three demand zones are visible: an ad hoc zone (Q below the Rd crossover), a zone where reserving an Rd path reduces cost, and a high-demand zone where F achieves zero penalty at $Q \geq 1$. The right panel shows difference in calculated penalties, implementing two calculation methods, $\Delta Z = Z^{old} - Z^{new}$ for the R path and two Rd variants: the current method consistently charges more in the shortfall range, and the gap is proportionally largest for small d_m .

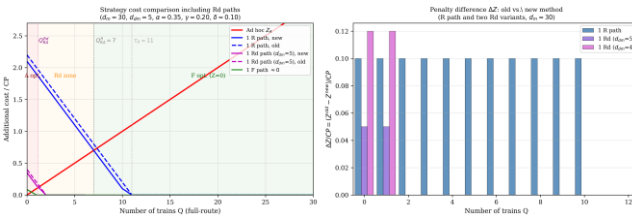


Figure 3. Left: cost curves for R , Rd ($d_m=5$), F , A under both calculation methods ($d_m=30$, $\alpha=0.35$, $\gamma=0.20$, $\delta=0.10$). Right: $\Delta Z = Z^{old} - Z^{new}$ for R and two Rd variants.

Figure 4 provides a unified sensitivity analysis: both panels plot the ad hoc crossover threshold vs. penalty rate γ for three values of α , comparing proposed (solid) and current (dashed) calculation methods. On the left side, R path ($d_m = 30$) is shown, while the right side shows Rd path (for the $d_m = 5$). For R paths, proposed and current crossovers track closely — the rounding of τ^R causes only a minor

upward shift in the current method curves. For Rd paths, all three dashed curves ($\alpha = 0.25, 0.35, 0.40$) collapse to a single line because $\lceil \alpha \cdot 5 \rceil = 2$ for all cases. The proposed method's solid curves' correctly diverge. There is no collapse for R paths, confirming that the distortion is specific to the integer-threshold treatment of Rd paths.

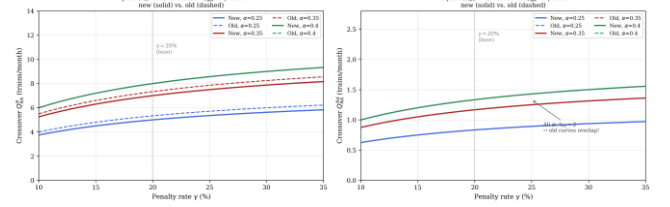


Figure 4. Sensitivity of crossover threshold for γ and α variations. Left: R path ($d_m=30$). Right: Rd path ($d_m=5$). All old-model Rd curves overlap ($\tau^{Rd} = 2$ for all α shown).

6. NETWORK EXTENSION

For a network of routes $i \in \mathcal{J}$ with different lengths L_i , charges c_i , and designated-day counts $d_{m,i}^d$, both models decompose into independent per-route subproblems, without shared capacity constraints. The network-level objective function for the proposed calculation method equals:

$$\begin{aligned} \min \sum_i [\gamma c_i \max(0, x_i^R, \alpha d_{m,i}^R L_i - v_i^R, i) \\ + \gamma c_i \max(0, x_i^{Rd}, \alpha d_{m,i}^{Rd} L_i - v_i^{Rd}, i) \\ + \gamma c_i \max(0, x_i^F, \beta n_m L_i - v_i^F, i) \\ + \delta c_i q_{0,i}] \end{aligned} \quad (6)$$

The Rd term carries the route-specific $d_{m,i}^d$, making the per-route distortion analysis of Section 4 directly applicable to each network arc. An identical decomposition holds for the current calculating method with $\tau^{Rd,i} = \lceil \alpha d_{m,i}^d \rceil$. Because per-route costs are separable, the global optimum is the union of per-route optimal strategies, enabling efficient parallel optimisation over an entire network.

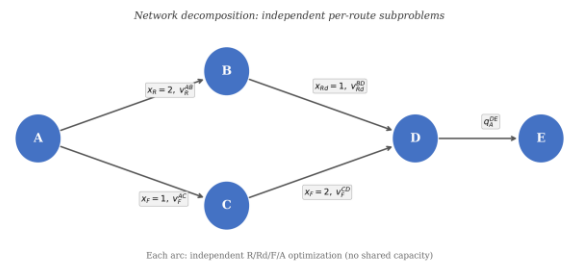


Figure 5. Network decomposition: each arc solved independently.

7. CONCLUSIONS

A cost-minimisation model for train path selection under current and proposed penalty calculation methods for unused reserved capacity has been formulated and solved analytically. Key findings are:

- F paths are optimal in the deterministic scenario: one departure per month eliminates the F -path

penalty, and F is cheaper to reserve than R for all $\beta < 7/d_m$, satisfied by all current Serbian parameter values.

- The R -path crossover $Q_a^R \approx 7$ trains/month (for months with $d_m=30$ days) marks the demand level below which ad hoc access costs less than reserving a R path.
- Rd paths have a critical cost boundary $d_m^{*d} = n_m$: above it, F is both cheaper and more flexible, making the Rd reservation economically unjustifiable.
- The current calculation methods systematically distorts Rd penalties: $d_m^d \in \{3,4,5\}$ always yield $\tau^{Rd} = 2$ and identical penalties, irrespective of the actual number of designated days reserved. The distortion ratio reaches $20\times$ for $d_m^d = 3$.
- The January example quantifies the impact: for $Q = 1$ train, the proposed calculation method correctly differentiates between months, charging $0.08 CP_i$ for the month with 4 Tuesdays (below the ad hoc cost of $0.10 CP_i$, so reserving is worthwhile) and $0.15 CP_i$ for the month with 5 Tuesdays (above ad hoc, so reserving is not worthwhile). The current calculation method charges $0.20 CP_i$ in both cases, failing to distinguish the two situations and

incorrectly signalling that the Rd reservation is never cost-effective relative to ad hoc access.

- The network model decomposes per route, enabling efficient operator's parallel optimisation over entire network.

Future work should extend the model to stochastic operator's transport demand, multi-month reservation windows, and competitive equilibria between multiple carriers sharing infrastructure capacity.

REFERENCES

- [1] Infrastruktura železnice Srbije, Izjava o mreži 2026 (Network Statement 2026), Belgrade, 2025.
- [2] European Commission, Directive 2012/34/EU establishing a single European railway area, Official Journal of the EU, L 343, pp. 32–77, Dec. 2012.
- [3] Borndörfer, R., Grötschel, M., Pfetsch, M.E., "A column-generation approach to line planning in public transport", *Transportation Science*, vol. 41, no. 1, pp. 123–132, 2007.
- [4] Caimi, G., Lübbecke, M., Möhring, R., Schaer, M., "A model for the optimization of the train scheduling problem", *J. Rail Transport Planning & Management*, vol. 1, no. 1, pp. 28–44, 2011.



APPLICATION OF MATHEMATICAL MODELS IN RAILWAY WASTE MANAGEMENT SYSTEMS

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Abstract – The development of railway transport has contributed to an increase in the volume and dispersion of travel, which has also led to certain negative consequences, with the generation of significant amounts of waste becoming an increasingly important issue. However, the utility value of waste can be significantly enhanced through a well-organized system of collection, sorting, storage, and recycling, with waste playing an increasingly important role in the raw materials market used for energy recovery. The specific objective of this research is to improve the theoretical–methodological and professional foundations for optimizing the waste management system and to develop a mathematical model based on the principles of integer linear programming, aimed at optimizing the transport process and reducing negative environmental impacts. The model will be validated under real conditions on a selected section of the railway network (case study: the railway network in Vojvodina). The scientific contribution of the research is reflected in the advancement of methodologies for data systematization and the development of an applicable mathematical model for process optimization, through a detailed analysis of the causes of their occurrence, their intensity, and consequences.

Keywords – Waste management, railway, linear programming, multi-criteria analysis.

1. INTRODUCTION

The issue of waste generated in railway operations has long been relevant in Western Europe. In Serbia, however, it has not received sufficient attention due to low employee awareness, limited funding, cheap energy, inadequate legal regulations, and weak systematic control.

Waste management procedures include collection, on-site treatment, transport to recycling or disposal facilities, temporary storage options, and cost evaluation, along with establishing a documentation system.

To optimize these processes, this paper proposes a mathematical model that supports planning and design by enabling efficient waste flow management, reducing costs, minimizing environmental impact, improving resource use, strengthening recycling, and promoting a closed-loop material cycle.

2. ANALYSIS OF THE WASTE MANAGEMENT SYSTEM ON SRI AND EXAMPLES OF GOOD PRACTICE

Serbian Railways Infrastructure has adopted strategic documents promoting waste reduction, circular economy principles, and improved

environmental standards. However, in practice, challenges remain, including insufficient equipment, limited funding, and weak system organization.

The most common waste types include metal, concrete, wood, ballast, and municipal waste, while hazardous waste consists of oils, batteries, e-waste, and contaminated materials. Proper classification and separation are essential, as they determine further treatment and recycling options.

Waste flows involve generation, collection, transport, storage, and final treatment, supported by documentation and reporting systems. However, gaps exist in data continuity, along with cases of illegal or improper disposal.

Temporary storage is highly fragmented, with over 280 locations, many do not meet required standards. This approach is inefficient, leading to proposals for centralized facilities in Belgrade, Novi Sad, Niš, and Užice.

Overall, the system is not fully aligned with modern standards but can be improved through a systemic approach, infrastructure investment, and innovative solutions.

In Europe, modern railway waste management is based on sustainability and circular economy principles. German Railways (Deutsche Bahn)

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represent a highly developed system, with over 95% recycling, centralized management, and advanced IT tools enabling efficient monitoring and reuse of waste as secondary raw materials.

Croatian Railways represent a transitional system aligned with EU regulations, focusing on impact reduction and resource efficiency. However, challenges remain, including incomplete records, data inconsistencies, and underdeveloped infrastructure, particularly for hazardous waste.

3. DEFINITION OF THE MATHEMATICAL MODEL

The proposed model aims to optimize costs and determine the optimal spatial allocation of waste collection and primary sorting points, with the possibility of direct transport to final destinations.

It is based on integer linear and mixed-integer programming and includes: generated waste by type (hazardous and non-hazardous), stations that generate or collect waste, hub stations with storage capacities, and regional landfills as treatment facilities.

Two scenarios are defined:

I) Scenario 1 – waste from smaller stations is transported directly to local landfills;

II) Scenario 2 – waste from smaller stations can be transported via larger hub stations.

The objective is to determine the most efficient transport routes, minimizing costs and environmental impacts, particularly CO₂ emissions, as follows:

Let set I represent railway stations, i.e., waste generators; set J railway stations where waste is collected within the network (hubs); and set K waste treatment facilities, i.e., regional landfills (figure below):

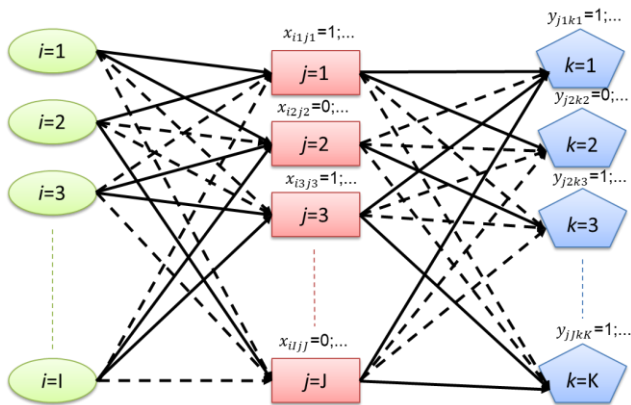


Fig.1. Representation of waste transport in the model

In addition, the set Q will represent the types of waste included in the model, i.e., hazardous and non-hazardous waste. From the above, it follows that the total quantity of waste of type q generated by station i is denoted as d_{iq} .

Transport costs for all relations “station – hub – facility” include the costs of waste collection and

transshipment. These aggregated and unified costs are determined separately for each type of waste and are denoted as:

- sfc_{ikq} – transport costs per ton of waste type q transported directly from station i to the disposal facility (regional landfill) k;
- sfc_{ijq} – transport costs per ton of waste type q transported from station i to the waste collection station (hub) j, including associated costs such as reception, storage, and necessary treatment within the hub j; and
- hfc_{jkq} – transport costs per ton of waste type q transported from the waste collection station (hub) j to the disposal facility (regional landfill) k.

The annual capacity for receiving and storing waste for each station j and waste type q is uniquely defined as the “capacity” of the waste collection station (hub) j and is denoted as A_{jq} . Similarly, the processing capacity of each waste treatment facility (regional landfill) k for individual waste types q is denoted as C_{kq} .

When referring to the fixed costs of opening and equipping waste collection stations (hubs) for waste type q, they are denoted as f_{jq}^{hub} , while for collection stations already in operation, these costs are proportionally lower. However, if the existing capacity of all stations is insufficient to accommodate the total generated amount of waste, it will be necessary to define, organize, and equip new waste collection stations (hubs). Therefore, f_{kq}^{fac} denotes the fixed costs of opening and equipping new waste collection stations (hubs) for waste type q.

Since the proposed model aims to answer the following key questions: (1) which stations and facilities are necessary for waste collection and treatment, and (2) how the collected waste should be distributed among stations, hubs, and regional landfills, decision variables and dependent variables are introduced into the model as follows:

u_{ikq} – the quantity of waste type q generated by station i (representing a portion of d_{iq}) that is transported directly from station i to the waste treatment facility k;

v_{ijq} – the quantity of waste type q generated by station i (representing a portion of d_{iq}) that is transported directly from station i to the waste collection station (hub) j;

w_{jkq} – the quantity of waste type q collected at the waste collection station (hub) j and transported from station j to the waste treatment facility k;

x_{jq} – a binary variable that takes the value 1 if the waste collection station (hub) j is “open” to receive waste type q, and 0 otherwise; and

y_{kq} – a binary variable that takes the value 1 if the

waste treatment facility (regional landfill) k is “open” to receive waste type q , and 0 otherwise.

In the case of Scenario 2, where it is allowed for waste generated at individual stations to be collected, stored, and consolidated at waste collection stations (hubs), the model is formulated as follows:

$$\begin{aligned} \text{minimize } F = & \sum_{i=1}^I \sum_{k=1}^K \sum_{q=1}^Q sf_{cikq} * u_{ikq} + \\ & \sum_{i=1}^I \sum_{j=1}^J \sum_{q=1}^Q sf_{cijq} * v_{ijq} + \\ & \sum_{j=1}^J \sum_{k=1}^K \sum_{q=1}^Q hf_{cj kq} * w_{jkq} + \\ & \sum_{j=1}^J \sum_{q=1}^Q f_{jq}^{hub} * x_{jq} + \\ & \sum_{k=1}^K \sum_{q=1}^Q f_{kq}^{fac} * y_{kq} \end{aligned} \quad (1)$$

where the constraints are defined as follows:

$$\sum_{j=1}^J \sum_{k=1}^K (u_{ikq} + v_{ijq}) = d_{iq}, \forall i \in I, \forall q \in Q; \quad (2)$$

$$\sum_{i=1}^I \sum_{q=1}^Q v_{ijq} = \sum_{j=1}^J \sum_{q=1}^Q w_{jkq}, \forall j \in J; \quad (3)$$

$$\sum_{i=1}^I v_{ijq} \leq A_{jq} * x_{jq}, \forall j \in J, \forall q \in Q; \quad (4)$$

$$\sum_{i=1}^I \sum_{j=1}^J (u_{ikq} + w_{jkq}) \leq C_{kq} * y_{kq}, \forall k \in K, \forall q \in Q; \quad (5)$$

For Scenario 1, where waste generated at stations is transported directly to waste treatment facilities, the model is simplified and formulated as follows:

$$\text{minimize } \Phi = \sum_{i=1}^I \sum_{k=1}^K \sum_{q=1}^Q u_{ikq} * sf_{cikq} + \sum_{k=1}^K \sum_{q=1}^Q f_{kq} * y_{kq} \quad (6)$$

The constraints ensure proper waste flow and capacity control in the model and require that all generated waste is fully collected from stations, while others ensures that no waste remains at collection hubs, meaning all collected waste must be transported to treatment facilities.

Finally, constraints also ensure that capacity limits at both hubs and treatment facilities are not exceeded, guaranteeing sufficient space for all waste.

4. VALIDATION OF THE PROPOSED MODEL AND DISCUSSION OF RESULTS

To verify the proposed mathematical model, a case study was conducted on the railway network of the Autonomous Province of Vojvodina in Serbia. The analysis covered 1,735 km of railway lines, 57 waste-generating stations, and existing and planned treatment facilities across an area of over 20,000 km².

Data for one representative month (October 2022) were used, with a total of 21,075 t of waste, including 16,367 t of non-hazardous and 4,708 t of hazardous waste. The model defines five hubs (Novi Sad, Pančevo, Ruma, Subotica, and Zrenjanin), with capacities based on current conditions and expert assessment, and includes detailed transport cost analysis.

Several scenarios were tested. The basic “do nothing” variant assumes direct transport to landfills without hubs, while other variants include hub-based systems with different facility combinations.

Results show that the non-optimized scenario generates the highest costs (EUR 1,087,003/month). The introduction of hubs significantly reduces costs to EUR 621,315–778,030, making these variants the focus of further analysis.

Transport flow analysis indicates that hubs greatly improve system organization, especially for non-hazardous waste (Figure 2), while hazardous waste is transported more directly due to strict safety and regulatory constraints (Figure 3).

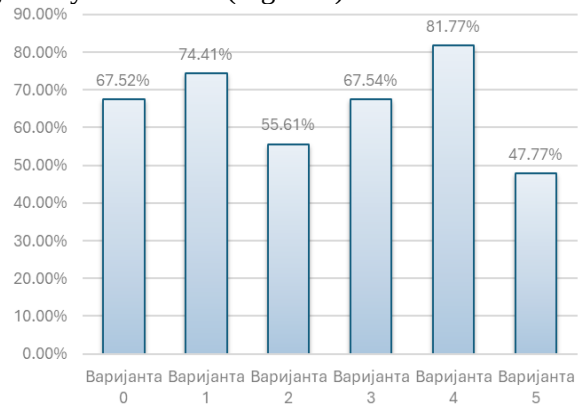


Fig.2. Quantity of non-hazardous waste treated via hubs

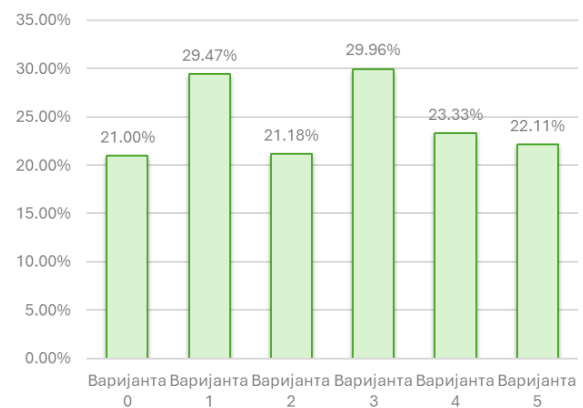


Fig.3. Quantity of hazardous waste treated via hubs

Transport work (ton-kilometers) is a key indicator affecting both total costs and environmental performance. Variant 2 achieves one of the lowest transport work values, while the least favorable variants show significantly higher levels.

CO₂ emissions analysis confirms that optimizing transport flows reduces environmental impacts, with

Variant 2 again ranking among the most favorable options.

Since no single variant is optimal across all criteria, a multi-criteria analysis was applied, considering financial, technical, environmental, social, and safety aspects. Using the TOPSIS method, Variant 2 achieved the highest utility value, which was further confirmed by the PROMETHEE II method, demonstrating the reliability and stability of the results.

Tab. 1. Result of the MCA using the TOPSIS method

	Var 0	Var 1	Var 2	Var 3	Var 4	Var 5
Result	0.482	0.625	0.688	0.464	0.545	0.529
Rang	5	2	1	6	3	4

Tab. 2. Result of the MCA using the PROMETHEE method

	Var 0	Var 1	Var 2	Var 3	Var 4	Var 5
Result	0.222	0.190	0.329	0.380	0.078	0.162
Rang	5	2	1	6	4	3

The synthesis of the obtained results shows that Variant 2 represents the optimal solution in terms of overall system efficiency. This variant ensures the lowest transport costs, reduced transport work, and favorable environmental performance, while maintaining adequate capacity utilization and meeting most technical and regulatory requirements. Compared to other variants, it achieves significant cost savings and a reduction in negative impacts, making it the most suitable option for practical implementation.

5. CONCLUSION AND FURTHER DEVELOPMENT

The developed mathematical model, based on linear integer programming, optimizes waste transport flows on the railway network to minimize costs and environmental impacts. The case study confirmed that introducing waste collection hubs and optimally selecting treatment facilities leads to financial savings, reduced transport and CO₂ emissions, and improved system efficiency. The model also proved to be universal and applicable across different network segments.

However, certain limitations were identified, mainly related to data availability and reliability, low digitalization, and the lack of a unified waste flow database, all of which affect analysis and decision-making.

Overall, the model represents a significant scientific and practical contribution to railway waste management, enabling cost and environmental optimization. Its further development requires a systemic approach, stronger institutional support, and greater environmental awareness among stakeholders as key conditions for sustainable railway development.

ACKNOWLEDGEMENT

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REFERENCES

- [1] Adeleke, O.J., Ali, M.M. (2021). *An efficient model for locating solid waste collection sites in urban residential areas*. International Journal of Production Research, volume 59, pg. 798-812;
- [2] Farahani, R., Seifi, M., Asgari, N. (2021). *Multiple criteria facility location problems: A survey*. Centre for Maritime Studies, National University of Singapore, Department of Industrial Engineering. Applied Mathematical Modelling journal;
- [3] Panić, M. (2010). Upravljanje opasnim otpadom – planiranje, organizacija, funkcionisanje sistema. Geografski institut "Jovan Cvijić" SANU, posebna izdanja, knjiga 80.
- [4] Ristić, N., Đorđević, D., Stanišić, J. (2015) Tretman otpada na železnici u funkciji održivog razvoja. V Međunarodni simpozijum „Novi horizonti saobraćaja i komunikacija”, Dobo, str. 161-166;
- [5] Ristić, N., Jovanović, P., Kecman, P., Optimal Allocation of Waste Transfer Facilities for Infrastructure Manager. The 10th International Conference on Railway Operations Modelling and Analysis (ICROMA), RailBelgrade2023, crp.142;



APPLICATION OF ARTIFICIAL INTELLIGENCE IN SINGLE WAGON LOAD (SWL) OPTIMIZATION: OPERATIONAL MODEL FOR RAILWAYS OF REPUBLIKA SRPSKA

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Abstract – In conditions of stagnation of the European Single Wagon Load (SWL) system, which records a market share decline from 50% to 35–36% between 2004 and 2011 (European Commission, 2015), and with the dramatic example of DB Cargo recording annual losses of ~€442 million directly attributed to SWL operations (2022), this paper investigates the possibility of introducing an AI-optimized SWL service on the Railways of Republika Srpska (ŽRS) network. Unlike established European operators burdened by inherited costs, ŽRS has no SWL history — which is positioned in this paper as a strategic advantage, not a disadvantage. The proposed model is based on four AI components: (1) demand aggregation module, (2) real-time transport chain optimization following the SBB Cargo TK-Module model (Moldenhauer et al., 2025), (3) ETA prediction for end users, and (4) backhaul optimization algorithm.

Key words: single wagon load (SWL), artificial intelligence, transport chain optimization, railway, ŽRS, digital logistics service, backhaul optimization.

1. INTRODUCTION

The aim of this paper is to present a theoretical framework for the application of AI in the SWL context, to define the architecture of the proposed digital service, to validate the model through a concrete operational scenario on the ŽRS network, and to demonstrate the commercial viability of the approach through a door-to-door cost analysis. Cost calculations are based on ŽRS tariff estimates from internal operational parameters, and on estimates of the tariffs of HŽ Cargo, SŽ-Freight Transport and Mercitalia Rail based on publicly available Network Statement documents and industry averages (estimation error $\pm 15\text{--}20\%$ for EU segments). Truck costs are based on the IRU European Road Freight Benchmark (Q4 2025), which for EU segments amounts to €1.10–1.60/km, and for Balkan segments €0.80–1.20/km. It should be noted that this paper has limitations: EU operator tariffs are estimates, not confirmed contractual amounts; the analysis does not include seasonal demand variations; and the AI model is conceptual

implementation would require deeper empirical research with ŽRS operational data.

2. STATE OF SWL IN EUROPE

The European Single Wagon Load (SWL) system has been experiencing a structural decline throughout the past two decades, with fundamental consequences for railway operators. Three structural causes of the SWL decline:

- (1) high operational costs,
- (2) delivery opacity and unreliable ETA that drives small users towards trucks, and
- (3) underutilization of return logistics 27% empty running.

Table 1. presents a comparative overview of the state of SWL in Europe. The table shows that ŽRS occupies a unique position: it is the only country in the analyzed set that possesses a complete railway infrastructure base but has no SWL history that would burden the system with inherited costs. This is treated in this paper as a strategic first-mover advantage, not a disadvantage

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Table 1. Comparative overview of the state of SWL in Europe

Country	Operator	SWL Status	Trend (20 yrs.)	Key Note
Germany	DB Cargo	Crisis	Drastic decline	Loss of €442 mil. from SWL (2022); considering cancellation of 80% of services
Slovenija	SŽ-Tovorni promet	Under pressure	Declining	Only SWL provider, 78 stations; unsustainable without state support [7]
Slovakia	ZSSK Cargo	Collapse	-78% in 20 years	From 23 mil.t (2003) to 5 mil.t (2022); without intervention
Hungary	MÁV + ostali	Stabilized	Slightly growing	State subsidy €16.1 mil./yr. from 2021; 400,000 fewer trucks/yr
UK	Nema	Discontinued	Nema SWL	Speedlink network shut down 1991; focus on block trains
BiH / ŽRS	Nema	Inactive	Never introduced	Unique potential: infrastructure exists, SWL experience does not burden the system

3. ARCHITECTURE OF THE PROPOSED AI DIGITAL SERVICE

Based on a review of the literature, a modular AI service architecture is proposed that addresses each of the identified structural problems of SWL (Table 2).

Module 1: Demand Aggregation and Predictive Planning

The central challenge of SWL is the coordination of fragmented demand: instead of one client filling an entire train, SWL involves dozens of clients with smaller shipments that need to be coordinated into a

single operationally and financially efficient consist. Traditionally, this coordination was carried out by phone and fax, with delays of 2 to 3 days. The proposed Module 1 uses clustering algorithms (k-means, DBSCAN) to identify geographically and temporally compatible shipments that can be consolidated into a joint collection train. Based on historical demand dynamics data, the module predicts optimal departure times and capacities for each part of the network 48 hours in advance, a period that Moldenhauer et al. (2025) identify as the critical threshold for effective transport chain planning.

Table 2. Architecture of the proposed AI digital service for SWL

AI components	Technical basis	Operating contribution
Demand Aggregation Module	Clustering algorithms (k-means, DBSCAN); predictive demand modeling	Identifies shipments that can be consolidated into a joint train; minimizes wagon waiting time at nodes
Transport Chain Optimization Module (TK-Module)	Graph search (BFS); integer programming; path-based formulation	Calculates optimal train sequences (transport chains) from loading to final destination in real time
ETA Prediction Module	LSTM neural networks; Random Forest regression; historical delay data	Provides clients with accurate estimated arrival time in real time; automatic notifications
Return Logistics Module (Backhaul Matching)	Matching algorithms (bipartite matching); real-time search for available wagons	Matches free wagons with import goods entering through Dobrljin; eliminates empty running
Digital Client Portal	API integration with HŽ/SŽ/Mercitalia Rail systems; automatic generation of CIM documents	Client enters a shipment and receives price and ETA for the entire route in < 60 seconds

Module 2: Real-time Transport Chain Optimization

This is the algorithmic core of the system, directly inspired by the SBB Cargo TK-Module. Moldenhauer et al. (2025) describe how SBB Cargo

transitioned from a rigid system of predefined geographical maps (Leitwege) to dynamic optimization based on a mathematical model that assigns wagons to trains in real time.

The key mathematical problem is formulated as a throughput optimization problem: maximizing the number of successfully routed requests subject to segment capacity constraints (weight, length) and time windows (pickup/delivery time). Moldenhauer et al. (2025) demonstrate that a path-based formulation, instead of column generation or flow-based approaches yields good results for SWL because transport chains are relatively short (3–6 blocks). In testing, a greedy strategy misses 7–12% of shipments compared to the optimized model when train capacities are tight. In the ŽRS context, this module would manage synchronization between 5 collection stations (Zvornik, Sočkovac, Dobo, Banja Luka, Prijedor) and optimize the stop sequencing to minimize the total train formation time.

Module 3: ETA Prediction and Client Transparency

A RailNetEurope survey (2025) shows that users of railway information systems cite inaccurate ETA as the primary problem, with explicit demands for automatic notifications. For small and medium-sized exporters considering the switch from trucks to rail transport, this lack of transparency is often the deciding factor keeping them with road haulage. The proposed Module 3 uses LSTM neural networks and Random Forest regression on historical delay data (including data on border procedures at Dobrljin, which are particularly variable) to generate probabilistic ETA predictions. Minbashi (2024) demonstrates the application of a similar approach for delay prediction at marshalling yards, with improved accuracy compared to a deterministic approach. Clients automatically receive notifications when ETA changes by more than one hour.

Module 4: Return Logistics Optimization

The fourth module addresses the problem of empty running which, according to global estimates, accounts for 27% of all freight miles. For ŽRS, this is a particularly relevant problem because a wagon that unloads in Italy or Slovenia must somehow

return — either empty or with new cargo. The module uses bipartite matching algorithms for real-time identification of import goods entering BiH/RS through Dobrljin whose characteristics (wagon type, weight, destination) match available wagons. The same principle that Aboutalib & Agard (2024) apply to LTL freight consolidation is here adapted for railway wagons: the AI system does not wait for a client to contact ŽRS, but proactively offers free wagons to clients with import shipments.

4. OPERATIONAL SCENARIO: COLLECTION TRAIN ZVORNIK → DOBRLJIN

In order to validate the proposed model, a concrete operational scenario was developed that illustrates the functioning of the AI service under real ŽRS network conditions. The scenario was selected to encompass all key elements of the proposed architecture: multiple collection stations, heterogeneous wagon types, different final destinations and a cross-border passage.

The scenario includes a collection train formed from shipments from 5 stations on the ŽRS network, with a loading date of 1 June 2026. All shipments were ordered for loading at 07:00 on handling tracks. Border exit at Dobrljin (HŽ Cargo), selected to maximize the distance covered on the ŽRS network (~315 km for the longest segment). The alternative exit at Šamac was rejected as it would reduce the ŽRS segment to ~80 km, which would significantly reduce operator revenue. Total consist: 18 wagons (11 Eas + 7 Rgs), 740 tonnes. Duration of the ŽRS segment from departure at Zvornik to handover to HŽ at Dobrljin cca 15 hours. Without AI coordination, the same train would require 2 to 3 days of administrative preparation and coordination between stations.

5. COMPARATIVE ANALYSIS: ŽRS AI MODEL vs. TRADITIONAL SWL

Table 3. compares the key parameters of the proposed ŽRS model with the traditional SWL approach that led DB Cargo to crisis, illustrating the concrete advantages of the AI-optimized approach.

Table 3. Comparison: ŽRS AI model vs. DB Cargo traditional SWL model

Parametar	DB Cargo (Germany) — traditional model	ŽRS (prijedlog) — AI-optimizovani model
Annual SWL loss / subsidy cost	Cca €442 mil. loss from SWL (2022); €172.6 mil. state subsidies (2023/24)	No state subsidies, business model based on AI cost optimization
Transport chain planning	Partially digitized; historical legacy of manual processes; rigid	AI TK-Module: real-time optimization based on the SBB Cargo model; dynamic capacity allocation
Client transparency	ETA unreliable; clients cite lack of transparency as main reason for switching to trucks	Digital portal: price and ETA for the entire route in < 60 sec.; automatic notifications
Return logistics / empty running	27% of all wagon-km empty running; minimal systematic optimization	AI backhaul matching: automatic pairing of free wagons with import goods through Dobrljin
Marshalling yard operation costs	High fixed costs; shunting loco. not optimized; frequent empty running	AI optimization of shunting sequences; Dobož as a smart hub cost reduction cca 40%
Target segment	All users; overly broad network; unprofitable segments burden the system	Selective focus: only routes where rail is commercially competitive

6. CONCLUSION

The Railways of Republika Srpska should not treat SWL a return to the past, but as an innovative logistics service that, with AI support, is capable to offer transparency, predictability and a competitive price for small and medium sized exporters on long European corridors, something that massive state subsidies to DB Cargo have failed to achieve.

REFERENCES

- [1] Interreg Central Europe: Work Paper D.2.1.2 — Single Wagon Load Transport, Version 1. Interreg Central Europe Programme, Januar 2024. URL: interreg-central.eu/wp-content/uploads/2024/06/D-2.1.2-Workpaper-Single-wagon-load-transport.pdf
- [2] DB Cargo: Single Wagonload Transport — Network, Funding and Service Portfolio. Deutsche Bahn AG, 2024. URL: dbcargo.com
- [3] ZSSK Cargo: Single Wagonload Transports — Why They Are Necessary. ZSSK Cargo, November 2023. URL: zscargo.sk
- [4] HUNGRAIL / RailMarket: Hungarian SWL Subsidy Scheme and Results. RailMarket, 2025.
- [5] Moldenhauer, C., Germann, P., Heimhofer, C., Spieckermann, C., Andresen, A.: Real-time Optimization of Transport Chains for Single Wagon Load Railway Transport. SBB Cargo AG / Accenture AG, arXiv:2507.06621, Juli 2025. URL: arxiv.org/abs/2507.06621
- [6] Aboutalib, Z., Agard, B.: Improvement of Freight Consolidation through a Data Mining-Based Methodology. International Journal of Logistics Systems and Management, 49(2):255–273, 2024. DOI: 10.1504/ijlsm.2024.141701
- [7] RailNetEurope: TIS Survey 2024 Results — A Roadmap for Enhancement. RailNetEurope, Mart 2025. URL: rne.eu/tis-survey-2024/
- [8] Minbashi, N.: Enhancing Freight Train Delay Prediction with Simulation-Assisted Machine Learning. IET Intelligent Transport Systems, Wiley, 2024. DOI: 10.1049/itr2.12573
- [9] Attar, A., Irawan, C.A., Akbari, A.A., Zhong, S., Luis, M.: Multi-Disruption Resilient Hub Location–Allocation Network Design for Less-Than-Truckload Logistics. Transportation Research Part A: Policy and Practice, 190:104260, 2024. DOI: 10.1016/j.tra.2024.104260
- [10] FarEye: Innovative Route Planning Solutions for Reducing Empty Backhauls. FarEye Blog, November 2024. URL: fareye.com
- [11] Credence Research: Rail Freight Digital Transformation Market — Size and Forecast 2032. Credence Research, Februar 2025. URL: credenceresearch.com
- [12] RSI Logistics: Rail Freight Industry Review — Biggest News of 2023. RSI Logistics Blog, December 2023. URL: rsilogistics.com



IMPACT OF OPERATIONAL DISRUPTIONS ON QUALITY INDICATORS IN SOFIA METRO UNDER DIFFERENT LEVELS OF AUTOMATION

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Abstract - Ensuring accurate and failure free movement of trains in the metro attracts a larger passenger flow and thus reduces environmental pollution by limiting passenger car transportation. Ensuring movement in the Sofia metro, as well as the systematization and analysis of various cases of its disruptions, will help in the implementation of new systems using artificial intelligence (AI), or in the development of more effective procedures for action. The main objective of the study is to identify and classify these specific operational disruptions that occur due to failures in occurring during the movement trains. In this way, an analytical basis is created for subsequent modeling of their quantitative impact on the key performance indicators (KPI) in service. The work consistently presents the technological ways to ensure movement on the lines and determines the levels of automation of GoA. KPIs under normal operating conditions are determined and the possible causes leading to disruption of the train schedule are analyzed. The structured analysis performed deduces the cause-and-effect relationships between operational disruptions and KPIs, assisting in future simulation or mathematical modeling of the transport process.

Keywords – levels of automation GoA, Train Schedule (TS), KPI, operational disruptions,

1. INTRODUCTION

The effective functioning of urban mass rail transport systems is a key factor for the sustainable development of modern megacities. Among them, the metro occupies a leading position due to its high throughput, speed and independence from street traffic. Ensuring reliable and continuous train movement requires a complex synergy between modern signaling, automation and dispatching control systems. In modern engineering practice, the degree of autonomy and the distribution of functions between the human factor and automated systems are defined by the internationally recognized Levels of Grade of Automation – GoA, according to the IEC 62290-1 standard. They range from partially automated control with a driver (GoA1/GoA2) to fully unmanned systems (GoA3/GoA4), with each level defining a specific approach to traffic control, speed regulation and train door management.

In real operating conditions, however, regardless of the degree of automation, the train schedule is subject to constant stochastic disturbances at the “passenger-

train” or “passenger-platform” interface. The nature of these disturbances directly depends on the technological generation of the line – from technical failures in the drive of the doors of the railcars to critical overcrowding of the platforms during mass events, which on older lines threatens safety with falling objects and people, and on lines with PSD slows down the synchronization process when closing. Therefore, it is necessary to systematize in detail the various cases of traffic disruption in the Sofia Metropolitan, viewed through the prism of the existing levels of automation of the Centralized Traffic Control (CTC) on the different lines. The main objective of the development is to identify, classify and analyze the mechanism of these specific operational violations, which will subsequently allow, through mathematical or simulation modeling of traffic, to establish and quantitatively assess their direct impact on the project KPIs for passenger service set out in the Nexus project[1].

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2. THE ANALYSIS OF DISPATCH MANAGEMENT IN METROS

Two different CTCs are used for traffic management in MetroS, respectively on metro lines 1 and 2, which started operating from 1998 year and including all new stations on these lines, and metro line 3, was put into operation from 2020 year.

2.1. Train Traffic Management System DISIM

The CTC "DISIM" used in managing train traffic on lines 1, 2 and 4 [2] must provide: -control over the devices for management of the position and occupancy of the switches, the occupancy of the tracks at the stations and the adjacent inter-station sections, as well as the repetition of the traffic lights at stations with track branches; -control from one place of the switches and signals at the stations and the possibility of transferring the control to local one of the switches and signals; -fulfillment of the requirements set for electrical centralization and auto-blocking systems; -automatic recording of the train movement schedule and a system for transmitting the train number.

Through DISIM, the train dispatchers on duty: monitor, control and manage the movement of trains, each for the route for which they are responsible, respectively for Line 1 and Line 2. The basic information about the status of the entire facility is displayed on the Light Information Board (LIB). This system also performs control and signaling functions, which is convenient for the train dispatcher [3]. The movement of all trains is visualized, as well as the location of the various vehicles (stationed, service) along the entire controlled route. The system is highly intelligent, with special software for managing train traffic, where in real time the train dispatcher receives information about the location of each metro train, number, route, rail circuit, delay, the status of security equipment and plenty of other information ensuring the security and safety of the train movement. The system allows for multiple functions and stores the complete information and all operations made by train dispatchers. The functional capabilities of the system are divided into the following main groups: train movement control functions, functions for managing the operation of the system itself, internal diagnostics, and functions related to information visualization, archiving, automatic forecasting, generation and presentation of relevant alarm messages /classified as functions/[4].

To ensure the movement of trains on Lines 1, 2 and 4, they are equipped with station devices: automated train control system, electrical centralization of switches and signals, and dispatcher centralization. Section devices include:

- autoblocking – the road is fenced off by traffic

lights, and their signals change automatically when the train moves in these sections,

- Automatic locomotive signaling with automatic speed regulation/ automatic regulation of the speed (ALS-ARS) – movement is carried out according to code signals transmitted to the driver's cabin.

The ALS-ARS system provides:

- Continuous monitoring of compliance with the maximum permissible speeds and automatic stopping when the train exceeds these speeds. In ALS-ARS, the speed of movement is continuously controlled;
- Automatic deactivation of the train braking after reducing the speed to the maximum permissible one and after confirming the driver's vigilance by pressing the brake acceptance button (BAB) or the safety pedal (SP);
- Indications of ALS signals on the remote control in the driver's cabin;
- Fixing the train braking to prevent the train from moving on a slope.

The maximum throughput is achieved by equipping with a complex ALS-ARS system, as the ARS contains a subsystem for the safety of the devices and the automatic control of the trains. The automatic block system refers to the devices of the railway automation. After turning off the AB, it is switched to the ALS-ARS system, which is fast-acting.

2.2. Dispatch Centralization Communication-Based Train Control (CBTC)

CBTC on line 3 - manufactured by Siemens for Sofia is based on technology using high-resolution train location determination, independent of the establishment of track clearance; continuous and highly efficient two-way data communication between the train and the trackside devices; on-board and trackside processors that can perform primary functions [5,6]. Fig. 1 shows CBTC elements.

Automatic Train Supervision (ATS). ATS of Control Guide OCS or simply ATS, manages and monitors the railway system thus that trains run according to the timetable and organization of the movement of the vehicles. This is related to the optimization of railway operations and service reliability, as well as minimizing the consequences of abnormal system conditions and equipment failures. ATS also provides a graphical interface for multiple users with different responsibilities and offers automatic train control, schedule management and calculation of schedule deviations.

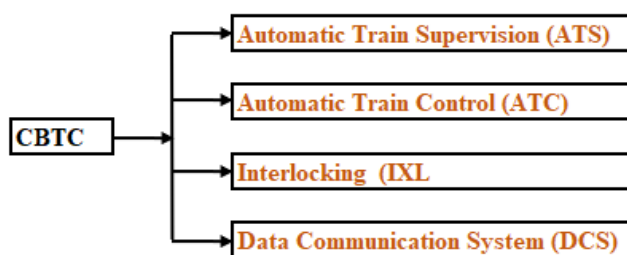


Fig.1. Communication-Based Train Control

Automatic Train Control (ATC) Automatic train and door control subsystem, ensuring train safety and guiding train operations. ATC includes automatic train protection (ATP) and automatic train operation (ATO). ATO is a component of the automatic train control system that provides functions such as speed control, programmed braking, door control, control of the level of technical parameters, etc. ATP is the other component of the automatic train control system that maintains fail-safe protection against collision, overspeed and other dangerous conditions through a combination of train detection, train separation and centralization, etc.

Interlocking (IXL) uses Clearguard ACM 200 and Trackguard Westrace Mk II (Siemens Mobility). As a secondary (backup) system for monitoring the track clearance, a Clearguard ACM 200 axle counting system is used. Trackguard Westrace Mk II is a modern computerized centralization/interlocking through which: remote control and management of switches, routing and issuing of train movement permits are carried out while observing all safety conditions.

Data Communication System (DCS). It provides high-resolution train location determination, regardless of the establishment of track clearance, continuous and highly efficient two-way data communication between the train and the trackside devices. The movement of trains is carried out in automatic mode, with the presence of a driver being provided for managing the system in case of emergencies and accidents.

3. KPIS FOR RAIL PASSENGER SERVICES

A significant number of KPIs have been adopted to assess passenger service and safety during metro transportation [1], but we will focus on the following indicators: Average train journey time (ATJT), representing the average time from the initial to the final destination; Average station waiting time (ATWT), including the time from entering the station to boarding the train; Average station dwell time (ASDT) including the time that trains spend at each station. Regularity of train (RT) movements measured in the interval between consecutive trains. Events leading to a reduction in the level of passenger safety related to station overcrowding (peak hours).

KPI	Times
ATJT	30 min
ATWT	depends on the size of the interval between trains and is defined as half of it
ASDT	30 seconds
RT	5 min
Safety	min

Tabl.1 KPI from Sofia metro

4. REASONS FOR TRAIN DELAYS

In cases of major events in the territory of Sofia or due to a strike of all other types of public transport, i.e. the movement of passengers in Sofia is carried out only by MetroS, a scenario arises in which there is a shortage of trains and the passenger flow during peak hours cannot be adequately transported, although additional trains have been assigned - there were passengers who could not board and were left for the next train. then the safety of passengers is compromised due to the large number of people on the platforms and the train movement times increase due to the increase in the waiting times on the stations. Other cases that lead to disruptions of train movement:

- ensuring the movement for both the network and the station

Problem with the opening of one of the train doors: The passengers usually decide to move to the adjacent doors to get on and off the carriage (vehicle), which leads to an increase in the train's stay at the stations. In such a case, the train arrives at the final station, then is sent to the depot, which is moved between regular train movement according to the train schedule. In the place of the train with the failure in the doors, another train from the final station is used, which is standing as a reserve;

Falling of an object on the track in stations without barrier doors – this is a variant of an object, obstructing the movement of trains, when it is necessary to remove it by the traffic controller. The delay can be from 5 to 15 minutes;

Problem with the platform screen doors/ barrier doors– assistance from the traffic controller – delay from 2 to 10 minutes.

- ensuring movement on the network

For metro line 3 at GoA3: delocalization of the train – it switches to manual mode and moves by the driver until it is localized – this can lead to delays from the train schedule [6];

Damage to the vehicle: passengers are dropped off at the next station, the vehicle continues to the depot, and the another train, from the reserve, is included in the schedule;

Unfortunately, more severe cases of unwanted events occur: interruption of the movement of trains

for an extended period of time, for example 2 or 3 hours (for example, in the event of a suicide at station 208) - depending on the location of the station, the movement is organized by making nearby stations with railway points as last stations and movement is reversing direction there, or if there are no stations with railway points there, a single train is launched as a shuttle (Fig.2).



Fig.2. Organization of train traffic

3. CONCLUSION

CTC "DISCIM" ensures the movement of trains when they are controlled by the driver. He drives the train, stops and starts from stations, opens and closes the doors, performs and monitors all accompanying operations. The special thing is that the speed of the train is controlled, that is, the driver cannot increase the speed higher than the specified one and in case of problems the locomotive is stopped automatically without the driver's participation. Therefore, DISCIM is between Go1 and Go2, but in terms of functions it does not reach Go2. The CBTC system for Metro Line 3 of Sofia underground complies with GoA3, as defined by the IEC 62290-1 standard, and with the IEEE1474.1 standard. An upgrade to GoA4 automation level is planned through a software update. The difference between GoA3 and GoA4 is that in GoA3 the train operating staff manages and controls the operation of the train during faults (e.g. malfunction of train doors), worsened performance and emergency situations.

In order to assess the quality of passenger service, key performance indicators (KPIs) have been introduced, such as: average train travel time, average station waiting time, average station dwell time and train regularity. In addition, for lines 1, 2 and 4 (except for stations equipped with vertical doors with a barrier mechanism), a safety metric is applied, defined as the total duration of traffic interruption when a person or object falls onto the tracks (such events trigger immediate emergency protocols). These KPIs have been determined under normal operating conditions of the Sofia Metro. With the implementation of this study, individual cases of train movement disruptions have been successfully classified and systematized. This classification serves as a key and mandatory prerequisite for future train movement modeling, allowing researchers to accurately determine and

measure the direct impact of these interruptions on the established KPIs. The data and structures collected in this study will serve as the main conceptual framework for developing these predictive models and optimizing future dispatching operations in the Sofia Metro network in accordance with the objectives of the Nexus project.

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REFERENCES

- [1] Nexus „Next-gen technologies for enhanced metro operations”, Project, 2024 <https://nexus-heproject.eu/>
- [2] Todorova M., *Simulation model – Simulator of dispatching control of a metro section – possibilities and requirements*, Yearbook VTU "T. Kableshkov", ISSN 1314-362X, 10/2019, Sofia
- [3] Instructions for the movement of trains and shunting work in the Metro, 2009, Metropolitan EAD Sofia
- [4] Todorova M., Kirchev T., *Organization and management of train traffic and work in metro stations* Book, VTU "T.Kableshkov", Sofia, 2020
- [5] Nikolov N., *Train traffic control on line 3 of the Sofia metro*, Scientific and Technical Union of Mining, Geology and Metallurgy. Sofia, ISBN 978-619-90939-9-3, 2023. pp. 176-183;
- [6] Dimitrova E., Tomov S., *Algorithm for Positioning of Metro Trains under Communications-Based Train Control*, 12th Electrical Engineering Faculty Conference XI-13 BulEF 2020 (IEEE Conference), <https://ieeexplore.ieee.org/document/9326061>



METAHEURISTIC OPTIMIZATION OF RESOURCE PLANNING AND BUSINESS PROCESS MANAGEMENT IN RAIL TRANSPORT

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Abstract – Modern rail transport operates under increasing requirements for capacity, reliability, safety and resource efficiency. The planning of rolling stock, locomotive crews, maintenance activities and infrastructure resources is a complex optimization problem involving multiple constraints and interrelated business processes. Traditional optimization methods often fail to provide solutions within an acceptable timeframe for large-scale problems, which motivates the use of metaheuristic algorithms. This article proposes a conceptual model for optimizing resource planning in rail transport by applying metaheuristic methods. The possibilities of using genetic algorithm, anthill colony optimization, particle swarm optimization, simulated annealing, and taboo search have been explored to optimize schedules, locomotive allocation, crew planning, and maintenance resources. A business process model is proposed, integrating optimization algorithms into operational planning and resource management. The expected results include reduced operating costs, better use of resources, increased reliability of the transport process and improved quality of services, providing a basis for the deployment of intelligent systems to support solutions in rail transport.

Keywords – rail transport, metaheuristic algorithms, optimization, resource planning, business processes, genetic algorithm.

1. INTRODUCTION

The digitalization of rail transport, together with the increasing complexity of modern rail networks, increases the need for efficient planning and use of resources such as locomotives, rolling stock, teams and infrastructure capacity. Rail operators solve various challenges in coordinating business processes, such as scheduling, rolling stock allocation, crew composition and maintenance planning, while satisfying operational, technical and safety constraints [1].

The growing volume of freight and passenger traffic, combined with ageing infrastructure and limited investment budgets, is forcing operators to extract more value from existing assets rather than relying solely on capacity expansion. This necessitates the replacement of manual, experience-based planning practices with data-driven, quantitative tools to support decisions capable of addressing the scale and interdependence of modern rail operations.

In this context, efficient resource planning becomes a key factor for the sustainability of rail services, as it allows for better alignment between capacity, demand and technical reliability. Integrating operational data into the decision-making process is important because it allows for a faster response to schedule deviations, accidents or

resource shortages. Metaheuristic methods offer an applicable toolkit for solving complex problems where traditional approaches are limited by the large number of possible combinations and interdependent constraints [2, 4].

The study presents a developed model for optimizing resource planning and management of business processes in railway transport through the application of metaheuristic algorithms. The processes in railway transport and the available resources are considered. A suitable metaheuristic optimization algorithm has been chosen.

2. ANALYSIS OF BUSINESS PROCESSES IN RAILWAY TRANSPORT

2.1. Main processes

Business processes in railway transport are a specific integrated system of management, operational and support activities that ensure safe, reliable and cost-effective train movement. They are characterised by the simultaneous interaction between infrastructure, rolling stock, human resources, information systems and external regulatory requirements. Rail transport operates under strict schedules, limited infrastructure capacity and a high degree of dependency between individual solutions.

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Therefore, business process analysis should be considered not only as a description of sequential operations, but as a basis for formalizing an optimization model for resource planning and management [2, 3].

Business processes can be grouped into three groups, strategic, tactical and operational. At strategic level, long-term network development objectives, infrastructure investments, rolling stock renewal and quality of service policies are defined. The tactical level includes planning schedules, allocation of locomotives and wagons, formation of train compositions, determination of repair windows and allocation of personnel. The operational level covers day-to-day traffic management, dispatching decisions, response to deviations, resource redeployment, delay control and coordination between stations, depots and control centres [2, 3, 4, 5, 6, 7].

Table 1. Diagram of the main business processes in rail transport

Input data	Main processes	Management decisions	Results
Search for transport Graph Available resources Infrastructure capacity	Transport planning and timetables	Determination of routes, train routes and priorities	Optimised schedule and higher accuracy of movement
Locomotives Wagons Depas Technical condition	Rolling stock management	Allocation of locomotives and wagons to trains	Better use of assets and lower costs
Machinist Teams Working hours Qualification	Personnel management	Composition of shifts and crews under regulatory restrictions	Balanced workload and compliance with labor rules
Wear data Accidents Repair windows	Infrastructure and rolling stock maintenance	Prioritize repairs and plan resources	Increased reliability, safety and availability

Each process in the rail system has its own purpose, but at the same time it affects the other processes. For example, a change in timetable may lead to the need for a new allocation of locomotives and crews, as well as the relocation of previously planned maintenance activities. Isolated optimization of individual processes cannot achieve effective management. A coordinated approach based on a common information base and uniform evaluation criteria is needed [2, 3, 4].

From the point of view of optimization, the main business processes can be described through variables, constraints, and performance criteria. Variables include choosing a locomotive for a specific train, appointing a driver, setting a departure time, choosing a route, length

of stay and time to carry out repair work. The limitations stem from the technical compatibility between the locomotive and the route, the available capacity of the infrastructure, the regulatory requirements for working hours, safety requirements, permissible delays and resource limits. Efficiency criteria include minimizing operating costs, reducing delays, increasing the usability of locomotives and wagons, optimal staff workload, and limiting unplanned disruptions [2, 5].

The maintenance process is of particular importance, as it both ensures safety and limits the available traffic capacity. Maintenance of railway infrastructure must be planned based on data, asset criticality and coordination with the train schedule. This management model allows repairs to be carried out in appropriate time windows without significantly disrupting the operational process. Such an approach is compatible with the digitalisation of the rail sector and with the use of asset management systems, dispatch systems and decision support modules [2, 4, 5, 11, 12].

The number of possible combinations between trains, locomotives, routes, crews and repair works increases significantly as the scale of the network increases. This makes classic manual planning methods insufficient under complex and dynamic conditions.

The main resources subject to optimization are locomotives, wagons, train drivers, maintenance teams, railway infrastructure, time and energy resources. Underutilization of these resources increases operating costs, while overuse increases the risk of delays, safety incidents, and reduced quality of service.

3. THEORETICAL BASIS OF METAHEURISTIC METHODS

3.1. Classical optimization methods

Classical optimization approaches, such as linear programming, integer programming, dynamic programming, and constraint-based methods, have traditionally been applied to transport and rail planning tasks. The mathematical model must be well structured, the constraints must be clearly defined, and the size of the problem allows you to find the exact optimal solution in a reasonable time. In real rail systems, the number of variables and constraints is rapidly increasing due to the need to simultaneously accommodate timetables, locomotives, crews, infrastructure capacity and repair windows. This leads to high computational complexity and practical difficulties in using accurate methods. For this reason, classical methods are often used as a basis for formulating the model, while the search for practically applicable solutions is supported by heuristic and metaheuristic approaches [8, 9, 10].

3.2. Metaheuristic methods

Metaheuristic methods are general search strategies

that combine local improvement and a higher level of demand management to avoid prematurely hitting a local optimum. These include Genetic Algorithm (GA), Simulated Annealing (SA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), Tabu Search (TS) and others, applicable to complex combinatorial and nonlinear problems. Their main strength is that they do not require a mandatory analytical description of all the properties of the target function and can work with discrete, continuous and mixed variables. In rail transport, this is important because timetable, routing, locomotive allocation and staff planning tasks often involve multiple interrelated constraints and conflicting objectives. Therefore, metaheuristics are seen as an effective alternative to precise methods for large-scale tasks, where it is more important to obtain a high-quality solution in an acceptable time than a formally proven global optimum [2, 3, 9, 10].

3.3. Advantages

The main advantages of metaheuristic methods include their ability to find near-optimal solutions within an acceptable computational time [9,10]. They are flexible when working with multiple constraints, different types of variables and several simultaneous performance criteria, which makes them suitable for real transport systems [2, 10]. For rail transport, this means the possibility of simultaneously optimising timetables, the use of locomotives, staff workload, delays and maintenance [2, 3]. It is possible to combine the use of a metaheuristic algorithm with mathematical programming or specialized rules for the specific subject area [9]. On this principle, an adaptive decision support system can be built, which can be adjusted according to the operational priorities of the railway operator, the current state of the network and the level of digital maturity of the organization [4, 10, 11].

4. PROPOSED OPTIMIZATION MODEL

Input data

The proposed model takes into account the following inputs: train timetable, available locomotives, available drivers, operational and technical constraints, maintenance windows and rolling stock specifications.

Target function

The target function to be minimized is defined as follows (formula 1):

$$F = \alpha C + \beta T + \gamma D + \delta R \rightarrow \min \quad (1)$$

Where:

C is the operating value,

T is the rest time (unused),

D is the delay,

R is the amount of unused resources,

α , β , γ and δ are weighting factors reflecting the relative importance of each component and can be adjusted according to the operator's priorities.

Limitations

The model is subject to restrictions related to the legal regulations on the working hours of the teams, the technical requirements of the rolling stock, the capacity limitations of the infrastructure, the operational restrictions and the safety requirements.

1. $0,60 \leq U \leq 0,90$
2. $0,75 \leq W \leq 0,95$
3. $5 \leq d \leq 20$
4. $g \geq 0$
5. $C, T, D, R \geq 0$
6. $\alpha, \beta, \gamma, \delta \geq 0$
7. $\alpha + \beta + \gamma + \delta = 1$

U - use of railcars, W - load of drivers, d - average delay
g - Cost reduction

The first three limits set the permissible limits for the use of rolling stock, the workload of drivers and the average delay. The condition $g \geq 0$ means that the optimised solution must not lead to an increase in operating costs compared to the baseline scenario. The constraints $C, T, D, R \geq 0$ guarantee non-negativity of the components of the target function, and the condition $\alpha + \beta + \gamma + \delta = 1$ normalizes the weighting factors and allows comparability between the individual criteria.

5. OPTIMIZATION ALGORITHM

The evolutionary algorithm has been proposed as the main method of optimization, as recent experimental studies of the railway timetable show high efficiency in terms of solution quality, convergence rate and infrastructure capacity utilization. The proposed algorithm follows the standard EA procedure, illustrated in Fig. 1:

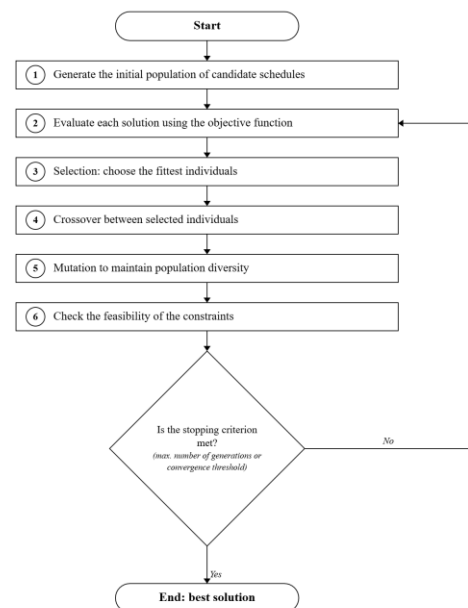


Fig. 1. Flowchart of the genetic algorithm for schedule optimization

6. EXPERIMENTAL SETUP

Case study

To evaluate the proposed model, a case study based on a regional railway network is considered, including 25 trains (railcars), 150-200 train drivers, 25 daily trains and 100 stations, technicians and maintenance 150, service personnel (conductors) 250, administration and management 100.

Scenarios

Three scenarios are compared: classical planning used as a basis; planning based on a standard genetic algorithm and planning based on a hybrid genetic algorithm combined with local search improvement in order to evaluate the benefits of the proposed approach.

The implementation is planned in Excel, Solver. The input data for the case study (timetable, availability of locomotives and crews, support windows) are defined on the basis of typical operational models of the regional rail network, in the absence of access to the live data of a specific operator at this stage of the study.

7. RESULTS ANALYSIS

The comparison focuses on operating costs, locomotive utilization, staff load, delays, calculation time, and resource utilization rates. The results will be visualized through charts, comparison tables, and Gantt charts, allowing for a clear assessment of the improvements made by the metaheuristic approach to the baseline scenario.

Based on the results reported for similar applications of genetic algorithms in transport planning, the hybrid scenario is expected to achieve the lowest operating costs and delays, at the expense of longer calculation times compared to the standard Genetic Algorithm. The classic planning scenario is expected to serve primarily as a starting point, illustrating the potential margin for improvement achievable through metaheuristic optimization. The proposed model can be applied to operational planning, locomotive fleet management, maintenance planning, human resource management, decision-making support for dispatchers, and integration with rail transport management systems (TMS) and corporate resource planning (ERP) systems used by railway operators.

8. CONCLUSION

This article presented a conceptual, integrated model for optimizing resource planning in rail transport by applying metaheuristic algorithms. The applicability of metaheuristic methods for managing interconnected

business processes – scheduling, locomotive allocation, crew planning and maintenance – is demonstrated. A methodology for improving the efficiency of the use of the locomotive, personnel and infrastructure is proposed. Future work will focus on experimental model validation on real operational data, comparison of alternative metaheuristic algorithms, and expanding the approach through the integration of digital twins and machine learning techniques for adaptive real-time resource management.

REFERENCES

- [1] Dimitrov D., Manchev I., *Methodological and technical aspects of models for digital management of transport systems*, ENVIRONMENT. TECHNOLOGIES. RESOURCES. Proceedings of the International Scientific and Practical Conference, vol. 2, June 2024, pp. 79-82, <https://doi.org/10.17770/etr2024vol2.8049>, 2024.
- [2] Huang, Z., Li, X. *A critical review of operations research on the operation and maintenance of railway systems*. Journal of Railway Science and Technology, 2026. Available online: <https://hub.hku.hk/bitstream/10722/360690/1/content.pdf>
- [3] Arenas, D., Chevrier, R., Hanafi, S., Rodriguez, J. *Solving the Train Timetabling Problem: a mathematical model and a genetic algorithm solution approach*. RailTokyo2015 / HAL Open Science, 2016. Available online: <https://hal.science/hal-01338609/document>
- [4] International Union of Railways (UIC). *Asset Management. UIC Rail System*. Available online: <https://uic.org/rail-system/asset-management/>
- [5] Boston Consulting Group. *Achieving World-Class Rail Infrastructure Maintenance*. BCG, 2025. Available online: <https://www.bcg.com/publications/2025/achieving-world-class-rail-infrastructure-maintenance>
- [6] Hansen, I. A., Pachl, J. *Railway Timetabling and Operations*. Hamburg: Eurailpress, 2014.
- [7] Varadinova J., Kostadinov P., *Overview Of Methods For Determining The Capacity Of The Railway Network*, XXI International Scientific- Expert Conference On Railway - RAILCON 2024, October 10-11, 2024, Niš, Serbia;, Assistant Mag. Eng. Petar Kostadinov, 2024.
- [8] Goldberg, D. E. *Genetic Algorithms in Search, Optimization, and Machine Learning*. Addison-Wesley, 1989.
- [9] Gendreau, M., Potvin, J.-Y. *Handbook of Metaheuristics*. 3rd ed. Springer International Publishing, 2019. Available online: <https://link.springer.com/book/10.1007/978-3-319-91086-4>
- [10] Talbi, E.-G. *Metaheuristics: From Design to Implementation*. Wiley, 2009. Available online: <https://www.wiley.com/en-ae/Metaheuristics%3A+From+Design+to+Implementation+-p-9780470496916>
- [11] Peneva, G., Andreev, O. *Assessing Bulgarian SMEs' Maturity for Industry 4.0 Implementing – the Case of Montana Hydraulics Ltd. Strategies for Policy in Science and Education*, Vol. 31, No. 3s, pp. 9–24, Az-buki National Publishing House for Education and Science, 2023. ISSN 1310-0270 (Print), ISSN 1314-8575 (Online), DOI: 10.53656.
- [12] Peneva, G., *Theoretical Aspects of Managing Technological Obsolescence*, WUTP Yearbook 2024, Vol. VIII, pp. 34–39, ISBN 2815-5440, 2024.

Infrastructure



LOW COST ELECTRONIC INTERLOCKING SYSTEM FOR THE RAILWAY STATION ELEMIR

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Abstract – This paper describes the low cost **Electronic Interlocking - EI** system installed at the railway station **Elemir** in Serbia. The system is developed and produced by Signalling & Control d.o.o. Belgrade. EI is a computer system based on the PLC family - HiMax, produced by the German company HIMA Paul Hildebrandt GmbH. The system is verified and approved for use on Serbian Railways by the Directorate for Railways of the Republic of Serbia and has the highest safety integrity level - SIL4 in accordance with European railway standards - CENELEC. Elemir EI is a standardized, modular and scalable system configured to the specific track layout of the Elemir railway station. The operational, functional and traffic requirements and safety principles of the previous, outdated Elemir electro-relay interlocking system are converted to general interlocking software of the Elemir EI. The track layout dependent data and particular interlocking requirements, which are presented in a form of a conventional control table are standardized and converted into a new form of the computer control table. This table is used as a simple data file for further computer processing and formal proving. Also, an advanced method of representing the layout of a railway station for HMI purposes in accordance to the standardized Catalogue of symbols of Serbian Railways is used. The described approach enabled a fast and efficient development and implementation and contributed to the low cost realisation of the complete Elemir EI.

Keywords - *Railway computer interlocking system, railway signalling, safety integrity level 4, safety critical software, control table, reliability, availability and maintainability, lifecycle cost.*

1. INTRODUCTION

EI system is installed at the Elemir station in December 2025, under contract with the Infrastructure of Serbian Railways, for the control and supervision of the traffic in the railway station Elemir. The control includes routes on the main line and two industrial lines in accordance with railway rules, regulations and technological processes required for the operation of the railway station [1]. It gives the authority for moves through the station areas and defines the route and the speed of the move in every particular situation. Hence, it is of paramount importance for the safety and security of the railway traffic [3].

Elemir EI system is a HIMA, HiMax and HiMatrix PLC, based controlling system of the highest safety integrity level - SIL4 in accordance with CENELEC European railway standards. EI is produced by Signalling & Control d.o.o., Belgrade and it is approved for use in Serbia by the Directorate for Railways of the Republic of Serbia.

Elemir EI covers area of the railway station Elemir with the track layout and the outside signalling equipment as shown on the signalling arrangement of the railway station Elemir presented in Figure 1.

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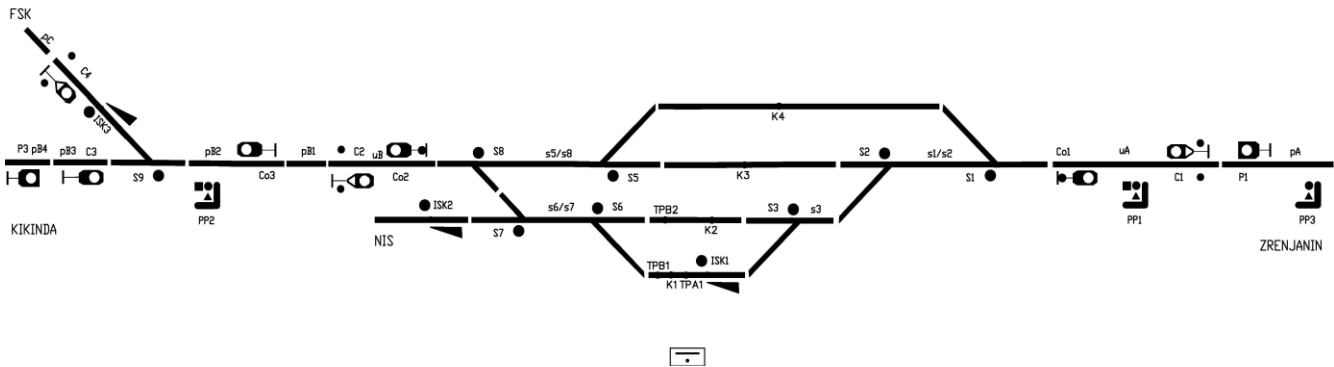


Fig.1. Elemir railway station - Signalling Arrangement

The task was to replace the existing, outdated electro-mechanical relay interlocking in the relay room, which is no longer functional, with a new computer system while maintaining the operational logic and signal dependencies of the existing interlocking.

Elemir EI represents an economical, low cost system, which supports the existing conventional outside equipment with LED signals and reuses the existing cable network. It has fully replaced the existing - Conventional Relay Interlocking system.

2. HARDWARE ARCHITECTURE

EI for railway station Elemir is realized as a modular and scalable system [1]. Architecture of the system consists of the following five levels:

- **Level 1:** EHMI - Operator console.
- **Level 2:** Central Safety Controlling system (SIL4) realized with HIMA PLC family HiMax, with DIM – digital input modules, and DOM – digital output modules.
- **Level 3:** EAC - Electronic Axle Counting system (SIL4) [4] - Safety controlling sub-systems realized with HIMA PLC family HiMatrix for the Train Detection functionality.
- **Level 4:** Interfaces for the control of the signalling elements are realized as standardized control modules:
 - SM - signal module,
 - PM - points module,
 - L-xing - level crossing module and
 - PS - power supply module.
- **Level 5:** Controlled signalling elements: signals, point machines, axle counter sensors, level crossings and power supply.

2.1. EHMI

EHMI (Electronic Human Machine Interface) is an electronic system that allows the interactive communication between the operator and the Central EI system. It is produced by Signalling & Control

d.o.o., Belgrade. Directorate for Railways of the Republic of Serbia issued the permanent approval for use of the EMMI - Electronic Man Machine Interface on the Serbian Railways in 2009.

The software package WinCC (Siemens) on the PC is used as a base for the realization of the EHMI.

Communication with HiMax PLC is realized over the Ethernet using the HIMA XOPC server.

An advanced method of representing the layout of a railway station for EHMI purposes is realized for EI. An example is EHMI layout presented in the following picture that is realized in accordance to the standardized Catalogue of symbols of Serbian Railways. EHMI installed at the railway station Elemir is presented in Figure 2.

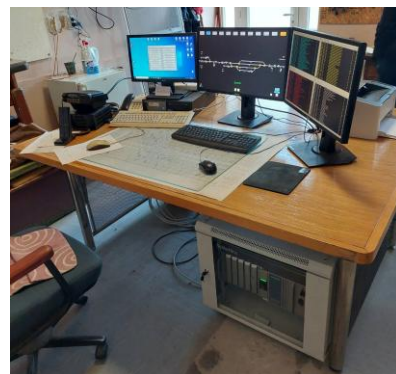


Fig.2. EHMI - at the railway station Elemir

2.2. Central Safety Controlling system (SIL4)

Central Computer Controlling system is realized by use of the safety HIMA PLC - HiMax (SIL4), which is also highly reliable and highly available system and provides low maintenance costs over its lifetime [2]. Each safety module individually is realized in the safety architecture - "2 out of 2". HiMax system for Elemir EI application is realized in the architecture - "2 times 2 out of 2" with a hot swap ability feature (warm replacement of the failed module). Elemir EI Central Safety Controlling HiMax system with the redundant DC power supply and

controlling interfaces to level crossings (the last three rows in cabinet) is presented in Figure 3.



Fig.3. Central Safety Controlling System of Elemir EI

2.3. EAC - Electronic Axle Counting system

The EAC system is realized as an independent safety sub-systems to cover Train Detection function. EAC system is developed and produced by Signalling & Control d.o.o., Belgrade [4]. EAC system is a HIMA, HiMatrix PLC based controlling system of the highest safety integrity level - SIL4 in accordance with CENELEC European railway standards. It is approved for use in Serbia by the Directorate for Railways of the Republic of Serbia. EAC train detection system at the railway station Elemir is presented in Figure 4.

2.4. Interfaces for control of signalling elements

Interface modules are realized as standardized functional modules (SM-signal module and PM-points

module) and placed into the appropriate cabinets. Cabinet for PM is presented in Figure 5 and cabinet for SM is presented in Figure 6.



Fig.4. EAC based Train Detection system for Elemir



Fig.5. Cabinet with PM modules for Elemir EI

3. MODULARITY AND SCALABILITY

Elemir EI is realized as a modular and scalable system. It contains 11 identical PMs and 13 SMs for signals and indicators. Also, the interface modules for 3 level crossings and one for PS. Elemir EI Central Controlling Computer HiMax uses single housing (rack) with 15 modules (12 active and 3 spare modules). It has 128 DI-digital inputs (64 redundant DI) and 96 DO-digital outputs (32 redundant DO). The redundant DIO are used for the outside signalling elements whose failure would cause the most

restrictive impact on system availability or would disable the greatest number of train routes, such as, for example, the facing points on the main track.



Fig.6. Cabinet with SM for Elemir EI

4. SOFTWARE

Software is realized as an integrated package that contains all necessary data and functional modules. It covers complete safety principles and functionality of Serbian Railways applicable for the railway station Elemir [1].

The operational, functional and traffic requirements and safety principles of the interlocking system Elemir are converted to general interlocking software of EI. The track layout dependent data and particular interlocking requirements, which are presented in a form of a conventional control table, are standardized and converted into a new form of the computer control table. This table is suitable for the application of formal proving methods and it is used as a simple data file for further computer processing.

5. COMMUNICATION

Elemir EI communication is duplicated (two channels) for the availability. Each communication channel is realized as an independent Safe-Ethernet (vital) ring and connects Central Controlling Computer HiMax (SIL4) with EAC sub-system for train detection

consisting of three HiMatrix (SIL4) PLCs. Elemir EI communication structure is presented in Figure 7.

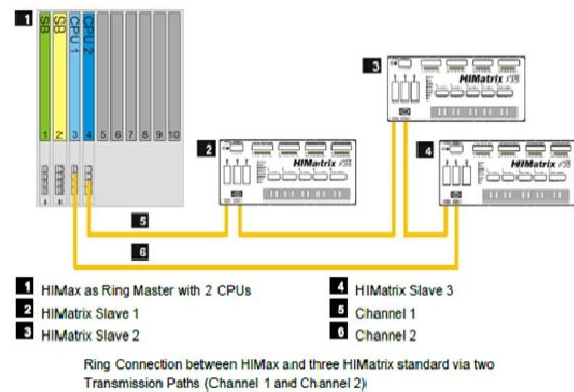


Fig.7. Elemir EI - Communication Structure

6. CONCLUSION

The described Elemir EI Computer Based Interlocking system represents continuation of the development efforts and good examples of the realisation of the domestic interlocking systems in the past. The first examples of the development and use of domestic electro-relay systems were "free wiring electro-relay system" and "coordinate system" developed at the Railway Research Institute (Institute Kirilo Savic, Belgrade) about 40 years ago and installed at several stations. The second example was discrete electronic interlocking who used fully electronic solid-state modules and was in service at the railway station Banja Koviljaca until few years ago. These systems have reached the end of their lifespan, and the manufacturing technology has been surpassed by new computer technology.

Elemir EI is based on newer generation computer technology that is current, state of the art, and still indispensable for points control, even for modern high-speed systems, so it can be used as an economical solution for securing railway stations for many years to come.

REFERENCES

- [1] Lutovac N.D., Lutovac A.T., *Electronic Interlocking*, XVIII RAILCON 2018, Nis, pp. 85-88. 2018.
- [2] Lutovac N.D., Lutovac A.T., *RAMS Considerations of Computer Based Interlockings During Their Lifetime Cycle in Practice*, XX RAILCON 2022, Nis, pp. 77-80. 2022.
- [3] Lutovac N.D., Lutovac A.T., *Approval of Computer Based Interlockings and Place of Conventional Safety Analyses*, XX RAILCON 2022, Nis, pp. 81-84. 2022.
- [4] Lutovac N.D., *Electronic Axle Counter*, XIX RAILCON 2020, Nis, pp. 69-72. 2020



SUPERSTRUCTURE MODERNIZATION OF THE HEAVY GANTRY CRANE TRACK IN TPP REK BITOLA

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Abstract – This paper presents a comprehensive engineering solution for the rehabilitation and structural modernization of a severely degraded gantry crane track at the Thermal Power Plant (TPP) REK Bitola. The investigated crane, a 383.4-tonne portal structure manufactured by Metalna in 1977, was withdrawn from operation due to significant geometric deterioration of the crane track. Long-term geodetic monitoring and recent levelling surveys identified vertical rail deflections exceeding 30–40 mm, far beyond the permissible operational tolerance of ± 3 to ± 5 mm. The investigation showed that the primary causes of deterioration were the structural decay of the existing wooden sleepers, ballast contamination and inadequate drainage, while the underlying platform exhibited excellent bearing capacity (CBR = 100%) and did not require rehabilitation. The proposed rehabilitation concept focuses on the complete modernization of the track superstructure, utilizing the high-bearing capacity of the existing subgrade. The existing wooden sleepers are replaced with pre-stressed reinforced concrete sleepers (type RAJS-K-B70) tailored for the 1500 mm track gauge, supporting S49 rails via an elastic Vossloh SKL 14 fastening system. Additionally, the configuration features an elevated ballast prism and a newly integrated longitudinal drainage system equipped with perforated Ø100 mm pipes. The structural design was developed in accordance with established railway track design principles to ensure adequate load transfer, improved track stability, efficient drainage and long-term preservation of the track geometry. The proposed solution provides a practical engineering approach for restoring the operational reliability of industrial gantry crane tracks and may serve as a reference for similar rehabilitation projects under comparable operating and environmental conditions.

Keywords – Crane track rehabilitation, Concrete sleepers, Track gauge 1500 mm, Rail S 49, Geodetic levelling, Substructure drainage.

1. INTRODUCTION

Industrial gantry crane tracks in coal-fired thermal power plants are subjected to extreme, concentrated, and cyclic structural loading. Over decades of service, these massive quasi-static forces, together with coal dust buildup and moisture entrapment, trigger severe track degradation and loss of geometric alignment [1][2].

The focus of this paper is the comprehensive reconstruction and geometric stabilization of the degraded heavy gantry crane runway at the Thermal Power Plant (TPP) REK Bitola. This infrastructure supports a 383.4-tonne steel portal crane (manufactured by "Metalna" Maribor in 1977) that performs critical block maintenance on the parallel S49 rail tracks, with dynamic wheel loads of up to 210 kN. After nearly five decades of unmaintained service, advanced biochemical decay of the legacy wooden sleepers and severe ballast fouling led to vertical and horizontal rail deflections of

30–40 mm. Because these distortions violate the crane's safe-operating tolerances of ± 3 to ± 5 mm, the track was officially decommissioned due to derailment risks and structural stress concentrations within the crane's steel portal frame..

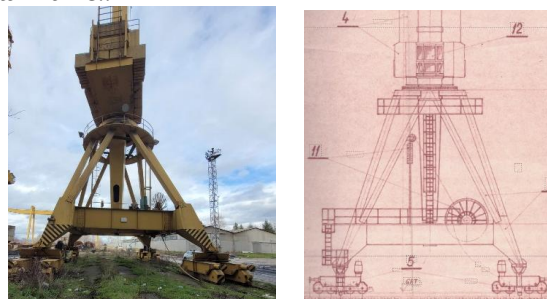


Fig.1. Portal crane at TPP REK Bitola

To engineer a definitive structural solution, a detailed forensic assessment was executed. While typical railway settlement failures are closely linked to subgrade shear

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failure, core-drilling profiles and laboratory testing in accordance with MKC EN 13286-47:2023 revealed a contrasting structural baseline: the underlying platform layers exhibit an exceptionally high bearing capacity, reaching a benchmark CBR value of 100%.

This boundary condition confirms that the systemic deformation was driven exclusively by superstructure degradation rather than by subgrade settlement. Consequently, the modernization design presented in this paper focuses on leveraging this rigid base to optimize construction costs. The engineered solution replaces the decayed timber system with custom pre-stressed reinforced concrete sleepers (type RAJS-K-B70) tailored for the unique 1500 mm track gauge, securing the S49 rails with elastic Vossloh SKL 14 fastening assemblies. The modernized layout elevates the track profile on a clean 35 cm ballast prism placed directly on the rigid subgrade and integrates a high-efficiency subsurface drainage network with perforated Ø100 mm pipes to permanently eliminate the formation of coal-dust slurry.

2. EXISTING CONDITION ASSESSMENT

The gantry crane track at TPP REK Bitola has two parallel runways, each 35 m long, with a center-to-center portal span of 7.50 m and a customized track gauge of 1500 mm [3]. The legacy superstructure used standard S49 rail profiles on wooden sleepers with rigid mechanical joints, and was supported by an aged crushed-stone ballast bed.

Multi-decadal exploitation under intense dynamic concentrations and severe environmental exposure, including coal dust and ash accumulation, triggered accelerated material degradation. Organic decomposition and internal rotting stripped the timber sleepers of their shear capacity, loosening the fastening anchorage and inducing dynamic rail spreading. At the same time, coal particles fully clogged the ballast prism voids. This severe ballast fouling choked the drainage path, leading to moisture retention and a destructive pumping effect under load.



Fig.2. Existing condition of the crane track.

Precise geodetic leveling and diagnostic structural surveys verified critical geometry loss across all parameters. The maximum recorded track gauge deviation reached a critical +44 mm, while localized vertical rail depressions plunged up to 30–40 mm, inducing extensive cross-level non-uniformities and track twist. When traversed by the 383.4-tonne portal crane, these geometric defects induced excessive dynamic impact forces, accelerated wheel-rail flange

friction ("wheel eating"), eccentric loading within the steel portal frame, and an immediate risk of structural derailment. Consequently, complete track reconstruction was mandated.

3. PROPOSED REHABILITATION CONCEPT

To restore structural strength and maintain long-term geometric stability, a complete superstructure modernization was developed based on a 210 kN wheel load envelope. The selected structural components comply with European design standards, using EN 13674-1 for rails [4], RAJS-K-B70 pre-stressed reinforced concrete sleepers [5], and Vossloh SKL 14 elastic fastening systems [6].



Fig.3. Proposed superstructure components: (a) RAJS-K-B70 sleeper; (b) Vossloh SKL 14 fastening; (c) S49 rail.

Given the exceptionally stable subgrade (CBR = 100%), additional granular subbase or artificial stabilization layers were omitted as structurally redundant. Instead, a clean, high-grade crushed-stone ballast prism with a minimum thickness of 35 cm is placed directly onto the existing rigid platform beneath the sleeper seat, preserving structural sufficiency while simplifying the section. This elevated configuration deliberately raises the track profile above the surrounding ground depression, placing it above the concrete perimeter to prevent the accumulation of falling coal dust and ash. To eliminate moisture pooling, a longitudinal subsurface drainage network with a perforated Ø100 mm pipe is embedded parallel to the alignment, combined with a 3% to 4% cross-slope on the platform surface to ensure rapid runoff evacuation.

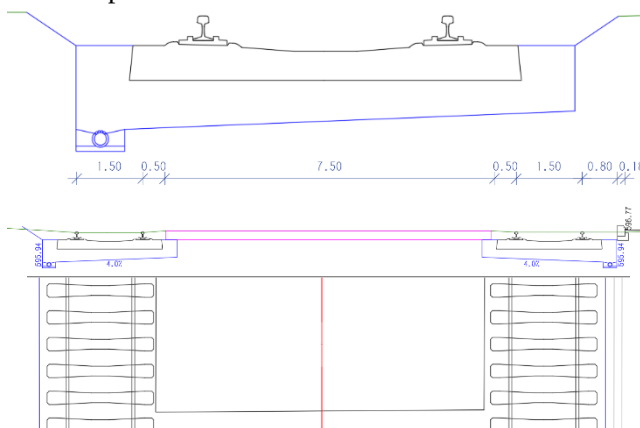


Fig.4. Proposed crane track layout and cross-section.

As illustrated in Fig. 4, the unified superstructure layout integrates continuous S49 rail profiles for smooth wheel transit, secured by elastic Vossloh SKL 14 clip assemblies. Dynamic impacts are attenuated by heavy-stiffness under-rail elastomeric pads that protect the

concrete interface. Finally, custom pre-stressed concrete sleepers (type RAJS-K-B70) permanently lock in the 1500 mm track gauge over an elevated 35 cm ballast prism and a longitudinal Ø100 mm drainage network.

4. TRACK STRUCTURE DESIGN AND ANALYTICAL MODELING

4.1. Input Parameters for the Analytical Model

The structural dimensioning of the modernized superstructure is performed using the classical Zimmermann framework, which treats the rail as an infinitely long beam supported on a continuous elastic Winkler foundation [7]. Based on the geotechnical reference (CBR = 100%), the track bed reaction modulus (C) is set to an elite value of 150 MPa/m ($150 \times 10^3 \text{ kN/m}^3$). The baseline analytical input parameters are:

- Maximum Dynamic Wheel Load (Q): 210kN,
- Rail Profile (S49): $I = 1819 \text{ cm}^4$, $W = 248 \text{ cm}^3$, $E = 2.1 \times 10^5 \text{ MPa}$,
- Sleeper Spacing (a): 0.60m (on-center spacing for RAJS-K-B70 units).

The Winkler model defines the vertical bed reaction force per unit length (p) as directly proportional to the elastic rail deflection (y), expressed as:

$$p = C * y * a \quad (1)$$

where p is the track bed reaction force [kN/m] and y is the vertical elastic deflection of the rail head [m].

4.2. Numerical Analysis and Numerical Results

The characteristic distribution length (L), defining the longitudinal zone of wheel load distribution, is determined via the governing equilibrium equation:

$$L = \sqrt[4]{\frac{4EI}{C}} = \sqrt[4]{\frac{4 * \left(2.1 * \frac{10^8 \text{ kN}}{\text{m}^2}\right) * (1819 * 10^{-8} \text{ m}^4)}{\left(150 * \frac{10^3 \text{ kN}}{\text{m}^3}\right) * 0.60 \text{ m}}} = 0.64 \text{ m} \quad (2)$$

The maximum bending moment ($M_{\max}$) induced directly under the wheel load is derived by incorporating a worst-case dimensionless shape coefficient ($\mu = 1.0$), assuming the wheel rests directly over a single concrete sleeper:

$$M = \frac{QL}{4} \mu = \frac{210 \text{ kN} * 0.642 \text{ m}}{4} 1.0 = 33.71 \text{ kNm} \quad (3)$$

Consequently, the maximum normal bending stress ($\sigma_{\max}$) developed within the extreme fibers of the S49 rail foot is evaluated via equation (4):

$$\sigma = \frac{M}{W} = \frac{33.71 * 10^{-3} \text{ MNm}}{248 * 10^{-6} \text{ m}^3} = 135.92 \text{ MPa} \quad (4)$$

The maximum vertical reaction force ($S_{\max}$) transferred to the custom RAJS-K-B70 pre-stressed concrete sleeper directly beneath the wheel loading is calculated as:

$$S_{\max} = \frac{Q * a}{2 * L} = \frac{210 \text{ kN} * 0.60 \text{ m}}{2 * 0.642 \text{ m}} = 98.13 \text{ kN} \quad (5)$$

Factoring the effective bearing area of the RAJS-K-B70 sleeper foot ($A_{\text{eff}} \sim 0.38 \text{ m}^2$), the maximum

compressive contact stress (σ_b) exerted onto the elevated 35 cm ballast prism is derived as:

$$\sigma_b = \frac{S_{\max}}{A_{\text{eff}}} = \frac{98.13 \text{ kN}}{0.38 \text{ m}^2} = 258.23 \text{ kPa} = 0.258 \text{ MPa} \quad (6)$$

4.3. Limit State Verification

The maximum calculated normal bending stress ($\sigma_{\max} = 135.92 \text{ MPa}$) remains well below the permissible fatigue limit state for the S49 rail steel grade, capped at $\sigma_{\text{perm}} = 225 \text{ MPa}$ according to EN 13674-1. Likewise, the maximum compressive contact stress at the sleeper-ballast interface ($\sigma_b = 0.258 \text{ MPa}$) stays below the critical degradation threshold for crushed stone ballast ($\sigma_{b,\text{perm}} = 0.30 \text{ MPa}$ under EN 13230).

Because the natural subgrade matrix exhibits excellent bearing capacity (CBR = 100%), it accommodates this stress distribution without plastic deformation. The analytical modeling confirms that direct application of the 35-cm-elevated ballast bed over the existing rigid platform satisfies all ultimate and serviceability limit states.

5. CONSTRUCTION METHODOLOGY AND SEQUENTIAL TECHNOLOGY

To achieve the rigorous millimeter-level alignment required by international tolerances (± 3 to $\pm 5 \text{ mm}$), a strict construction sequence is enforced. Geotechnical testing confirmed an exceptionally rigid foundation layer (CBR = 100%), so traditional deep subgrade excavation and subbase installation are entirely omitted. All works are executed directly on the exposed, stable platform. To manage the restricted 35-meter working front without dismantling the 383.4-tonne crane, the work is carried out in two phases: first one half, then the other.

- Stage 1: Site Securing and Temporary Crane Dislocation

Prior to mechanical intervention, the industrial perimeter within the TPP REK Bitola maintenance block is isolated, and high-voltage power lines are decommissioned. To facilitate a continuous workflow within the short 35-meter runway limits, the massive "Metalna" portal crane is systematically moved at minimum speed toward the first designated end half of the alignment. Once positioned safely, the portal structure is mechanically locked, counter-wedged, and anchored. This eliminates the risk of overturning during the reconstruction of the newly exposed adjacent half.

- Stage 2: Rail Cutting, Superstructure Dismantling, and Ballast Scraping

Following crane stabilization, mechanical rail saws make a precise transverse cut through the existing S49 rails at the track midpoint, dividing the runway into two isolated working sections. On the vacant half, unbolt the fasteners, carefully extract and store the preserved S49 rail strings laterally for immediate re-use, and remove and dispose of the degraded wooden sleepers. Excavate the heavily fouled, coal-dust-saturated ballast bed down to the hard gravel-sand platform level (CBR = 100%).

Then thoroughly clean the exposed subgrade surface, high-pressure wash it to remove abrasive slurry accumulations, and geodetically survey it.

- Stage 3: Longitudinal Sub-drainage Infrastructure Integration

To permanently prevent water pooling and the formation of coal-dust mud, integrate the drainage network before laying new ballast. Excavate a shallow longitudinal trench parallel to the track alignment. Grade the subgrade platform to a strict 3%-4% outward cross-slope toward the drainage zone so runoff is directed away from the track. Embed a perforated polyvinyl chloride (PVC) sub-drainage pipe (Ø100 mm) within uniformly graded filter gravel (4-16 mm fraction) to ensure immediate evacuation of surface runoff away from the active track infrastructure.

- Stage 4: Ballast Prism Deposition and Concrete Sleeper Distribution

High-efficiency, sharp-edged crushed stone ballast (Class I, fraction 31.5 to 63 mm) is tipped directly onto the cleaned CBR 100% platform. The lower lift is spread and mechanically compacted with heavy vibratory rollers to a uniform thickness of 20 cm. After base compaction, custom-manufactured pre-stressed reinforced concrete sleepers (type RAJS-K-B70) are distributed over the bed using a hydraulic excavator with a synchronized-spacing lifting beam. The sleepers are aligned at a strict 60 cm on-center longitudinal spacing. Their orientation is verified by laser-guided geodetic positioning to ensure absolute parallelism.

- Stage 5: Rail Re-laying, Continuous Welded Rail (CWR) Welding, and Tamping

The preserved S49 rail strings are re-threaded onto the new concrete sleeper seats over high-stiffness elastomeric under-rail dampening pads. The rails are secured with elastic Vossloh SKL 14 clip assemblies, and the anchoring bolts are mechanically torqued to 220 Nm. Once secured, the rail joints and cut segments are joined via aluminothermy welding. This converts the section into Continuous Welded Rail (CWR), thereby eliminating dynamic mechanical joints.

Finally, top ballast is distributed to fill the sleeper cribs. Final alignment is achieved through sequential passes of mechanical tamping, lining, and leveling equipment until the cross level, longitudinal grade, and 1500 mm track gauge are locked within millimeter operational tolerances. After geodetic verification of this first half, the crane is carefully lowered onto the newly modernized concrete track segment. The sequence from Stage 2 through Stage 5 is then repeated for the remaining half of the runway.

6. CONCLUSION

The engineering approach implemented in this study shifts the paradigm of industrial runway rehabilitation by demonstrating that systemic loss of geometry does not automatically dictate foundation failure. By isolating the true structural root cause—progressive material decay of

legacy timber elements under aggressive exposure to coal dust and moisture—the developed design leverages the exceptional bearing capacity of the existing rigid subgrade platform (CBR = 100%). This eliminates redundant subgrade excavation and granular subbase layers, establishing a highly cost-effective and structurally optimized rehabilitation layout.

The modernized superstructure configuration successfully establishes a uniform, high-stiffness track modulus. Custom pre-stressed concrete sleepers (type RAJS-K-B70) permanently lock in the specialized 1500 mm track gauge, which, when paired with elastic Vossloh SKL 14 fastenings and continuous S49 rail strings, mitigates the risk of gauge spreading under cyclic 210 kN wheel-load envelopes. Simultaneously, intentionally elevating the ballast prism to 35 cm, combined with a 3% to 4% platform cross-slope and a longitudinal subsurface drainage network, eliminates environmental vulnerabilities by preventing water pooling and the formation of coal-dust slurry within the track bed.

Ultimately, the technical feasibility of this project is validated by its sequential execution technology. Slicing the rails at the midpoint and staging the reconstruction in two distinct phases provides a highly practical logistical template for short industrial runways, ensuring that the massive 383.4-tonne portal crane remains safely on-site without interrupting plant operations. Transforming the re-laid rails into Continuous Welded Rail (CWR) successfully eliminates dynamic joint impacts, prevents catastrophic track twist, and restores the heavy gantry crane to certified, long-term operational reliability.

REFERENCES

- [1] Nedevska, I., Zafirovski, Z., Lazarevska, M., Ristov, R., Gacevski, V., Track Geometry Degradation and Maintenance of the Railways, Sustainable Civil Engineering Journal, Vol. 11, No. 1, Faculty of Civil Engineering, Ss. Cyril and Methodius University in Skopje, Skopje, 2022
- [2] Šestáková, J., Pultznarová, A., Mečár, M., The Maintenance of the Railway Superstructure and Its Influence on the Track Geometry of Regional Line, Acta Technica Jaurinensis, Vol. 15, No. 3, Győr, Hungary, 2022. DOI: 10.14513/actatechjaur.00664
- [3] Geodetic Survey Report of the Existing Condition of the Gantry Crane Track at TPP REK Bitola, Technical Report, TPP REK Bitola, Bitola, 2024
- [4] European Committee for Standardization (CEN), EN 13674-1: Railway Applications – Track – Rail – Part 1: Vignole Railway Rails 46 kg/m and Above, Brussels, Belgium, 2021
- [5] ŽGOP, Prestressed Concrete Sleeper RAJS-K-B70, Technical Catalogue, Ljubljana, Slovenia, 2023
- [6] Vossloh Fastening Systems GmbH, SKL 14 Elastic Rail Fastening System, Technical Catalogue, Werdohl, Germany, 2023
- [7] Esveld, C., Modern Railway Track, MRT-Productions, Zaltbommel, The Netherlands, 2001.
- [8] Lichtberger, B., Track Compendium – Formation, Permanent Way, Maintenance, Economics, Eurailpress, Hamburg, Germany, 2011.



COMPARATIVE ANALYSIS OF TRACK QUALITY INDEX CALCULATION METHODOLOGIES USING REAL GEOMETRY DATA

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Abstract – In modern railway systems, maintaining a high track quality is a key prerequisite for safe and efficient railway traffic operations. The Track Quality Index (TQI) serves as a quantitative indicator reflecting the technical and geometric properties of the track, forming the foundation for maintenance planning and intervention activities. This paper presents a comparative analysis of several TQI calculation methods to determine their advantages, limitations, and applicability across various contexts of railway infrastructure. The research evaluates three widely used methods for determining the track quality index: the Polish quality indicator (*J*), the multi-parameter unified index, and the percentage-based index. For the purpose of this analysis, all three methods were applied to a specific 5-kilometer railway section, utilizing available track geometry measurement data (longitudinal profile, gauge, alignment, and twist). The results demonstrate that while all three approaches show a high correlation in the overall assessment, they exhibit varying sensitivity to specific types of defects. The weighted-factor method (unified index) allows for a more precise identification of critical track locations, whereas the standard deviation-based approach is easier to apply and interpret but proves less informative in complex geometric deformation scenarios. The statistical approach provides a solid foundation for automated analysis, though it requires precise calibration of threshold values according to national or operator standards. The study concludes that there is no universally superior method for calculating the track quality index; rather, the selection of an appropriate methodology should depend on specific infrastructure management goals, data availability, and the required balance between accuracy and simplicity. The combined use of multiple methods is recommended for long-term planning, alongside the future development of a hybrid index that integrates the strengths of existing approaches for real-time track condition assessment.

Keywords – Track quality, Track Quality Index (TQI), Railway infrastructure, Track geometry, Track maintenance.

1. INTRODUCTION

The railway track represents a complex dynamic system subjected to stochastic and cyclic loading conditions. Under the continuous action of wheel-rail interaction forces, compounded by environmental factors and the natural consolidation of the ballast bed, progressive degradation of the designed track superstructure geometry occurs [1]. If left uncorrected, these deformations evolve into geometric defects that severely compromise traffic safety, accelerate rolling stock wear, and degrade passenger ride comfort [2].

To manage infrastructure budgets efficiently, modern railway infrastructure managers utilize automated monitoring systems, such as track recording cars, to calculate various quality indices [3]. However, a single, universally accepted index does not exist in global engineering practice. Different railway administrations apply mathematical models with varying sensitivities to local irregularities versus systemic track degradation [4]. This paper aims to address this gap in the comparative literature by parallel testing three established methodologies on a specific Montenegrin railway

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section characterized by demanding operational conditions.

2. PREVIOUS RESEARCH

The evaluation of track geometry quality using composite metrics has been a major focus of railway infrastructure research over the past few decades. Various international railway administrations have developed distinct mathematical formulations for Track Quality Indices (TQIs) to move away from evaluating isolated geometric defects toward a holistic assessment of track sections [5].

Early research primarily focused on using individual standard deviations of geometric parameters over specified segment lengths (typically 100 m to 200 m) to characterize track quality, as outlined in the historical development of the EN 13848 series [6]. Literature indicates that while standard deviation is an excellent indicator of systemic track degradation, its sensitivity varies significantly depending on whether the analyzed section is a straight track or a sharp curve [7].

Recent comparative studies have increasingly emphasized the limitations of relying on a single, local TQI methodology. Researchers have pointed out that different TQI formulations weight geometric parameters differently; for instance, some models place higher mathematical weight on vertical irregularities (longitudinal level), while others emphasize lateral deviations (alignment) [8]. Comparative analyses in European light rail and heavy rail systems demonstrate that applying different TQI models to the same dataset can lead to contrasting maintenance priorities. This variation underscores the necessity of testing and calibrating multiple established methodologies on specific corridor sections that exhibit complex operational and spatial constraints before selecting a definitive management metric.

3. TRACK GEOMETRY PARAMETERS AND NORMATIVE FRAMEWORK

In accordance with the EN 13848 standard series [9] and the TSI Regulation No. 1299/2014 [10], track quality is determined by five primary geometric parameters requiring continuous measurement and analysis:

- Track Gauge (G): The minimum distance between the inner running faces of the two rails, measured 14 mm below the running surface.
- Longitudinal Level (z_p): The vertical deviations of the longitudinal rail profile from its design geometry along both rails.
- Alignment (y_p): The horizontal (lateral) deviations of the rail running line relative to its design alignment.
- Cross Level (h): The height difference between the left and right rail heads, which is critical for balancing centrifugal forces in curves.
- Twist (v): The algebraic difference between two cross levels measured over a specific base (1 to 5 m), acting as a safety-critical parameter for derailment

prevention.

The EN 13848-5 standard establishes three strictly defined deviation limits for each parameter, depending on the operational speed class [11]:

- Alert Limit (AL): Defines thresholds where standard operational values are exceeded, utilized for scheduling routine maintenance.
- Intervention Limit (IL): Indicates conditions that affect ride comfort and accelerate component wear, requiring mandatory maintenance planning.
- Immediate Action Limit (IAL): The critical safety threshold regarding derailment risk, necessitating immediate technical repair or train speed restrictions [12].

4. MATHEMATICAL FORMULATIONS OF TRACK QUALITY INDICES (TQIS)

To transform raw, high-frequency spatial measurements from track recording cars into actionable infrastructure management data, composite indicators are required. This section presents the formal mathematical frameworks of the three compared methodologies, detailing how discrete geometry deviations are aggregated into unified indexes.

4.1. The Polish Quality Indicator (J)

The Polish methodology employs a multi-parameter composite index calculated based on the standard deviations (σ) of four fundamental track geometry parameters over a standardized section length [13]. The mathematical formulation is defined as follows:

$$J = \frac{\sigma_z + \sigma_y + \sigma_w + 0.5 * \sigma_e}{3.5} \quad (1)$$

where:

- σ_z is the mean value of the standard deviations of the longitudinal level measured on both rails,
- σ_y is the mean value of the standard deviations of the alignment measured on both rails,
- σ_w is the standard deviation of the track twist,
- σ_e is the standard deviation of the track gauge.

Tab. 1. Classification of track quality based on the Polish J indicator

Track Qual. Class	Threshold Range	Maintenance Implications and Actions
Excellent	$J < 1$	Stable track geometry; no intervention required.
Good	$1 \leq J < 2$	Standard condition; routine monitoring.
Satisfactory	$2 \leq J < 3$	Acceptable state; baseline maintenance scheduling.
Poor	$3 \leq J < 4$	Accelerated degradation; triggers priority remediation planning.
Very Poor	$J \geq 4$	Critical state; necessitates immediate corrective action.

The denominator (3.5) acts as a normalization constant derived from empirical operational thresholds. Based on the calculated J value, the track quality is categorized into five distinct structural condition classes, as defined in Table 1.

4.2. Multi-Parameter Unified Combined Index (CI)

A known limitation of traditional standard deviation aggregates is their inability to compensate for the different physical units and nominal boundaries of distinct geometric parameters. The Unified Combined Index (CI) addresses this by introducing a normative normalization technique [14], where each parameter's standard deviation (σ_i) is scaled directly against its maximum allowable tolerance threshold (T_i) specified by the EN 13848-5 standard for the line's corresponding speed class:

$$CI = \sum_{i=1}^n \frac{\sigma_i}{T_i} \quad (2)$$

where

- σ_i represents the standard deviation of parameter i ,
- T_i denotes the normative EN 13848-5 boundary limit (such as the Alert Limit or Intervention Limit) for that specific parameter, and
- n is the total number of evaluated geometry metrics ($n=5$).

This dimensionless formulation mathematically benchmarks localized track degradation directly against regulatory European reference framework constraints.

4.3. Percentage Track Quality Index (PTQI)

In contrast to variance-based indicators (σ) that focus on average defect amplitudes, the Percentage Track Quality Index (PTQI) evaluates the continuous spatial frequency of geometric non-conformities [15]. It operates fundamentally as a spatial binary filter that quantifies the exact proportion of discrete measurement coordinates where the geometry violates predefined structural tolerances over the entire length of the segment:

$$PTQI = \left(\frac{N_{exceed}}{N_{total}} \right) * 100\% \quad (3)$$

where:

- N_{exceed} represents the total number of discrete sampling points along the track segment where at least one geometric parameter simultaneously violates the normative tolerance limit (AL or IL),
- N_{total} is the cumulative number of discrete spatial matrix points generated during the recording run.

A PTQI value approaching 100% indicates near-absolute spatial degradation along the route, demonstrating that geometric anomalies are continuous throughout the asset's length, irrespective of whether individual peak amplitudes are localized or systemic.

5. CASE STUDY AND DATA PREPARATION

5.1. Description of the Analyzed Railway Section and Data Acquisition

The empirical evaluation of the three TQI methodologies is conducted using real-world track geometry data obtained from a specific section of the Vrbnica–Bar railway line in Montenegro. The analyzed corridor is located between km 38+570 and km 39+000, comprising a total length of 430 meters. This particular section faces demanding operational environments and significant geometric challenges. To evaluate the track quality over time, historical geometry datasets from two distinct measurement years—2022 and 2024—are utilized. The track geometry during both measurement campaigns was recorded using the same specialized Sever 1435 track recording car. Using the exact same diagnostic vehicle ensures that the spatial resolution, sensor filtering, and baseline measurement conditions are fully identical, providing a mathematically robust and highly comparable temporal framework for analysis.

5.2. Data Structuring and Matrix Formulation

The raw geometric signals recorded by the Sever 1435 car along the analyzed 430-meter section are structured into a continuous spatial dataset. For the mathematical calculation of the indices, the dataset captures four primary geometric parameters: track gauge (G), longitudinal level (z_p), alignment (y_p), and track twist (v). To perform the parallel evaluation, the discrete measurement points from both 2022 and 2024 are processed through the mathematical filters of the Polish Quality Indicator (J), the Unified Combined Index (CI), and the Percentage Track Quality Index ($PTQI$). This structured approach ensures that all three models are evaluated against the exact same spatial matrix across both historical years, allowing for a direct and objective comparative analysis of their calculation sensitivities.

6. RESULTS AND DISCUSSION

The mathematical processing of the geometry datasets recorded by the Sever 1435 track recording car yielded distinct numerical trends for each of the three evaluated TQI models. The aggregated calculation results for both historical periods are systematized in Table 2.

Tab. 2. Comparison of TQI Results for 2022 and 2024

Evaluated Index / Parameter	Year 2022	Year 2024	Qualitative Condition Assessment
Polish Indicator (J)	4.64	4.34	Degraded State (Class V to Class IV)
Unified Combined Index (CI)	15.11	6.36	Significant Deviations (Poor Condition)
Percentage TQI ($PTQI$)	99.61%	99.69%	Critical Spatial Degradation (>99%)

6.1. Analysis of the Divergence Phenomenon and Model Sensitivity

A detailed analysis of the results uncovers a highly compelling engineering and mathematical phenomenon: a clear divergence in index behavior between the two observed timelines. The variance-based metrics—namely the Polish Indicator (J) and the Unified Combined Index (CI)—both exhibited a numeric reduction, signaling an apparent improvement in track geometry quality. The J value shifted downward from Class V (Critical) toward the upper boundary of Class IV (Poor), while the CI index dropped sharply from 15.11 to 6.36. Mathematically, this behavior is strictly governed by the nature of standard deviation (σ). If localized maintenance interventions or spot repairs were executed on the section between 2022 and 2024 to eliminate a few extreme isolated defects (peak amplitudes), the standard deviation decreases drastically. Consequently, these two indices reflect an overall reduction in peak variance, suggesting a better asset condition. Conversely, the Percentage Track Quality Index (PTQI) did not follow this improving trend; instead, it registered a slight marginal increase from 99.61% to 99.69%. This contrasting behavior highlights the structural nature of the PTQI as a spatial binary filter. Even though isolated maintenance might have successfully capped the maximum peak amplitudes (thereby dropping the CI and J values), nearly every single discrete sampling point along the 430-meter section on the 25 cm grid still violates the regulatory EN tolerances (AL or IL boundaries). This proves that variance-based indices (J and CI) can inadvertently mask systemic wear if isolated severe defects are repaired, whereas the percentage-based methodology (PTQI) remains highly resilient against localized data shifts, providing an objective representation of continuous, systemic track superstructure degradation.

7. CONCLUSION

This paper presented a comparative evaluation of three distinct Track Quality Index (TQI) methodologies: the Polish Indicator (\$J\$), the Unified Combined Index (\$CI\$), and the Percentage Track Quality Index (\$PTQI\$). These models were applied to real-world track geometry data from a 430-meter section of the Vrbnica–Bar railway line in Montenegro. The analyzed datasets were recorded across two distinct timelines, 2022 and 2024, utilizing the same Sever 1435 track recording car. The analytical results demonstrate a significant divergence in index behavior, highlighting the unique mathematical sensitivities of each model:

- The variance-based metrics (J and CI) exhibited a numerical reduction, implying a false or localized improvement in track quality due to their extreme sensitivity to the suppression of peak amplitudes via isolated spot repairs.
- The spatial frequency metric (PTQI) remained stagnant in a critical zone (>99%), acting as a robust

binary filter that successfully captured continuous, systemic geometric degradation across the entire asset length.

Ultimately, the study underscores that no single index can universally address all infrastructure asset management requirements. While variance-based indicators are highly effective for high-speed lines where passenger comfort depends on capping amplitude spikes, the percentage-based approach (PTQI) provides an invaluable and objective tool for conventional and highly stressed corridors, ensuring that systemic structural wear is not masked by localized maintenance interventions.

REFERENCES

- [1] Dahlberg, T. (2001). "Some railroad track dynamics-related research topics: a review." *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 215(3), 143-159.
- [2] Zhai, W., Wang, K., & Lin, J. (2004). "Modelling and simulation of vehicle-track coupled dynamics." *Vehicle System Dynamics*, 41(sup1), 213-222.
- [3] Alfelor, R. M., Carr, G., & Resendiz, M. (2010). "Using track geometry data to measure track quality and performance." *Joint Rail Conference, American Society of Mechanical Engineers*, Vol. 43956, 443-451.
- [4] Sadeghi, J. (2002). "Development of track quality index." *Journal of Transportation Engineering*, 128(4), 392-400.
- [5] Esveld, C. (2001). *Modern Railway Track*. MRT Productions.
- [6] European Committee for Standardization (CEN). (2017). EN 13848-5: Railway applications - Track - Track geometry quality - Part 5: Geometric quality levels - Plain line, switches and crossings. Brussels, Belgium.
- [7] Soleimanmeigouni, I., Ahmadi, A., & Letot, C. (2018). "Cost-effective maintenance planning for railway track geometry." *Journal of Quality in Maintenance Engineering*, 24(2), 198-217.
- [8] Sadeghi, J., & Askarinejad, H. (2011). "Development of an improved zone-based track quality index." *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 225(2), 115-125.
- [9] European Committee for Standardization (CEN). (2019). EN 13848-1: Railway applications - Track - Track geometry quality - Part 1: Characterisation of track geometry. Brussels, Belgium.
- [10] European Union. (2014). "Commission Regulation (EU) No 1299/2014 of 18 November 2014 on the technical specifications for interoperability relating to the 'infrastructure' subsystem of the rail system in the European Union." *Official Journal of the European Union*, L356, 1-110.
- [11] European Committee for Standardization (CEN). (2017). EN 13848-5: Railway applications - Track - Track geometry quality - Part 5: Geometric quality levels - Plain line, switches and crossings. Brussels, Belgium.
- [12] Andrade, A. R., & Teixeira, P. F. (2011). "A Bayesian model to predict track geometry degradation." *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 225(2), 151-160.
- [13] Bałuch, H., & Bałuch, M. (2010). Determining the layouts of synthetic track quality indices. *Instytut Kolejnictwa (Railway Research Institute)*, Warsaw.
- [14] Madejski, J. (2017). "Synthetic indices of track geometry condition." *Rail Vehicles*, (3), 32-41.
- [15] Lasisi, A., & Attoh-Okine, N. (2018). "Principal component analysis (PCA) and track quality index (TQI) – A necessary variance-frequency combination." *Construction and Building Materials*, 186, 1269-1277.



WELDING OF COGIDUR BLOCKS (1.8715 GROUP 3.2) WITH SELF-SHIELDING WIRE-PROCESS 114

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Abstract – This paper presents the welding technology used for a tramway turnout, whose main components are Cogidur blocks (material No. 1.8715, Group 3.2). The blocks are joined by a butt weld using copper backing plates and a self-shielded flux-cored wire, employing the 114 welding process. The paper also provides an overview of the inspection and testing performed on the welded joint, including visual testing (VT), penetrant testing (PT), ultrasonic testing (UT), hardness testing, and macrographic examination of the weld cross-section.

Keywords –tramway turnout, Cogidur block(s), self-shielded flux-cored wire.

1. INTRODUCTION

The processes used for joining tramway switch components in accordance with EN 14811 are as follows:

- aluminothermic welding (AT);
- electric resistance welding (ET);
- flux-cored arc welding with self-shielded wire (FCAW);
- MAG welding using solid wire with inert gas shielding (MAG-IBE).

Electric resistance welding (ET) of rails is predominantly used under workshop conditions, although mobile welding equipment for on-site applications is also available. Nevertheless, aluminothermic welding (AT) remains the most commonly used rail welding process, both in workshops and in the field. Since 1996, self-shielded flux-cored arc welding (FCAW) has also been applied for rail joining. With the approval of Deutsche Bahn AG, the American company Lincoln Electric developed and introduced this process for welding railway switch components made of rail steels with tensile strength values ranging from ($R_m=685 \text{ N/mm}^2$) to ($R_m=885 \text{ N/mm}^2$). The process was intended for railway lines with axle loads of up to 10 t and operating speeds below 80 km/h.

Since self-shielded FCAW is an American welding technology, the consumables and welding equipment required for this process have traditionally been manufactured in the United States of America (USA). In Europe, particularly in France, there was a growing interest in developing a European-based technology for welding tramway switch components, using welding consumables and equipment manufactured in Europe.

This led to the development of a rail and block welding process based on the MAG welding process. In this technology, a specially designed extension is fitted to the welding torch, enabling welding to be performed within grooves with depths exceeding 150 mm.

2. EXPERIMENT

2.1 Base Material

During the fabrication of tramway switches at crossing sections, the rails were replaced with Cogidur (Hardox 400) blocks due to their higher hardness. Following welding, a groove is machined into the blocks to reproduce the rail groove geometry.

The block material is Cogidur (1.8715, Group 3.2), with a hardness exceeding 400 HB.

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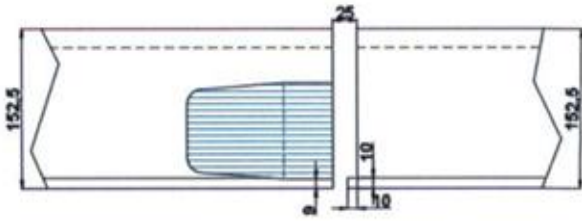


Fig 1. Joint preparation drawing of the blocks

Table 1. Chemical composition of the base material

Basic material	C %	Mn %	Si %	Ni %	Cr %
Cogidur	0,17	1,3	0,42	0,47	1,8
Basic material	Mo %	Ti %	V %	Cu %	Fe %
Cogidur	0,1	0,005	0,003	0,35	0,001

Table 2. Mechanical properties of the base material

Basic material	Rm N/mm ²	Rv N/mm ²	L %	Pv (J)	Hardness HB
Cogidur	1355	1005	13	-40°C 53J	414-427

2.2 Methodology

Prior to welding, the blocks are positioned with a root gap of 25 mm. The edges of the blocks are ground to a bright metallic surface. After verifying the alignment and concentricity of the blocks, clamps are installed to maintain the specified distance accurately.

Copper backing plates are then positioned on both sides of the blocks, while a grooved copper backing plate is previously installed underneath the joint. Prior to welding, the blocks are preheated using a propane-butane gas torch over a length of 500 mm on each side of the joint. This procedure ensures that the material is adequately preheated through the thickness of the blocks.

The preheating temperature is maintained at 150 °C, with a maximum permissible temperature of 200 °C. Following preheating, the blocks are welded using two passes. The copper backing plates are then removed, and an additional welding pass is deposited.



Fig 2. Preheating of the joint



Fig 3. Preheating temperature control

Since the copper backing plates are installed after the initial preheating, the joint is reheated due to heat loss and subsequent cooling of the material. Positioning the copper backing plates on a previously heated joint is difficult to perform and requires a high level of welder skill. The temperature of the block material is therefore measured, and provided that the measured temperature does not deviate by more than 10% from the recommended value, welding is continued.

Welding is performed continuously until approximately 30 mm of the joint height remains unwelded. At this stage, the copper backing plates are removed, and the weld is cleaned of slag using a pneumatic tool equipped with vibrating wires.

The remaining 30 mm of the joint height is welded using stainless steel electrode wire by the

MAG-IBE process. In the SS-FCAW process, this section is deposited using a self-shielded hardfacing wire with a hardness of approximately 30 HRC.

Throughout the welding process, the welding current is continuously monitored, with deviations kept to a minimum relative to the values specified in the WPS.

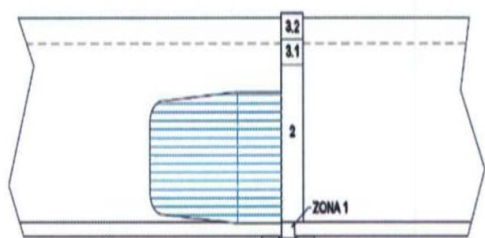


Fig 4. Welded joint – cross-sectional view along the joint height

2.3 Welding Consumables for the Joint

For welding the Cogidur blocks using the MAG-IBE process, an electrode wire conforming to EN 14341-A, classification G42 5 M/CG3Si1, commercially designated OK AristoRod 12.50, with a diameter of Ø1.2 mm, was used.

The final 30 mm of the joint was welded using stainless steel electrode wire conforming to EN 14343-A, classification G 18 8 Mn, commercially designated OK Autrod 16.95, with a diameter of Ø1.2 mm.

Table 3. Chemical composition of the welding consumables

Additional material	C %	Si %	Mn %	P %	S %
OK AristoRod 12.50	0,07	0,8	1,46	0,009	0,01
OK AutRod 16.95	0,08	0,9	6,9	0,03	0,01

Additional material	Cr %	Ni %	Mo %	Cu %	Ti %
OK AristoRod 12.50	0,02	0,01	0,01	0,02	/
OK AutRod 16.95	19,0	8,1	0,02	/	/

Table 4. Mechanical properties of the welding consumables

Additional material	Rm (N/mm ²)	Rv (N/mm ²)	Izduženje (%)	Pv (J)
OK	560	480	26	-40°C

AristoRod 12.50				60
OK AutRod 16.95	640	450	41	-20°C 130

For welding the Cogidur blocks using the SS-FCAW process, a self-shielded flux-cored electrode wire conforming to EN 17632, classification T 38 Z V N3, commercially designated NS 3M, with a diameter of Ø2.0 mm, was used. The final 30 mm of the joint was deposited using a self-shielded hardfacing electrode wire conforming to EN 14700, classification T Fe 1, commercially designated Lincore 33, with a wire diameter of Ø2.0 mm.

Table 5. Chemical composition of the welding consumables

Additional material	C %	Si %	Mn %	Al %	Cr %
Innershield NS-3M	0,2	0,26	0,36	1,36	/
Lincore 33	0,15	0,7	2,0	1,6	2,0

2.4 Welding

Two welding techniques are used. In the first technique, the electric arc is directed along the centerline of the joint, while welding is performed at higher current levels.

The second technique employs lower welding currents, while the electric arc is directed toward one side of the joint during one pass and toward the opposite side during the subsequent pass. This technique enables greater penetration into the side walls of the joint.



Fig 5. SS-FCAW welding process

The preheating temperature for the specimen welded using the MAG-IBE process was 200 °C, whereas for the SS-FCAW welding process, the preheating temperature was 150 °C.

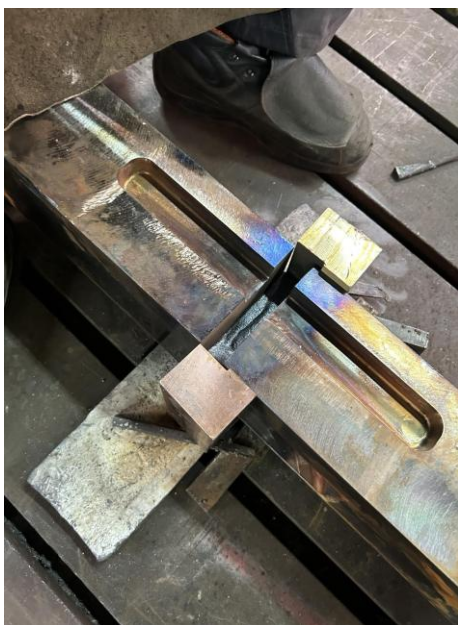


Fig 6. Appearance of the welded joint prior to hardfacing

After welding using the MAG-IBE process, the specimen is post-heated to a temperature of 200 °C and maintained at this temperature for 1 h. It is subsequently covered with a heat-resistant blanket and allowed to cool slowly. In the case of the SS-FCAW process, no post-heating is applied after welding; however, the specimen is covered with a heat-resistant blanket to ensure controlled cooling. The welding parameters for the MAG-IBE process are specified in the WPS. The welding current ranges from 250 A to 270 A, while the arc voltage is approximately 29 V. The welding speed ranges from 25 cm/min to 27 cm/min, depending on whether the root section or the final passes of the joint are being welded. The heat input ranges from 1.22 kJ/mm to 1.39 kJ/mm.

The welding parameters for the SS-FCAW process are specified in the WPS. The welding current ranges from 300 A to 320 A, while the arc voltage is approximately 30 V. The welding speed ranges from 22 cm/min to 24 cm/min, depending on whether the root section or the final passes of the joint are being welded. The heat input ranges from 1.83 kJ/mm to 2.09 kJ/mm.



Fig 7. SS-FCAW welded specimen

3. RESULTS AND DISCUSSION

3.1 Non-Destructive Testing

Twenty-four hours after welding, a visual and dimensional inspection was performed, covering both the welded joint itself and the parallelism of the blocks, as well as any possible deformation or shrinkage.

Subsequently, the welded specimens were subjected to liquid penetrant testing and ultrasonic testing. A critical stage occurs when the copper backing plates are removed and, following cleaning and preheating, welding is resumed. At this stage, welding imperfections such as lack of fusion and non-metallic inclusions may occur.

3.2 Destructive Testing

Since the results of the non-destructive testing of the specimens were satisfactory for both welding processes, the specimens were subjected to destructive testing, including macrostructural examination and hardness testing.

The specimen welded using the MAG-IBE process was additionally subjected to a dynamic fracture test under cyclic loading.

The destructive testing was performed by RD Dijagnostika d.o.o., Belgrade, a laboratory authorized by TÜV SÜD Industrie Service GmbH



Fig 8. Ultrasonic testing of the welded joint

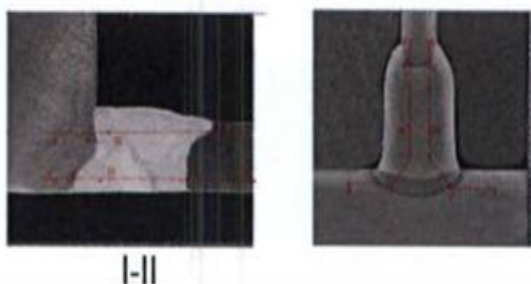


Fig 9. Macrosection of the specimen welded using the MAG-IBE process



Fig 10. Macrosection of the specimen welded using the SS-FCAW process

3.3 Hardness Testing (MAG-IBE Process)

Table 7. Hardness test results

Art./Last: - Type / Load: - Type / Charge: HV 10 – nur Informationen / only information

Nr. No.	Meßreihe Measuring Line Ligne de mesure	Grundwerkstoff Base Material Métal de base	WEZ HAZ ZAT	Schweißgut Weld Metal Métal déposé	WEZ HAZ ZAT	Grundwerkstoff Base Material Métal de base
366/24	1-5-11-7-3	423 425 420	212 214 216	161 164 158	225 224 221	430 428 427
366/24	2-6-13-8-4	426 419 422	215 218 219	163 161 157	218 216 220	431 426 424
366/24	1-5-11-7-3	421 420 425	214 212 215	159 157 155	224 220 218	432 430 427
366/24	2-6-13-8-4	420 421 427	218 220 221	161 162 158	219 223 225	428 427 424
366/24	1-5-11-7-3	414 424 426	208 210 212	158 156 154	224 221 218	420 424 425
366/24	2-6-13-8-4	422 425 427	211 213 215	159 161 163	216 214 217	415 417 419
366/24	1-5-11-7-3	417 419 421	210 212 215	157 159 161	215 217 218	421 419 417
366/24	2-6-13-8-4	415 414 418	213 216 218	155 157 159	210 212 214	414 415 418

Table 8. SS-FCAW process

HÄRTEPRÜFUNG EN ISO 9015 *)
HARDNESS TEST *) - ESSAI DE DURETÉ *)

Lage der Messungspunkte (Stellen) *)
Location of measurement points (Stellen) *)

Art./Last: - Type / Load: - Type / Charge: HV 10 (Anforderung / requirement: max. - 425 HV)

Nr. No.	Meßreihe Measuring Line Ligne de mesure	Grundwerkstoff Base Material Métal de base	WEZ HAZ ZAT	Schweißgut Weld Metal Métal déposé	WEZ HAZ ZAT	Grundwerkstoff Base Material Métal de base
1114/24	1-5-11-7-3	378 386 381	336 337 340	301 304 305	344 348 351	388 392 401
1114/25	2-6-13-8-4	358 380 408	319 330 342	311 318 321	305 369 378	377 384 398

3.4 Fracture Testing

A load test was performed on a CQB429 AWBW Cogidur-to-Cogidur-VMS specimen in accordance with procedure T15002P01. The specimen had a total length of 1200 mm and was welded using the MAG-IBE process at VOSSLOH MIN SKRETNICE d.o.o., Niš.

The four-point bending test was carried out at the Vossloh Cofiger Technology Center in Reichshoffen, France. The distance between the supports was 1100 mm, while two laser sensors were used to measure the displacement amplitude.

Prior to testing, the hydraulic cylinder was certified and the laser sensors were calibrated. The maximum applied stress was 130 MPa, with a stress amplitude ranging from 13 to 130 MPa. The test consisted of 3,000,000 cycles at a frequency of 5 Hz. The test was conducted from 24 June to 1 July 2024.

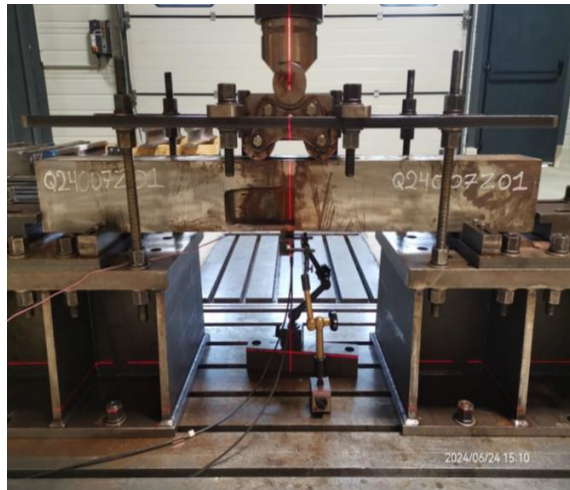


Fig 11. Fracture testing apparatus

Following the fracture test, no cracks were detected in the welded joint, indicating that the welding procedure was successfully performed.

A fracture test of the Cogidur specimen itself was not performed, since fracture testing of rail-to-rail and rail-to-Cogidur block specimens had previously been conducted. Both specimens successfully passed the fracture test. The rail-to-rail specimen withstood 5,200,000 cycles, after which a crack appeared in the welded joint; however, the crack length was less than 3 mm.

4. CONCLUSIONS

Welding using the MAG-IBE process is considerably more demanding than welding using the self-shielded FCAW process. This is primarily due to the lower heat input associated with the MAG process, which increases the likelihood of lack of

fusion at the side walls of the joint.

In addition, productivity is significantly lower for the MAG-IBE process than for the SS-FCAW process. The SS-FCAW process also requires a lower preheating temperature and does not require post-heating of the welded specimen. The hardness measured in the heat-affected zone (HAZ) is considerably lower for the MAG-IBE process, ranging from 210 to 225 HV, whereas for the SS-FCAW process it ranges from 311 to 370 HV. However, the SS-FCAW process provides significantly greater penetration into the side walls of the joint. This is consistent with the higher heat input values: 1.22–1.39 kJ/mm for MAG-IBE compared with 1.83–2.09 kJ/mm for SS-FCAW.

Based on the results presented above, it can be concluded that the SS-FCAW process provides greater reliability and productivity and is less sensitive to variations in welding technique and strict control of the welding parameters.

If the MAG-IBE process is applied, the use of a 1.6 mm diameter welding wire could be considered in order to increase the heat input and, consequently, improve penetration into the side walls of the joint.

REFERENCES

- [1] Atlas of Fatigue Curves, ASM International, Materials Park, Ohio 44073-0002.
- [2] Kralj, S., Dunder, M., "Ispitivanje sklonosti zavarenih spojeva čelika 25CrMo4 i Ck45 prema nastajanju hladnih pukotina," Zavarivanje (0044-1902), Vol. 43, No. 1/2, 2000, pp. 5–16.
- [3] Kou, S., Welding Metallurgy, 2nd ed., John Wiley & Sons, New York, USA, 2002.

TGPS+ TRACKING OF FREIGHT FLOWS, TRAIN MOVEMENTS AND RECORDS IN RAIL FREIGHT TRANSPORT

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Života ĐORĐEVIĆ³

Abstract – Rail freight transport is an efficient and environmentally favourable mode for moving large and heavy consignments over long distances. It includes wagonload, block-train, combined and intermodal transport, as well as dangerous, exceptional and oversized consignments. Although GPS systems are commonly used for train positioning, location data are often not integrated with the operational records maintained by railway undertakings. TrainGPS+ (TGPS+) is a multilingual enterprise system that links train and freight data with real-time telemetry, enabling tracking, operational control and generation of statistical reports.

Keywords – freight, GPS, tracking, reports, records.

1. INTRODUCTION

Railway undertakings and transport organizers require real-time information on freight movement and status at border, departure and intermediate operating points. TGPS+ addresses this need by linking the train consist with satellite tracking through the locomotive, providing current status data and a basis for reporting and operational control. Each train consist is identified by a unique Transport Consignment Number (TBP), which remains unchanged along the route regardless of train number, station operations, locomotive changes or crew changes. Wagons and freight are linked to the TBP through the train list/S-3 document and to movement data through the locomotive. This enables continuous positioning of wagons and freight, freight-flow monitoring and movement history.

2. TGPS + SYSTEM



Fig. 1. Architecture and main functionalities of the TGPS Plus system

Train GPS+ (TGPS+) is a multilingual enterprise system for real-time telemetry and tracking of trains and freight. Its main components are:

- TGPS+ Server Frontend: central data hub for dispatchers, observers and controllers according to carrier procedures.
- TGPS+ Server Backend: CMS for managing users, permissions, routes, personnel, locomotives and wagons.
- TGPS+ Android application: used by drivers to report train activities, enter S-1 explanations and automatically transmit location.
- TGPS+ Station Android application: used by station staff to prepare and update train lists.

2.1. TGPS+ Server (Website/Web) Backend

Opening the TGPS+ Server link displays the administration screen and menu shown in Fig. 1.

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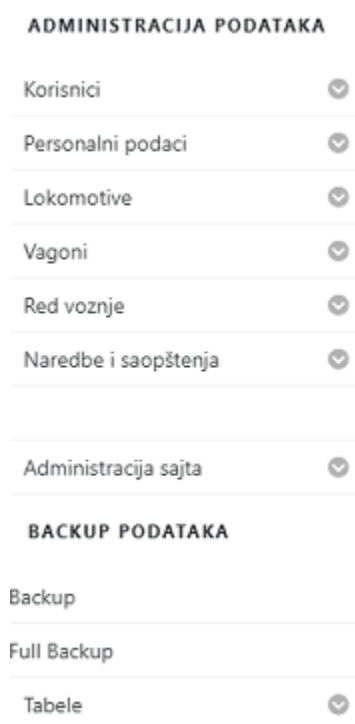


Fig. 2. TGPS+ Server administration menu

In addition, the server database contains data on stations, line numbers, station chainage, GPS coordinates and polygons defining station areas, based on working timetable documents and the infrastructure manager network statement, together with a rule table used for working-time calculation.

These data are prerequisites for operation of the system.

2.2. TGPS + Server (Website/Web) Frontend

The menu of this part of the system contains the options shown in Fig. 3.

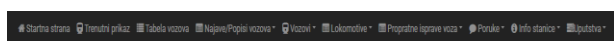


Fig. 3. Main navigation menu of the TGPS Plus web application

The most important option is the train announcements/train lists submenu, particularly the New announcement/list function.

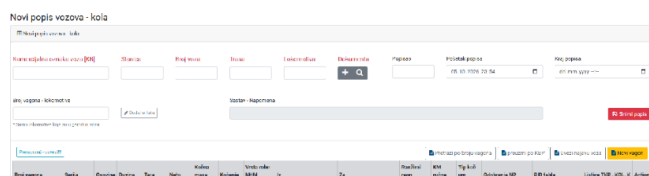


Fig. 4. Interface for creating a new train composition in the TGPS Plus web application

In the form shown in Fig. 3, the train announcement received from the transport organizer or CIT-23 is entered together with the TBP, receiving or train-forming station, train number and locomotive

data, if known when the train list is created.

Train-consist data can be imported from predefined XLS tables for a standard consist, a container train or an individual wagon, including data on freight, wagons and containers.

For larger transport operations, an electronic CIT-23 received from the transport organizer can also be imported directly into the train list.

Documents accompanying the train can also be uploaded to the server as image, PDF, DOC or other supported file formats.

After the train list is saved, the system automatically generates the S-3 train consignment document, the S-4 train composition and braking report, K-200 and KOL-65. If wagons are added or removed, or a brake is isolated, saving the change automatically updates all generated S-3, S-4, K-200 and KOL-65 documents.

The S-4 document is generated so that the braking-type field is selected according to the train mass.

ИЗВЕШТАЈ О СASTAVУ И КОЧЕЊУ ВОЗА				
За воз бр. 40873		од 04.10.2026 18:38		
1.	Маса воза:	1066.9+120 = 1186.9 t		
2.	Број осовина:	15 kola / 60 осовине	Дужина воза 210.6 m	
3.	Врста кочења воза	P 40 [%]		
	P (RIC) R	G	P+G	РУЧНО
	ваздушно брзим дејством	ваздушно спирал дејством	ваздушно механичким дејством	
4.	Количина кола са	коч. пачуцама од композит. матер.	(K) (LL) (L)	15
5.	Стање кочних маса	ПКМ 475	СКМ 787.5+787	
6.	Положај мањача кучић возила	(G) P R		
7.	Употреба пачуца	ДА НЕ		
8.	Где су укривљена кола товарена дугачким предметима спојена кљачицом			
9.	Где су укривљена кола товарена оквирним теретом			

ПРИМЕДБА:

Fig. 5. Example of a train composition and braking report generated by the TGPS Plus system

If the train list is generated by the dispatcher and the locomotive and train number are known, once the locomotive is assigned and the Android application is started, the driver immediately receives the train number and TBP and the system links them.

If the locomotive is already crewed but the train list has not yet been created, entering the train number causes the system to assign a temporary TBP in the format PNNNN and reserve an entry that can later be completed.

2.3. TGPS+ Android Application

The application is installed on the locomotive tablet and is used to transmit current movement parameters. It sends the following data to the server:

- Geographic location;
- Train position;
- Time;
- Speed;

- Train activities and explanations for intermediate delays.

In addition, when linked to the locomotive, the application enables:

- Recording of locomotive handover, takeover and crew changes;
- Transfer of locomotive mileage and fuel quantities at takeover, handover and refuelling;
- Activation of an alarm to the driver by the dispatcher or sending a message to the dispatcher;
- Supervision of locomotive and crew operation by authorized observers through the web interface.

The two basic application screens are shown below.

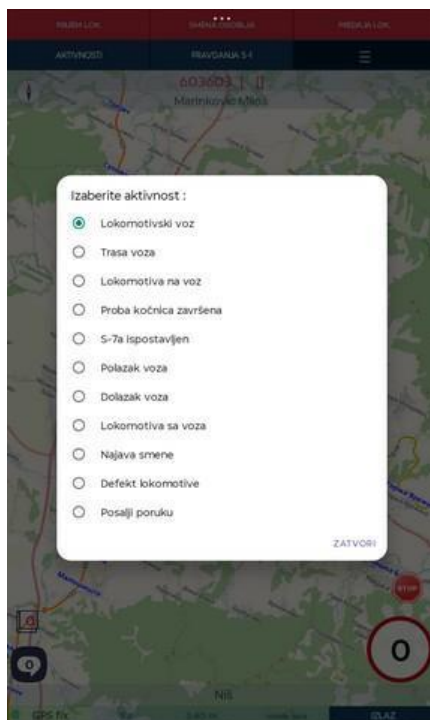


Fig. 6. Activity selection interface in the TGPS Plus mobile application

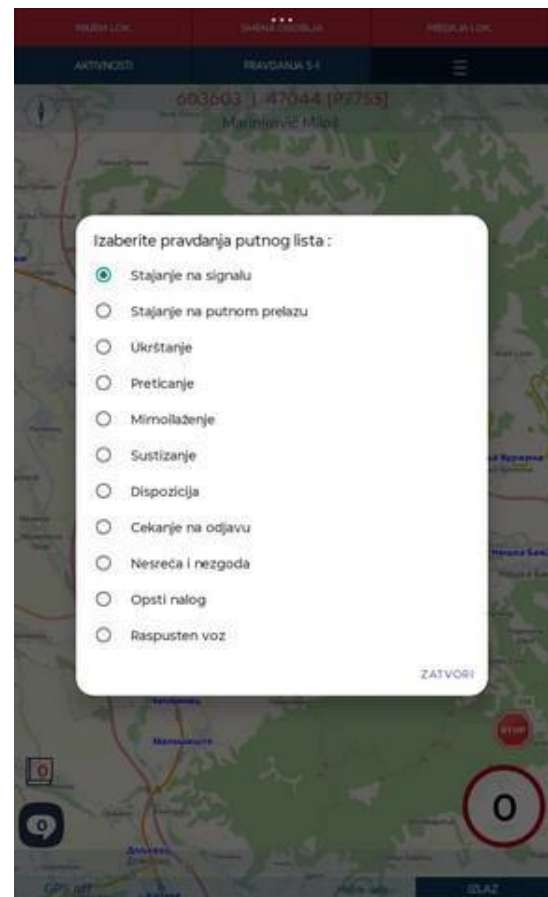


Fig. 7. Interface for selecting the reason for travel order justification in the TGPS Plus mobile application

By selecting and confirming an option, the information is sent to the TGPS+ server without any additional text entry. This reduces driver interaction with the device and allows attention to remain focused primarily on driving and traffic operations.

2.4. TGPS+ Station Android Application

The TGPS+ Station application is intended for station staff responsible for preparing train lists. In accordance with the railway undertaking procedures, the staff member can prepare a list while forming a train consist or modify a previously prepared list using the individual-wagon form.

Fig. 8. Wagon data entry interface

The entered data are immediately transferred to the server and the current status is updated.

3. SYSTEM NOTES

Communication between system components is interactive and bidirectional.

If the internet connection to the server is interrupted, data are stored locally on the tablet or phone and transmitted when the connection is restored.

Administration and reporting are handled through the CMS panel, including automatic e-mail notifications and urgent SMS alarms.

Required equipment includes one 8–10 inch Android 14–15 tablet with a SIM slot per locomotive, plus a leased domain and web server.

Mobile printers may additionally be used to print S-3 and S-4 documents at locations without carrier offices.

4. OUTPUT REPORTS AND SYSTEM RECORDS

- Attachments to the S-1 journey form: S-3 and S-4
- K-200 and KOL-65
- Crew working time with graphical presentation by day and period
- Locomotive mileage with graphical presentation by day and period
- Diesel-locomotive refuelling and fuel status at takeover and handover
- Tabular and graphical train-movement tracking
- Tabular and graphical train-stop tracking
- Train-speed XY diagram
- Routes-used report
- Gross tonne-kilometre report
- Freight-flow tracking by commodity and route
- Wagon-movement overview
- Monitoring of technological operations at stations
- Tracking of dangerous goods (RID), exceptional

consignments and wagon defects through additional fields in the train list and S-3 document, including approval numbers and AVV/GCU Appendix 9 defect codes.

5. CONCLUSION

By linking freight, wagons, trains and locomotives in real time, TGPS+ enables rapid information exchange, tracking and operational control with timely intervention.

Movement data and train documents are archived electronically on the web server and can be accessed remotely.

The system can exchange data electronically with other railway undertakings and transport organizers using agreed protocols.

It also supports direct communication between locomotive crews and dispatchers or other authorized staff.

Human error is reduced by checking personnel prerequisites and automatically setting expired qualifications or conditions to inactive status.

Automatic e-mail notifications and urgent SMS alarms enable fast transmission of important information.

Monitoring the duration of technological operations at departure and intermediate stations helps identify recurring delays and locations requiring corrective action.

Train-speed diagrams and explanations for stops or passage over malfunctioning level crossings help detect irregularities and support timely action to improve traffic safety.

The system is aligned with:

- Railway Directorate secondary legislation;
- the General Contract of Use for Wagons (GCU/AVV);
- CIT (International Rail Transport Committee);
- the COTIF Convention and CIM consignment note;
- RID regulations for dangerous goods by rail.

This ensures conformity with the relevant railway regulatory framework.

A planned wagon-inspector module will further complete the system from traffic and technical perspectives.

TGPS+ is expected to improve carrier efficiency, reduce operating costs and raise service quality with relatively low initial investment. With carrier-specific adaptation, it provides a practical solution focused on freight as the core revenue-generating element of rail freight transport.

Vehicle and Infrastructure Maintenance



SMART RAIL VEHICLE MONITORING: A STUDY OF CNN ARCHITECTURES

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Abstract – This paper presents performance analysis of two deep learning architectures for object detection YOLOv2 and YOLOv4-Tiny aimed at identifying the model state for inspecting the braking systems of Series 441 and 444 locomotives. These models were trained and evaluated using a unified dataset comprising images of 3220 Braking system, as well as instances where these components were absent. Model evaluation was conducted using standard metrics, with a particular focus on the Precision-Recall curve and Average Precision (AP). Experimental results demonstrate that the YOLOv2 architecture achieving a high AP value of 0.97199 after 700 training iterations, accompanied by rapid loss function convergence. In contrast, YOLOv4-Tiny achieved stable convergence after 2500 iterations but yielded a lower AP value of 0.92546. These findings indicate that YOLOv2 can deliver superior performance and higher precision in object detection tasks where fine details are not the primary focus, while simultaneously significantly reducing the demand for complex computational resources.

Keywords – Monitoring, object detection, YOLOv2, YOLOv4-Tiny, locomotive braking systems.

1. INTRODUCTION

The concept of smart maintenance of rail vehicles has become a pillar of the modernization of modern railway transport. In systems where safety does not allow for compromises, such as locomotive braking systems, the transition from periodic manual inspections to automated, continuous inspection is a technological imperative [1,2]. Brake shoes and their fuses are exposed to extreme mechanical and thermal stresses, which is why their damage or falling out directly threatens the stability of the train and traffic safety. Nevertheless, the visual inspection of these components on the undercarriage still relies predominantly on the human factor, which slows down processes in the depot and increases the risk of oversights due to controller fatigue. With the advent of Industrial Revolution 4.0, computer vision and deep learning algorithms have transformed material and component inspection systems [3,4]. Convolutional neural networks made it possible to automate the process of recognizing anomalies with a precision that rivals that of a human, but with a

drastically higher speed [5,6,7]. The key challenge in practice is no longer just achieving high accuracy, but finding computationally efficient models that can be successfully implemented in the field, often on hardware with limited performance [8,9].

This paper analyzes and provides a solution to the problem through the development and evaluation of a system for automatic detection of brake system elements on electric locomotives series 441, 444 and 461. In the paper, a robust detection model was developed based on the analysis of a unique set of 3220 photos, which includes correct conditions, but also critical situations of the absence of brake shoes or fuses. The research focus is set on a rigorous comparison of two architectures of different generations: YOLOv2 and YOLOv4-Tiny. Through the analysis of convergence speed, loss functions and precision-recall curves, the paper demonstrates how older and more optimized architectures under certain conditions can outperform more complex models, offering high accuracy with minimal hardware requirements, which is crucial for economically viable

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application in railway depots.

2. CNN ARCHITECTURES

In this research, the architectures YOLOv2 and Yolov4 - tiny are taken, these CNN models, treat detection as a unique regression problem. By dividing the image into a grid, the prediction of boundary frames and classes is performed in only one pass (single-stage detection), which enables extremely high processing speed in industrial and transport systems. YOLOv2 relies on the DarkNet-19 classification network with convolutional layers (3×3 and 1×1) and mandatory mini-group normalization. The key innovations of this architecture are the introduction of Anchor boxes (predefined frames obtained by clustering) and a Passthrough layer that merges high- and low-resolution feature maps for more efficient detection at a single output scale [10,11]. YOLOv4 brings a technological leap through a more complex topology divided into three segments, the first of which is called Backbone, which uses CSPDarknet53 that shares feature maps, which drastically reduces computing operations and memory load. The second segment is the Neck, which combines SPP (Spatial Pyramid Pooling) and FPN/PAN (Path Aggregation Network) structures for top-down and bottom-up semantic pooling of information. The third segment is the Head, which performs detection on several different scales (multiple scaling), which significantly increases the accuracy of recognizing extremely small or large objects in the same scene [12,13].

3. BRAKE SYSTEM

Continuous monitoring of railway braking systems is critical for traffic safety, as brake shoes and their lock pins (keys) endure extreme mechanical and thermal stresses. Traditional visual inspections performed by drivers or inspectors are labor-intensive, prone to human error from fatigue, and require shifting locomotives to specialized inspection channels, which reduces operational availability and increases maintenance costs. To automate this process and enhance inspection reliability, deep learning models combined with automatic undercarriage image acquisition offer a highly efficient alternative. Consequently, this paper focuses on detection of mechanical brake and analysis of architectures between YOLOv2 and Yolov4 - Tiny.

Monitoring in the railway transport is a critical aspect of ensuring the safety, efficiency, and reliability of rail transport systems. It involves the continuous observation and assessment of various components, systems, and operations to detect potential issues before they escalate into failures [14].

4. DATASET AND IMAGE ANNOTATION

The images were captured using a GoPro Hero 11 camera. A total of 3220 images were used for detector training. The original resolution of images, 2774 high-resolution images measuring 5568×4872 pixels and 566 images, with a resolution of 1920×1080 pixels. During preprocessing, the final resolution was adjusted to 416×416 for YOLOv2 and 608×608 for YOLOv4-Tiny.

Each image is manually annotated by drawing a bounding box around the entire braking system. The annotations formed in this way, which contain information about the position and dimensions of the observed object in the image, were used to train the YOLOv2 and YOLOv4-Tiny detector.

The first state of Braking system “Brake shoes and key present” included 1529 images, the second state “Brake shoes and key missing” included 686 images, while the third state “Brake shoe key missing” included 1005 images.



Fig.1. Braking system on locomotive 441/444

5. DETECTION

To simplify the localization process, the task is defined as a single-class detection problem, where the model focuses exclusively on identifying and bounding the complete mechanical brake system on the vehicle's undercarriage (Figure 2).

For the development and performance assessment of the detectors, a subset of 3220 images was extracted from the main dataset. This annotated image corpus was randomly split, allocating 60% of the data for training, 10% for validation during the optimization phase, and the remaining 30% as an independent test set.

Parameters used in training CNNs is shown in Table 1.

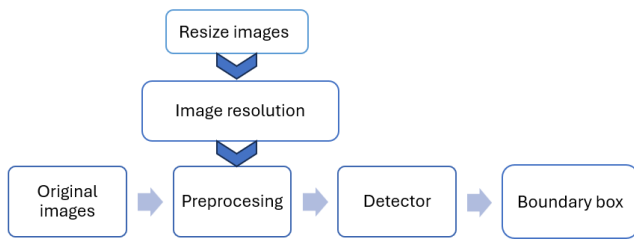


Fig.2 Flow of data processing from the input image to the output (boundary box)

Tab. 1. Parameters used in training CNNs.

Parameter	Value
Optimizer	adam
Gradient Decay Factor	0.9
Learn Rate Schedule	piecewise
Initial learning rate	0.001
Max Epochs	80
Mini-Batch Size	64
Learn Rate Drop Period	10
Learn Rate Drop Factor	0.6

6. RESULTS AND DISCUSSION

The training processes and experimental detection performances of the YOLOv2 and YOLOv4-Tiny detectors are evaluated using their respective loss

convergence trajectories and Precision - Recall characteristics. The learning behaviors of the two models exhibit distinct patterns in terms of optimization speed and convergence stability. The loss curve of the YOLOv2 detector demonstrates a highly rapid decrease and reaches early stabilization, achieving an optimal state within 1000 training iterations. Conversely, the YOLOv4-Tiny detector requires a prolonged learning process of 2500 iterations to achieve stable convergence, which is visualized using a logarithmic loss scale due to its structural complexity. For these architectures, the minimal gap between the final training and validation loss values indicates strong generalization capabilities and confirms that the models avoided overfitting on the undercarriage dataset.

The Precision-Recall curves further illustrate the definitive detection capabilities of the trained models. Evaluating the detection quality via Average Precision (AP) reveals that YOLOv2 significantly performs YOLOv4-Tiny, achieving an AP value of 0.97199 (97.199%) compared to 0.92546 (92.55%) for the latter. This performance gap provides a crucial architectural insight for locomotive undercarriage inspection. Consequently, YOLOv2 delivers higher localization accuracy and stable detection performance under varying confidence thresholds.

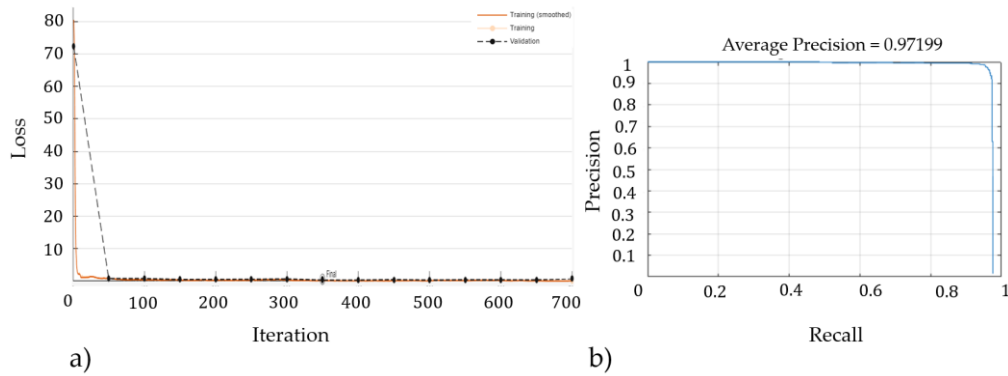


Fig. 3. Training loss curve (a) and precision-recall curve (b) for the proposed YOLOv2 object detector.

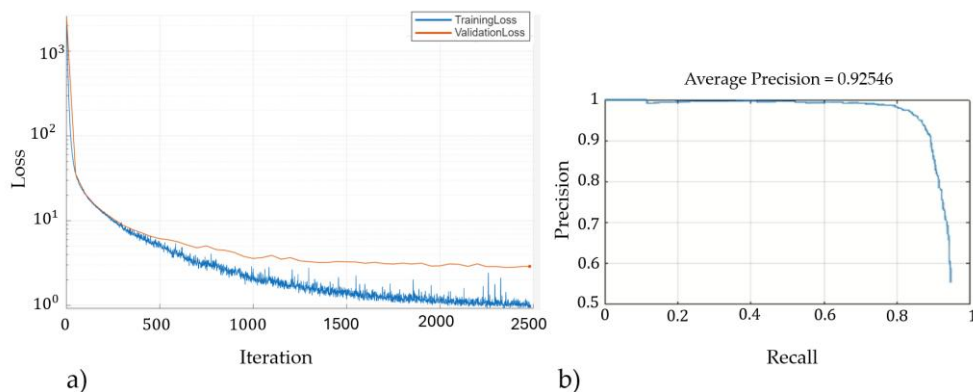


Fig. 4. Training loss curve (a) and precision-recall curve (b) for the proposed YOLOv4 - Tiny object detector.

CONCLUSION

Through this architectural evaluation, the paper demonstrates that under reduced input resolutions, a direct single-scale architecture like YOLOv2 also can give good results, achieving a high average precision of 0.97199 for less complex target objects. In contrast, newer, models like YOLOv4-Tiny struggle to leverage their structural advantages when fine spatial details are minimized. In the railway sector, these results confirm that traditional, manual visual inspections of locomotive undercarriages can be effectively enhanced using artificial intelligence. By expanding the dataset, ensuring precise annotations, and balancing model capacity with input scaling, the efficiency and safety monitoring of railway maintenance can be significantly improved.

ACKNOWLEDGEMENT

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REFERENCES

- [1] D. Stamenković, A. Miltenović, M. Banić, M. Simonović, M. Perić and D. Rangelov, *Application of the Device for Inspecting the Undercarriage of Railway Vehicles in the Framework of Inspection*, *Železnice* Vol. 69, 95-101, 2024.
- [2] R. Lagneback, *Evaluation of wayside condition monitoring technologies for condition-based maintenance of railway vehicles*, Luleå University of Technology, Sweden, 2007.
- [3] S. Mittal and D. Rao, *Vision Based Railway Track Monitoring using Deep Learning*, Computer Science, <https://doi.org/10.48550/arXiv.1711.06423>, 2018.
- [4] R. L. Rocha, A. Carolina Q. Siravenha, A. Cláudia S. Gomes, and other, *A Deep-Learning-Based Approach for Automated Wagon Component Inspection*, DOI: 10.1145/3167132.3167157, April 2018.
- [5] S. Takaya and M. Rehmsmeier, *The precision-recall plot is more informative than the ROC plot when evaluating binary classifiers on imbalanced datasets*, *PLOS ONE* Vol. 10, Issue 3, e0118432, 2015.
- [6] S. K. Bussa and N. K. Boppana, *Enhanced ResNet50 deep learning algorithm for classification of crack images in RCC structures*, *Asian J. Civ. Eng.* Vol. 26, 3773–3784, <https://doi.org/10.1007/s42107-025-01396-7>, 2025.
- [7] K. Krishnamohan, Ch. Raghava Prasad and P. V. V. Kishore, *Train rolling stock video segmentation and classification for bogie part inspection automation: a deep learning approach*, *Journal of Engineering and Applied Science*, <https://doi.org/10.1186/s44147-022-00128-x>, 2022.
- [8] J. Sánchez-Cubillo, J. Del Ser and J. L. Martín, *Toward Fully Automated Inspection of Critical Assets Supported by Autonomous Mobile Robots*, *Vision Sensors, and Artificial Intelligence*, MDPI, *Sensors* Vol. 24, Issue 12, 3721, <https://doi.org/10.3390/s24123721>, 2024.
- [9] Marko Perić, Aleksandar Miltenović, Milan Banić, Szabolcs Fischer, *Visual Inspection in Transport Using Autonomous Robots*, *Cognitive Mobility*, 2024.
- [10] J. Redmon and A. Farhadi, *YOLO9000: Better, Faster, Stronger*, *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, 6517-6525, 2017.
- [11] P. Jiang, D. Ergu, F. Liu, Y. Cai and B. Ma, *A Review of Yolo Algorithm Developments*, *Procedia Computer Science* Vol. 199, 1066-1073, 2022.
- [12] A. Bochkovskiy, C.-Y. Wang and H.-Y. M. Liao, *YOLOv4: Optimal Speed and Accuracy of Object Detection*, arXiv preprint, arXiv:2004.10934, 2020.
- [13] T. Diwan, G. Anirudh and J. V. Tembhurne, *Object detection using YOLO: Challenges, architectural successors, datasets and frameworks*, Elsevier, *Image and Vision Computing* Vol. 131, 104639, 2023.
- [14] V. Aleksandrov, *Železnička vučena vozila*, 1st ed.; Želnid: Belgrade, Serbia, 2000; pp. 352–371.



A REVIEW OF WHEEL INSPECTION DEVICES AND CONDITION MONITORING SYSTEMS FOR RAILWAY VEHICLES

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Abstract – Railway wheel wear changes the wheel profile and affects wheel–rail interaction, making reliable inspection essential for maintenance planning. This paper reviews wheel inspection devices and condition monitoring systems, focusing on wheel profile geometry, flange height, flange thickness, the qR dimension, and wear assessment. Portable measuring devices are compared with stationary systems that inspect wheels during train passage. The review considers measurement principles, operating conditions, data handling, and the contribution of each approach to maintenance decisions. Particular attention is given to the transition from individual measurements to historical wear monitoring and maintenance prediction. Portable devices provide flexibility for workshop inspections, whereas automatic wayside systems enable frequent measurements across a fleet. However, increased measurement frequency alone does not establish predictive capability. Reliable predictions also require consistent wheel identification, comparable measurements, and records of operating conditions and reprofiling. The review highlights the importance of measurement quality and data continuity when selecting inspection systems and integrating their outputs into condition-based maintenance.

Keywords – railway wheels, wheel profile measurement, qR dimension, wear monitoring, predictive maintenance.

1. INTRODUCTION

Railway wheels undergo wear and damage during service, progressively changing their geometry and contact conditions. Wheel inspection therefore supports both operational safety and decisions concerning reprofiling and replacement. Recent reviews distinguish workshop inspection, wayside monitoring, and on-board monitoring, which differ in sensor placement, measurement frequency, and the condition indicators they provide [1,2].

For wheel profile assessment, portable instruments and automatic wayside systems are particularly relevant. Portable devices allow targeted measurements on stationary vehicles, while wayside systems inspect passing vehicles at designated locations. Both approaches can produce geometric information, but their contribution to maintenance depends on how measurements are identified, stored, and evaluated over time.

This paper presents a focused review of wheel

profile inspection and its connection to wear monitoring and maintenance prediction. Representative commercial devices are examined alongside recent scientific literature. The comparison covers measurement outputs, deployment conditions, and data management. Manufacturer documentation is used to identify declared product capabilities, while scientific publications provide the basis for discussing measurement methods and predictive maintenance. The review does not constitute an independent performance ranking.

2. WHEEL PROFILE PARAMETERS AND WEAR ASSESSMENT

Wheel profile inspection provides information on the geometry of the flange and tread. Common outputs include flange height (Sh), flange thickness (Sd), the qR dimension, and the measured profile curve. Depending on the instrument and its configuration, additional outputs include wheel diameter, hollow tread, rim thickness, and equivalent

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conicity [2].

These quantities describe different aspects of wheel condition. Flange height and thickness characterize the flange geometry, while qR describes a geometric feature associated with flange steepness. Full profile acquisition provides additional information by enabling comparison with a reference contour or previous measurements of the same wheel. Laser measurement and machine vision can also be combined to assess geometry and visible surface damage [3].

Profile comparison requires consistent alignment and reference definitions. Otherwise, changes in sensor positioning or profile registration may be interpreted as wear. Similarly, a percentage-based wear indicator is meaningful only when its calculation, evaluated region, and reference profile are explicitly defined.

Geometrical wear assessment should also be distinguished from damage detection. Measuring a transverse profile does not, by itself, establish the absence of cracks or localized defects around the wheel circumference. Broader wheel inspection may require complementary techniques [1,2]. Within the present review, the primary concern is the measurement and evolution of profile geometry.

3. WHEEL INSPECTION DEVICES AND SYSTEMS

Figure 1 outlines the two inspection approaches considered here and their common use in maintenance planning. Both provide profile data; monitoring additionally requires wheel identification and measurement history, while prediction requires a validated model.

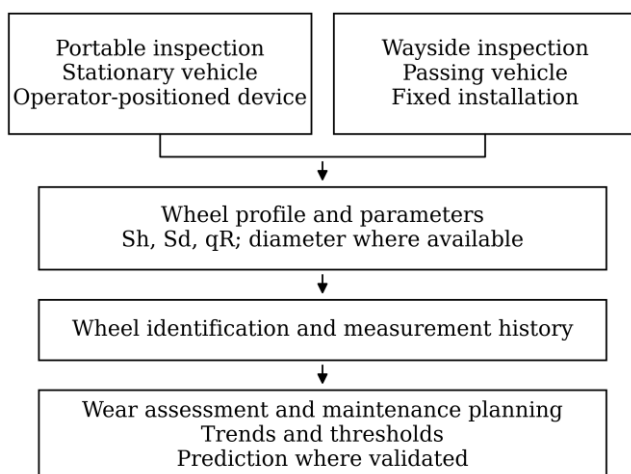


Fig. 1. Inspection approaches and use of wheel profile data in maintenance planning.

3.1. Portable measuring devices

Portable devices are suitable for workshop inspections and measurements at selected locations.

Their use allows individual wheels to be examined without a permanent measuring installation. Digital instruments can reduce manual transcription and retain profile data for subsequent analysis.

The CALIPRI C42 measures the wheel profile cross-section and evaluates parameters including flange height, flange thickness, qR , and hollow tread [4]. Goldschmidt's Wheelgauge Profile supports measurements directly on railway and tramway vehicles without removing the wheelsets [5]. ELAG's OPTIMESS WP uses contact-free laser scanning, automatically calculates profile parameters, and provides profile comparison and data export functions [6]. Figure 2(a) shows the OPTIMESS WP positioned on a wheel, illustrating the local access required for portable inspection.

Other examples include the Paragon LPM-5 and Althen FDKP. The LPM-5 reports flange dimensions, qR , and wear-related parameters; its published specification identifies supported Indian Railway profiles [7]. The FDKP combines laser profile acquisition with magnetic positioning, reference comparison, and database storage [8].

These devices illustrate different implementations of digital profile inspection. However, automatic acquisition after positioning should not be confused with unattended inspection of a moving train. Portable measurements still involve operator access, instrument placement, and association of the result with the correct wheel.

3.2. Automatic wayside measuring systems

Wayside systems inspect wheels as vehicles pass through a fixed installation. Their principal advantage is the opportunity to collect repeated fleet measurements without stopping each vehicle for a dedicated manual inspection. Nevertheless, permissible measuring speeds vary substantially between systems.

CALIPRI X is a permanently installed automatic wheel profile measurement system that can be integrated with CALIPRI Predictor [9]. KLD Labs' WheelScan uses lasers and imaging to determine profile parameters, including flange height, flange thickness, qR , and wheel diameter. Measurements are linked to vehicle identification and can be transferred to a fleet database [10]. Figure 2(b) shows CALIPRI X installed beside the rails to inspect passing wheels.

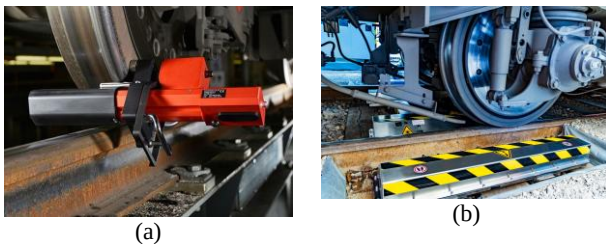


Fig. 2. Measurement arrangements: (a) portable OPTIMESS WP (source: ELAG [6]); (b) automatic wayside CALIPRI X (source: Hexagon [9]).

MERMEC's Profile and Diameter system provides full profile reconstruction and several wheel dimensions, with a declared measuring speed of up to 250 km/h [11]. HEGENSCHIEDT's ARGUS 2 is intended for lower-speed passage, with a specified measuring range of 3–15 km/h [12]. ARGUS S addresses higher-speed applications; its technical table specifies 0–80 km/h, with a design capability up to 160 km/h [13].

Table 1 summarizes representative solutions. The listed capabilities are based on supplier documentation and should be interpreted for the stated system configuration.

Tab. 1. Representative wheel profile inspection devices and systems.

Device / system	Deployment and capabilities
CALIPRI C42 [4]	Portable; full profile, flange dimensions, qR, hollow tread
Wheelgauge Profile [5]	Portable; profile inspection directly on the vehicle
OPTIMESS WP [6]	Portable; laser profile and diameter; comparison and data export
LPM-5 [7]	Portable; flange dimensions, qR and wear parameters
FDKP [8]	Portable; profile, Sh, Sd, qR; comparison and database
CALIPRI X [9]	Wayside; profile measurement and wear analysis integration
WheelScan [10]	Wayside; profile and dimensions; identification and fleet data
MERMEC [11]	Wayside; profile and diameter; up to 250 km/h
ARGUS 2 / S [12,13]	Wayside; profile and diameter; historical data and maintenance integration

3.3. Criteria for comparison

A useful comparison must consider the complete measurement process. Sensor resolution, measurement accuracy, repeatability, and uncertainty represent different characteristics and should not be treated as interchangeable. For example, the distance precision specified for a laser sensor does not necessarily describe the uncertainty of a calculated qR value.

Operating conditions also matter. Accessibility and

positioning influence portable inspection, while vehicle motion, environmental exposure, and measurement availability affect wayside applications. The proportion of successfully measured wheels should therefore be considered alongside the quality of individual measurements.

Portable and wayside devices can serve complementary roles. A wayside installation may identify wheels requiring attention, followed by a targeted workshop measurement. Such a workflow requires compatible parameter definitions and an understanding of differences between instruments.

4. WEAR MONITORING AND MAINTENANCE PREDICTION

An individual measurement describes wheel condition at a particular time. Repeated measurements can reveal the evolution of profile parameters, provided they are associated with the same wheel and obtained using comparable procedures. For this purpose, a measurement record should include wheel identification, date, measured profile, calculated parameters, and, where available, accumulated mileage. As indicated in Fig. 1, data acquisition is therefore only the first stage of the maintenance workflow.

Reprofiling records are particularly important because machining changes wheel geometry and interrupts the preceding wear trend. Analysing measurements across a reprofiling event without identifying that intervention could produce a misleading estimate of wear progression.

Commercial software illustrates how inspection data can support this process. CALIPRI Predictor provides historical storage, tolerance monitoring, profile comparison, and wear trend analysis [14]. WheelScan can operate with TrainBase and related applications for fleet evaluation, trending, and maintenance reporting [10]. Such functions support condition assessment, although their presence does not independently demonstrate prediction accuracy for a particular fleet.

Recent research addresses maintenance prediction through both data analysis and physical modelling. Lourenço et al. [15] discuss the formulation and evaluation of data-driven approaches for wheel and track monitoring, including difficulties in transferring research methods into operational use. Zeng et al. [16] examine wheel wear modelling and reprofiling strategy optimization using maintenance data. Miao et al. [17] investigate wheel wear prediction while considering wheel–rail elastic deformation and measurements collected during a reprofiling cycle.

For practical implementation, the predicted quantity should be clearly defined. Examples include the expected evolution of flange thickness or the mileage remaining before a specified maintenance

threshold is reached. Predictions should be evaluated against subsequent measurements and should account for uncertainty. A trend estimated for one operating regime may require updating when routes, loads, or maintenance practices change.

Accordingly, the transition to predictive maintenance requires more than additional sensors. It depends on reliable measurements, continuous records, an appropriate prediction method, and a defined connection between the predicted condition and the maintenance action.

5. CONCLUSION

Wheel profile inspection devices provide a basis for assessing wear and planning maintenance. Portable instruments offer flexibility for targeted inspections, while automatic wayside systems enable repeated measurements during vehicle passage. Their suitability depends on operating conditions, required parameters, measurement quality, and the integration of results into maintenance records.

The review indicates that full profile data and consistent wheel identification are particularly valuable for tracking changes over time. Automatic data acquisition can improve the availability of condition information, but predictive maintenance additionally requires validated methods and accurate records of interventions. A practical inspection strategy should therefore combine appropriate measuring equipment with reliable data management and clearly defined maintenance criteria.

REFERENCES

- [1] Ye, Y., et al., "Fault diagnosis of railway wheelsets: A review," *Measurement*, Vol. 242, 116169, 2025. <https://doi.org/10.1016/j.measurement.2024.116169>
- [2] Shaikh, M. Z., et al., "State-of-the-Art Wayside Condition Monitoring Systems for Railway Wheels: A Comprehensive Review," *IEEE Access*, Vol. 11, pp. 13257–13279, 2023. <https://doi.org/10.1109/ACCESS.2023.3240167>
- [3] Emoto, T., Emaru, T., Ravankar, A., Ravankar, A., and Kobayashi, Y., "A method for detecting wear and damage on railcar wheel tread surface using a combination of laser measurement and machine vision," *Mechanical Engineering Journal*, Vol. 11, No. 3, 23-00352, 2024. <https://doi.org/10.1299/mej.23-00352>
- [4] Hexagon, "CALIPRI C42 wheel profile gauge," product documentation. <https://www.calipri.net/en/products/wheelset-railway/wheel-profile-gauge>
- [5] Goldschmidt, "Wheelgauge Profile," product documentation. <https://www.goldschmidt.com/portfolio/wheelgauge-profile/>
- [6] ELAG Elektronik AG, "Wheel profile measuring device OPTIMESS WP," product documentation. <https://www.elag.com/en/wheel-profile-measuring-device-optimes-wp/>
- [7] Paragon Instruments, "Laser Wheel Profilometer Model LPM-5," product documentation. <https://paragoninstruments.com/railway-measurement/laser-wheel-profilometer-model-lpm-5/>
- [8] Althen Sensors, "FDKP Wheel profile gauge," product documentation. <https://www.althensensors.com/measurement-systems/railway-measurement-tools-systems/wheel-profile-measurement-tools/fdkp-wheel-profile-gauge/>
- [9] Hexagon, "CALIPRI X wayside monitoring system," product documentation. <https://www.calipri.net/en/products/wayside-monitoring-system>
- [10] KLD Labs, "Digital Solutions for Wheel Profile Measurement Monitoring," product documentation. <https://www.kldlabs.com/fleet-monitoring/wheel-profile-measurement/>
- [11] MERMEC, "Wheel Parameters: Profile and Diameter," product documentation. <https://mermecgroup.com/northamerica/inspect/train-monitoring/87/wheel-parameters.php>
- [12] HEGENSCHIEDT-MFD, "ARGUS 2," product documentation. <https://www.hegenscheidt.com/en/machine-portfolio/wheelset-diagnostics-systems/argusr2/>
- [13] HEGENSCHIEDT-MFD, "ARGUS S," product documentation. <https://www.hegenscheidt.com/en/machine-portfolio/wheelset-diagnostics-systems/argusr/>
- [14] Hexagon, "CALIPRI Predictor," software documentation. <https://nexus.hexagon.com/home/product/calipri-predictor/>
- [15] Lourenço, A., Ribeiro, D., Fernandes, M., and Marreiros, G., "Time series data mining for railway wheel and track monitoring: a survey," *Neural Computing and Applications*, Vol. 36, pp. 16707–16725, 2024. <https://doi.org/10.1007/s00521-024-10138-w>
- [16] Zeng, Y., Chen, B., Chi, Q., and Zhang, X., "Wheel Wear Modeling and Re-Profiling Strategy Optimization Based on the Maintenance Data of a Three-Axle Bogie Locomotive," *Transportation Research Record*, 2025. <https://doi.org/10.1177/03611981241263351>
- [17] Miao, G., Luo, R., and Shi, H., "Wheel wear prediction for high-speed trains by considering wheel-rail elastic deformation," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 2024. <https://doi.org/10.1177/09544097241239089>

Online product documentation [4–14] accessed on 5 October 2026.



FRICITION STIR WELDING OF ALUMINIUM ROOF PANELS FOR METRO VEHICLES

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Abstract – This paper presents the development and industrial implementation of Friction Stir Welding (FSW) for aluminium roof panel assemblies of metro vehicles within the Stadler SBB project. The base material is EN AW 6005A T6 extruded aluminium alloy (group 23.1, EN 15608), with a wall thickness of 3.5 mm and panel dimensions of 2,214 × 2,348 mm. FSW (ISO 4063, process No. 43) was selected for its advantages over fusion welding: reduced heat input, no filler material or shielding gas, minimal distortion, and superior surface finish. Welding was performed on a CNC milling machine at 170 cm/min using a tool with a 15 mm concave shoulder and 6 mm threaded probe. Process qualification per ISO 25239-4 included tensile, bend, and macrographic testing, with all results meeting quality level C (ISO 25239-5). The symmetrical welding sequence covered 12 joints per assembly (27.7 m total), with a maximum pre-weld gap of 0.3 mm, under a three-phase quality control plan. The results confirm FSW as a reliable, efficient, and environmentally sound solution for serial production of aluminium railway components.

Keywords – Friction Stir Welding, aluminium alloy EN AW 6005A, metro vehicles, ISO 25239, railway manufacturing.

1. INTRODUCTION

The railway vehicle manufacturing industry is undergoing a structural transformation driven by growing demands for weight reduction and environmental sustainability. Modern metro vehicles are increasingly designed as aluminium structures, primarily due to their favourable strength-to-weight ratio, inherent corrosion resistance, and high recyclability at end of service life [1]. However, the application of conventional fusion welding processes - MIG and TIG - to aluminium alloys introduces a range of technological limitations: a pronounced heat-affected zone (HAZ), residual stresses and distortions, and thermal softening of the material. In the EN AW 6005A-T6 alloy, which is widely used in the manufacture of extruded profiles for railway vehicles, these effects can locally reduce mechanical properties by 30–40% [2].

Friction Stir Welding (FSW *Friction Stir Welding*), developed at TWI in 1991 [3], represents a fundamentally different approach to joining metallic

materials. The process is based on generating heat through friction between a rotating tool and the workpiece, causing material plasticisation without reaching the melting point - typically at temperatures of approximately 80% of the solidus temperature [4]. FSW joints exhibit superior mechanical properties compared to fusion welding: a narrower heat-affected zone, lower residual stress levels, and negligible distortions [5]. Industrial application of FSW in the railway sector was pioneered by Japanese manufacturers in the late 1990s, soon followed by leading European players - Bombardier, Alstom and Stadler - establishing FSW as the dominant joining technology for aluminium extruded components in this industry [6, 7].

Existing research on FSW joints of EN AW 6005A-T6 alloy confirms tensile strengths in the range of 74.4–80.8% of the base material value [2], noting that the dominant factors influencing joint quality are shoulder diameter, rotational speed, and travel speed [8]. It has been shown that a concave

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shoulder geometry yields superior mechanical results compared to a flat geometry [9], while compressive residual stresses in the weld nugget zone contribute to improved fatigue characteristics relative to fusion welding [10, 11]. The environmental sustainability aspect further supports FSW technology: the process consumes 40–60% less energy, eliminates toxic fume emissions [4], and on average requires approximately 42% less energy per unit weld length compared to the GMAW process [12], resulting in a substantially higher sustainability rating in systematic comparative analyses [13].

This paper presents the complete industrial development of FSW technology for extruded aluminium panels of metro vehicle roof assemblies within the Stadler SBB project. The work encompasses base material characterisation, tool geometry design, process parameter optimisation,

welding sequence definition, qualification according to ISO 25239-4, and the three-phase quality control programme applied in serial production.

2. MATERIAL, EQUIPMENT AND FSW WELDING PARAMETERS

2.1 Base Material

All components were manufactured from extruded aluminium in accordance with EN 755-2: EN AW 6005A T6. This alloy belongs to the 6xxx series (Al-Mg-Si), with minor additions of manganese and chromium that improve corrosion resistance and toughness. According to EN 15608, the material is classified in group 23.1. Chemical composition and mechanical properties are presented in Table 1 and Table 2.

Tab. 1. Chemical composition of EN AW 6005A T6 (EN 573-3)

Si [%]	Fe [%]	Cu [%]	Mn [%]	Mg [%]	Cr [%]	Zn [%]	Ti [%]	Al [%]
0.5-0.9	0.35	0.3	0.5	0.4-0.7	0.3	0.2	0.1	balance

Tab. 2. Mechanical properties EN AW 6005A T6 (EN 755-2)

Yield Strength R_e [MPa]	Tensile Strength R_m [MPa]	Elongation [%]	Hardness [HBW]
215	255	6	85

2.2 Welding Machine

Welding was performed on a CNC milling machine manufactured by Fooke, equipped with an integrated FSW module (Fig. 1). The machine is designed for single-pass welding of 6xxx series aluminium alloys at material thicknesses up to 27 mm, and its main technical specifications are shown in Fig. 4.



Fig. 1. FSW welding machine

2.3 Tool Geometry

For this project, an FSW tool (Fig. 2) was selected with a concave shoulder of 15 mm diameter and a tapered probe with a nominal diameter of 6 mm and right-hand thread. The concave shoulder geometry was designed to form a local "reservoir" of plasticised material, ensuring continuous mixing in the joint zone, stable heat input, and proper weld face

formation. The geometry of both the shoulder and probe is critical for weld quality: the shoulder generates approximately 70% of the total frictional heat input through friction with the workpiece surface, while the probe contributes the remaining 30% by stirring the material at weld depth [8].



Fig. 2. FSW tool geometry

2.4 Clamping Fixture and Assembly

The high thermal expansion coefficient and pronounced thermal conductivity of aluminium result in rapid heat redistribution during the welding process. As the tool approaches the end of the joint, the accumulated heat may cause a tendency for the profiles to spread apart due to thermally induced forces, which negatively affects the dimensional accuracy of the assembly and the weld quality. These effects were successfully mitigated through the use of an appropriate clamping system.

Horizontal clamping was achieved using a specialised pneumatic system with diaphragm cushions, thereby eliminating surface damage to the profiles during clamping. For vertical restraint, manual clamps were used, positioned individually for each profile. Due to the characteristic FSW profile geometry defined by the customer, the use of a hydraulic clamping system was not required. The procedure for assembling the profiles into a sub-assembly prior to welding is shown in Fig. 3.

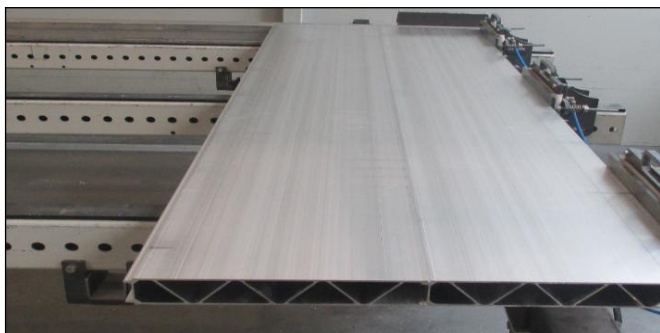


Fig. 3. Assembly of profiles into the FSW sub-assembly

After completing the sub-assembly installation in the clamping fixture (Fig. 4) and activating the mechanical and pneumatic clamping systems, a visual inspection of the gaps at all joints between profiles was carried out. The maximum permissible gap was 0.3 mm - a value above which characteristic FSW defects such as voids and tunnel defects in the weld root zone may occur.

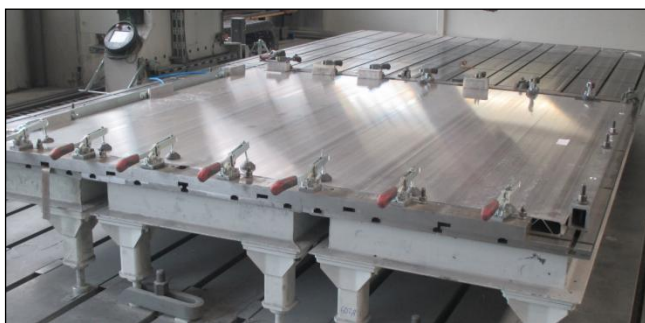


Fig. 4. Clamping fixture for FSW welding of the sub-assembly

2.5 Surface Preparation Prior to Welding

Prior to welding, a standard inspection and preparation procedure was carried out, encompassing: visual inspection of the FSW tool condition, mechanical-chemical cleaning of the clamping fixture working surfaces, verification of ambient conditions in the workshop, and checking of all fluid levels in accordance with the machine preventive maintenance procedure.

Preparation of the profile contact surfaces at the joint locations was carried out in three steps:

mechanical cleaning with stainless steel brushes to remove the oxide layer, degreasing with technical alcohol, and final wiping with clean white cloths. Following surface preparation, the profiles were assembled, the sub-assembly was formed, and placed into the clamping fixture.

2.6 Welding Parameters

Welding parameters were determined through the production of test welds and preliminary welding procedure qualification (pWPS), in accordance with the requirements of EN ISO 25239. According to this standard, the first and last 50 mm of each welded joint are treated as technological run-off and excluded from weld quality assessment. The adopted welding parameters are presented in Table 3.

Tab. 3. Key FSW Welding Parameters

Parametar	Vrednost
Welding speed	170 cm/min
Tool rotational speed	3200 min ⁻¹
Tool tilt angle	2 °
Axial force	7000 N

2.7 Welding Sequence

Welding was performed according to a predefined symmetrical sequence (Fig. 5), with the aim of achieving uniform heat input distribution and minimising thermally induced panel distortion during the process.

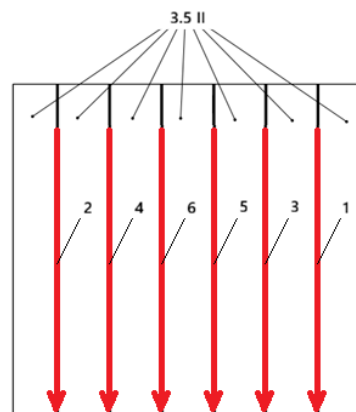


Fig. 5. Welding sequence

The sequence began with weld 1 at the far right of the panel, then continued symmetrically with weld 2 at the far left, following an alternating pattern through to the final weld pair - of the assembly — yielding a total of 12 welds per panel. The defined sequence was entered and stored in the machine control programme, fully automating the process. The operator's role was limited to defining the axis zero positions and initiating the welding cycle. Upon completion of welding on the first side of the panel, the identical

sequence was applied to the second side of the assembly.

3. QUALITY CONTROL PLAN

Primenjen je program kontrole kvaliteta u tri faze u skladu sa ISO 25239-5 (nivo kvaliteta C):

3.1 Pre-Weld Inspection

Verification of base material certificates (EN 10204: 3.1), dimensional inspection of extruded profiles, fit-up and joint gap inspection (≤ 0.3 mm), FSW tool geometry inspection, laser calibration of the CNC machine, and verification of operator qualification (ISO 25239-3).

3.2 In-Process Inspection

Continuous monitoring of welding parameters (rotational speed, axial force, travel speed) by the machine control system; verification of the welding sequence; real-time visual inspection of the weld face via a camera system.

3.3 Post-Weld Inspection

Visual Testing (VT) of 100% of welds following each panel assembly. Macrographic examination is periodically performed on 50 mm specimens cut from the start and end of each assembly, as agreed with the customer. All joints demonstrated full compliance with ISO 25239-5, quality level C.

4. CONCLUSION

1. FSW process No. 43 (ISO 4063) has been confirmed as the optimal joining technology for serial production of extruded aluminium metro vehicle roof panels, satisfying both customer requirements and ISO 25239 standards.
2. EN AW 6005A T6 alloy demonstrates excellent weldability by the FSW process. Neither preheating nor post-weld heat treatment is required for the wall thickness range of 3.5 mm.
3. The symmetrical welding sequence with 12 joints effectively minimises panel distortion through balanced heat distribution.
4. All mechanical test results (tensile, bend, macro) comply with the requirements of ISO 25239-5 for quality level C.
5. As a solid-state process with zero emissions, requiring no consumables other than the FSW tool, FSW represents a fully green manufacturing technology aligned with current sustainability objectives in the railway industry.

REFERENCES

- [1] Xiaoguang S., Xiaohui H., Chaofang D., Xiaogang L., *Applications of Aluminum Alloys in Rail Transportation*, IntechOpen, Chapter, 2021.
- [2] Liu, X., Xie, P., Wimpory, R., Li, W., Lai, R., Li, M., Chen, D., Liu, Y., Zhao, H., *Residual Stress, Microstructure and Mechanical Properties in Thick 6005A-T6 Aluminium Alloy Friction Stir Welds*, Metals, 9(7), 803, 2019.
- [3] Thomas, W.M., Nicholas, E.D., Needham, J.C., Murch, M.G., Temple-Smith, P., Dawes, C.J., *Friction Stir Butt Welding*, International Patent Application PCT/GB92/02203, 1991.
- [4] Habba, M.I.A., Ahmed M.M.Z., *Friction stir welding-based technologies: A comprehensive review from the sustainable manufacturing perspectives*, Journal of Materials Research and Technology, 38, pp. 1-29, 2025.
- [5] Mishra, R.S., Ma, Z.Y. *Friction stir welding and processing*, Materials Science and Engineering R, 50(1-2), 1-78, 2005.
- [6] TWI Global. *Friction Stir Welding for Railway Rolling Stock*, TWI Technical Knowledge, 2002. <https://www.twi-global.com/technical-knowledge/published-papers/railway-rolling-stock-manufacturers-implement-friction-stir-welding-october-2002>
- [7] TWI Global. *Friction Stir Welding for the Fabrication of Aluminium Rolling Stock*, TWI Published Paper, 2008. <https://www.twi-global.com/technical-knowledge/published-papers/friction-stir-welding-for-the-fabrication-of-aluminium-rolling-stock-may-2008>
- [8] Khalafe, W. H., Sheng, E. L., Bin Isa, M. R., Omran, A. B., & Shamsudin, S. B., *The Effect of Friction Stir Welding Parameters on the Weldability of Aluminum Alloys with Similar and Dissimilar Metals: Review*, Metals, 12(12), 2099, 2022.
- [9] Alkhafaji, A., Camas, D., Lopez-Crespo, P., Al-Asadi, H., *The Influence of Tool Geometry on the Mechanical Properties and the Microstructure of AA6061-T6 Aluminum Alloy Friction Stir Spot Welding*, Materials, 16(11), 4135, 2023.
- [10] Guo, Y., & Li, P., *Effect of Residual Stress and Microstructure on the Fatigue Crack Growth Behavior of Aluminum Friction Stir Welded Joints*, Materials, 17(2), 385, 2024.
- [11] Sennewald, M., Wüstefeld, R., Hasieber, M., Löhn T., Pierre J., *Determination of the load acting on the probe by separating force and torque during FSW of AA 6060 T66*, Weld World 68, pp. 2927–2940, 2024.
- [12] de Resende, A.A., Duarte, C.A.R. *The role of sustainability in the welding process: Context, technologies and challenges*, Environment Development and Sustainability, 2025.
- [13] Hoyos, E., Serna, M. C., De Backer, J., Martin, J., *Sustainability Score Comparison of Welding Strategies for the Manufacturing of Electric Transportation Components*, Sustainability, 15(11), 8650, 2023.



MODERNIZATION OF RAILWAY VEHICLE MAINTENANCE WORKSHOPS AT ŽRS A.D. DOBOJ

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Abstract: *The capacities for maintenance of railway vehicles for freight traffic include the Doboj maintenance workshop, the Banja Luka maintenance workshop and the Prijedor maintenance workshop. These workshops can provide maintenance services for various types of locomotives and wagons such as diesel locomotives, electric locomotives and freight wagons. The workshop at the Zvornik border station (which belongs to the Doboj maintenance workshop) and the workshop at the Omarska station (which belongs to the Prijedor maintenance workshop) are also included in the maintenance for the purpose of emergency and ongoing maintenance. Based on the field inspection of the condition of the existing railway vehicle maintenance workshops, it was concluded that they can meet the maintenance needs of the existing locomotives and vehicles. ŽRS still has a large number of railway vehicles out of exploitation, and the capacities were able to meet the maintenance needs of all railway vehicles (operational and non-operational) many years ago. The buildings, facilities and equipment in these workshops are deteriorating, and the working environment is poor, and they need to be renovated or modernized. In addition, newly purchased rail vehicles should also be equipped with appropriate buildings, facilities and maintenance equipment and devices.*

Keywords: *maintenance workshops, railway vehicles for freight traffic, workshop.*

1. INTRODUCTION

Currently, ŽRS has various types of rolling stock, including diesel locomotives 661, electric locomotives 441 and freight cars of various models, all of which are manufactured in European countries. The average lifespan of the existing rolling stock is close to 30 years. Most of the rolling stock is not in operational condition. The number of available rolling stock is small, and the demand for freight traffic is mostly defined by permanent contracts for the transport of bulk goods according to the requirements of the economy. In order to extend the lifespan of locomotives and vehicles, it is necessary to comply with all prescribed maintenance deadlines, and the various levels of work are limited, in addition to the lack of financial resources, by the fact that the existing rolling stock models have not been produced for a long time, and it is not possible to purchase the necessary equipment and devices.

2. CAPACITIES FOR MAINTENANCE OF FREIGHT VEHICLES

The maintenance capacities for railway vehicles for freight traffic include the Doboj maintenance workshop, the Banja Luka maintenance workshop and the Prijedor maintenance workshop. These workshops can provide maintenance services for various types of locomotives and wagons such as diesel locomotives, electric locomotives and freight wagons. The workshop at the Zvornik border station (which belongs to the Doboj maintenance workshop) and the workshop at the Omarska station (which belongs to the Prijedor maintenance workshop) are also included in the maintenance for the purpose of emergency and ongoing maintenance.

➤ Doboj railway vehicle maintenance workshop;

The Doboj maintenance workshop is the most important maintenance workshop of the ŽRS, which is responsible for the ongoing and investment maintenance of all traction and hauled railway vehicles (locomotives, diesel-motor trains and freight

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wagons), as well as vehicles for railway purposes (track maintenance vehicles and contact network). The Doboj maintenance workshop is located on the eastern side of the Doboj station. The maintenance workshop and the station are arranged in parallel, and both ends of the workshops are connected to the station. In addition to the current and investment maintenance of the above types of railway vehicles for the needs of ŽRS, the workshop also provides inspection services, as well as repairs (overhauls) of locomotives, cars and individual assemblies, equipment and devices from them, for the needs of third parties. The workshop also contains modernized machine equipment for processing all types of wheel profiles of railway vehicles. Since May 2009, the workshop has received an ISO standard certificate for maintenance and overhaul of rolling stock, which allows it to participate equally in international tenders for the maintenance of railway vehicles in the region. Overall, the Doboj railway vehicle maintenance workshop is divided into two parts: the locomotive maintenance area and the freight car maintenance area. The Zvornik maintenance workshop belongs to the Doboj maintenance workshop and performs current maintenance and temporary repairs of freight cars at the border station.

➤ **Banja Luka railway vehicle maintenance workshop;**

The Banja Luka railway vehicle maintenance workshop performs bodywork and painting work on diesel and electric locomotives. The workshop also includes a modern painting workshop for the protection and painting of all ŽRS rolling stock.

➤ **Prijedor Rail Vehicle Maintenance Workshop;**

The Prijedor Workshop performs current and investment maintenance of freight wagons of all types and series. The workshop's annual capacity is 100 regular and several hundred current repairs. The Prijedor Workshop has modernized equipment for testing the buffer-traction device and brake system elements. The workshop contains mechanical equipment for pressing axle assemblies. The technological process of investment maintenance in this workshop is carried out according to the highest standards of TSI norms as well as internal instructions and regulations of ŽRS. The Prijedor Workshop is ISO 9001: 2000 certified. A department of the Prijedor Wagon Maintenance Section has been established at Omarska station and a workshop has been formed for emergency current repairs of freight E wagons for all damages caused by manipulation during loading or unloading, where most of the smaller-scale emergency works are carried out on the track itself.

3. MODERNIZATION OF RAIL VEHICLE MAINTENANCE WORKSHOPS

In Based on the field inspection of the existing rail vehicle maintenance workshops, it was concluded that they can meet the maintenance needs of existing locomotives and vehicles. ŽRS still has a large number of rail vehicles out of operation, and the capacities were able to meet the maintenance needs of all rail vehicles (operational and non-operational) many years ago. The buildings, facilities and equipment in these workshops are deteriorating, and the working environment is poor, and they need to be renovated or modernized. In addition, newly purchased rail vehicles should also be equipped with appropriate buildings, facilities and equipment and maintenance devices. Given the existing problems, it is planned to modernize the maintenance workshops in Doboj, Banja Luka and Prijedor. Taking into account the volume of passenger and freight transport, the organization of train traffic and the locations of existing maintenance workshops in the railway network, the functional positioning of the three workshops was carried out as follows:

- ✓ The Doboj Maintenance Workshop is the most important maintenance workshop owned by the Railways of the Republic of Srpska, which is responsible for the maintenance of all locomotives and electric trains, part of freight cars, as well as for the maintenance of infrastructure maintenance machinery.
- ✓ The Banja Luka Maintenance Workshop performs maintenance work on passenger cars of all series, part of freight cars, passenger cars for narrow-gauge traffic and vehicles for railway purposes. This workshop performs painting work on rail vehicles.
- ✓ The Prijedor Maintenance Workshop performs maintenance on freight cars of all types and series. The Omarska Freight Car Maintenance Workshop specializes in ongoing maintenance work on freight cars that are mainly used for ore transport.
- ✓ It is recommended that the Doboj Maintenance Workshop be modernized in the first phase and the Banja Luka Maintenance Workshop and Prijedor Maintenance Workshop in the second phase.

➤ **Doboj Maintenance Workshop;**

Locomotive maintenance facilities at the Doboj Workshop mainly include a workshop for current and capital maintenance of electric locomotives, a workshop for current maintenance and capital maintenance of diesel locomotives and DMV trains, a specialized workshop for maintenance of brake equipment and other special-purpose facilities. The field inspection determined that the entrance doors, windows, roofs, walls and floors of each maintenance

workshop have varying degrees of damage, and the working environment in the workshop halls is poor, so the aforementioned facilities need to be urgently renovated. It was also determined that the Doboj Workshop lacks specialized facilities for painting locomotives, as the Banja Luka Workshop is currently the only one responsible for painting locomotives. Given that the process of painting locomotives produces harmful gases due to paint evaporation, and that there are certain risks to the health of workers and the environment, it is necessary to build a new paint shop. Given that the purchase of new electric locomotives is planned, it will also be necessary to adapt the maintenance of new types of locomotives to the requirements prescribed by the manufacturer. In order to meet the maintenance requirements of electric motor trains and improve the working environment in workshop halls, it is proposed to build a new facility for testing electric motor trains and equip it with appropriate equipment for control, testing and maintenance. At the same time, for maintenance and parking of electric trains, it is necessary to have four tracks, and it is necessary to build two additional tracks intended for this purpose. The truck maintenance facilities at the Doboj Workshop mainly include a truck maintenance workshop, a sandblasting room, a brake maintenance room, a wheel lathe workshop and a press workshop. On site inspection, it was determined that the buildings, facilities and equipment of the truck maintenance workshop are very old and in poor condition, and it is proposed to demolish the existing truck maintenance workshop and rebuild it at the same location. It is also proposed to reconstruct the room for sandblasting freight cars and equip it with complete electrical and pneumatic plants and the necessary equipment for sandblasting. Description of planned works:

1. New EMU maintenance hall;
2. New painting hall;
3. Removal of existing and construction of new facilities for maintenance of freight cars and sandblasting;
4. Equipping the halls with devices and equipment for maintenance of new locomotives and new EMUs and replacing existing equipment;
5. Adaptation of all other maintenance halls;
6. Adaptation of existing facilities for accommodation of administrative and other staff;
7. Other unspecified works.

➤ **Maintenance Workshop Banja Luka;**

The Maintenance Workshop Banja Luka performs current and investment maintenance of passenger cars of all series, individual freight cars and vehicles for railway purposes of ŽRS, and is also responsible for the external painting of locomotives. It consists of a workshop for maintenance of passenger and freight

cars, a hall for maintenance of rotary stands, a paint shop, an electrical testing room, a washing hall, a hall for wheel processing and maintenance of axle assemblies for railway vehicles, two transmissions, a hall for controlling axle pressure on railway vehicles, administration buildings and more. According to the field inspection, the main problem of the Banja Luka Maintenance Workshop is that the workshop halls are old and urgently need renovation, and the equipment in them is outdated and there is a need for urgent renovation. For example, the roofs and systems for collecting and draining atmospheric precipitation on some facilities have serious damage, some hydraulic cranes and other lifting devices have exceeded all periods for performing regular repairs and now require urgent investment, some metalworking machines do not fully meet functional needs and must be reconstructed, and in general there is a lack of various maintenance equipment. Description of planned works:

1. Replacement and overhaul of maintenance equipment;
2. Adaptation of all other maintenance halls;
3. Adaptation of existing facilities to accommodate administrative and other staff;
4. Other unspecified works.

➤ **Prijedor Maintenance Workshop;**

The Prijedor Maintenance Workshop has a workshop for periodic repairs of wagons, a workshop for current repairs of wagons, a workshop for axle assemblies, a workshop for rafamet, a blacksmith shop, a carpentry workshop, a warehouse for spare parts and technical gases, a warehouse for flammable liquids, an administrative building with a restaurant and a boiler room with a compressor station, etc. The workshop halls and facilities in the Prijedor Maintenance Workshop are old, the equipment in them is outdated and there is a lack of an appropriate sandblasting facility and a painting facility. Due to the aforementioned problems in the current work of the Prijedor Maintenance Workshop, it is planned to renovate the existing halls and facilities in the coming period and to overhaul or purchase part of the equipment for maintaining rail vehicles. In addition, adaptation or construction of sandblasting and painting facilities will be required. Description of the planned works:

1. Replacement and overhaul of maintenance equipment;
2. Adaptation of all other maintenance halls;
3. Adaptation of existing facilities to accommodate administrative and other staff;
4. Other unspecified works. [3].

4. FINANCIAL ANALYSIS

The financial analysis was performed using

standard dynamic indicators of investment justification: Net present value; Internal rate of return. Net present value is an indicator that takes into account time values and represents the sum of net income over the economic life of the project discounted to the present moment, i.e. at the beginning of the investment. The net present value method is based on the assumption of discounting all future income and expenses at the beginning of the project implementation, with a specific discount rate determined in advance. The project is acceptable if the net present value is greater than zero. Internal rate of return is the discount rate that reduces the present value of the project to 0. This rate reflects the market-financial efficiency of the project. The eligibility criterion is that it be greater than the discount rate. A prerequisite for a dynamic assessment of profitability is the determination of an appropriate discount rate, which in this research was taken in accordance with the data specified in the document "*Guide to Cost-Benefit Analysis of Investment Projects*" (European Commission, 2014), where the financial discount rate of 4% is specified. Overview of project feasibility indicators:

- ✓ Financial net present value (FNPV) 12,242,869 EUR.
- ✓ Financial internal rate of return (FIRR) 4.94%.
- ✓ The financial net present value (FNPV) of this project is positive in the amount of 12,242,869 EUR, which means that if the company expects a return of 4%, it will be in profit by the amount of the net present value.
- ✓ The financial internal rate of return (FIRR) of this project is 4.94%, which can be considered a favorable internal rate if we consider that a project is acceptable if it has an IRR of at least 4%.

5. SENSITIVITY ANALYSIS

Sensitivity analysis is an analysis that considers the elasticity of an investment project. The goal of sensitivity analysis is to assess the acceptability of an investment project if critical investment parameters change. Critical investment project parameters are those parameters that, by their occurrence, have the greatest impact on the efficiency of the investment project and are at the same time highly uncertain. Sensitivity analysis is used to predict the impact of changes in the input variables in the model on the model results. Project sensitivity analysis:

- ✓ Base case 4.94% 12,242,869 EUR.
- ✓ Increase in regular current maintenance

costs by 10% 4.98% EUR 12,849,430.

- ✓ Reduction of regular current maintenance costs by 10% 4.89% EUR 11,636,308.

As can be seen, the project showed resistance to all realistic types of changes in input parameters. In all cases, there is a return on investment solution.

6. CONCLUSION

During the crisis period of 1992-1995, the railway infrastructure and rolling stock on the territory of the Republika Srpska suffered serious losses. The lack of adequate maintenance, primarily of the rolling stock, electric traction facilities and the catenary network, further increased the overall damage rate in the railway sector in the post-crisis period. Railway vehicle maintenance facilities mainly include workshops for current and investment maintenance of electric locomotives, workshops for current maintenance of passenger and freight wagons, workshops for investment maintenance of diesel locomotives and DMV trains, as well as specialized workshops for maintenance of brake equipment and other special-purpose facilities. The field inspection determined that in many facilities, the entrance doors, windows, roofs, walls and floors of the maintenance workshops have varying degrees of damage, and the working environment is poor, so some of them need urgent renovation. It was also determined that some workshops lack specialized facilities for painting, sandblasting, turning and other types of craft work or control of equipment and devices with special tools and devices. In accordance with the plans for the procurement of new railway vehicles, the construction of new halls and/or the renovation of existing facilities will be required to meet the specific maintenance requirements of specific types of railway vehicles in accordance with the technology applied to them. For now, the recommended urgent procurements are the replacement and overhaul of maintenance equipment, the adaptation of existing halls for vehicle maintenance, the adaptation of existing facilities for the accommodation of administrative and other staff, as well as other necessary minor works not listed.

REFERENCES

- [1] Rodić, J., *Financial restructuring of companies*, Second Symposium, SRRRS, Teslić, 1998.
- [2] Rodić, R., *Privatization of state capital of the companies in Republika Srpska - a problem or a prerequisite for solving the problem*, Finrar, SRRRS, Banja Luka, 2003.
- [3] *Analysis of potential steps in restructuring of Republika Srpska Railways jsc. Doboj*, Advantis broker a.d. Banja Luka, Banja Luka, 2017.



SAFETY ASPECTS OF RAILWAY VEHICLE MAINTENANCE PLANS WITHIN THE EUROPEAN REGULATORY FRAMEWORK

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Abstract – Maintenance of railway vehicles constitutes a fundamental control function within the Safety Management System (SMS), with direct implications for system reliability and risk mitigation. Deficiencies in maintenance planning may result in unmitigated risks and compromised operational safety. EN 17023 provides a structured framework for compliance with Directive (EU) 2016/798 and Regulation (EU) 2019/779 governing Entities in Charge of Maintenance (ECM), particularly regarding traceability, documentation, and continuous improvement based on operational feedback. This study evaluates the role of EN 17023 in enhancing safety through the integration of a systematic feedback loop between in-service failure data and maintenance planning. Although failure data is routinely collected through technical inspection reports, its integration into maintenance optimization remains limited. The analysis is based on empirical data obtained from official Technical Wagon Inspection (TWI) points of Užice between September 2022 and January 2024. The results demonstrate that implementing risk-informed, data-driven maintenance strategies (supported by targeted inspections of critical components) significantly improves safety performance and system reliability. The proposed approach facilitates alignment with EU regulatory frameworks, including ECM certification and the Common Safety Method (CSM), thereby enhancing safety levels in railway operations.

Keywords – maintenance planning, Safety Management System (SMS), Entity in Charge of Maintenance (ECM), Common Safety Method (CSM), risk-based maintenance.

1. INTRODUCTION

Across Europe, rolling stock maintenance is mandated by EU Directives, specifically Directive (EU) 2016/798 [1], and operationalized via the European standard EN 17023 [2], which governs the creation, modification, and validation of maintenance plans. Adopted widely across non-EU states to ensure interoperability, EN 17023 translates the legal provisions of Regulation (EU) 2019/779 [3] into standardized operational steps.

To satisfy the Regulation's requirement for comprehensive documentation, EN 17023 prescribes specific documentation criteria for each maintenance phase and provides a methodology for linking every installed component to a specific vehicle and the

technician who installed it. This simplifies the process of establishing accountability for executed work tasks. A key feature of EN 17023 in railway vehicle maintenance is its ability to outline a procedure for implementing changes in technology or regulations directly into the workshop technicians' workflows. The feedback loop within railway vehicle maintenance is a process that enables a connection between field operations (specifically within traffic and workshops) and the entities in charge of maintenance (ECMs) [4].

The objective of this paper is to examine the role of EN 17023 in improving railway vehicle maintenance planning through systematic integration of operational feedback into maintenance plans. The study further evaluates how this approach supports

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compliance with the European railway safety framework, particularly within the ECM certification process and the Common Safety Method for Risk Assessment (CSM-RA).

The scientific contribution of this paper is reflected in: (1) presenting a systematic framework for integrating operational failure data into the maintenance plan revision process in accordance with EN 17023; (2) linking the maintenance planning process with the CSM-RA; (3) proposing key performance indicators (KPIs) for continuous monitoring of maintenance effectiveness; and (4) validating the proposed approach using empirical data collected from freight wagon inspections in operational service.

2. REGULATORY FRAMEWORK

Railway safety in the European Union and the Republic of Serbia is governed by Directive (EU) 2016/798 and national legislation, which mandate a Safety Management System (SMS) to systematically control operational risks. Within this framework, a certified Entity in Charge of Maintenance (ECM) must ensure a vehicle's technical fitness across four dimensions: risk management, documentation control, fleet maintenance management, and maintenance execution.

The primary objective of a maintenance plan is to leverage preventive maintenance to ensure safety-relevant functions are continuously restored. To manage these safety-critical elements, the system must implement three actions:

- Identification: Map components against hazard lists and perform risk analyses.

- Evaluation & Definition: Assess wear patterns to define targeted maintenance intervals.
- Documentation: Trace and flag safety-critical tasks to facilitate future modifications.

The European standard EN 17023 defines processes for creating, modifying, and validating railway vehicle maintenance plans, translating the legal provisions of Regulation (EU) 2019/779 into operational steps. It harmonizes fleet maintenance across freight, passenger, and traction rolling stock. To govern the vehicle lifecycle, EN 17023 systematically covers data selection, plan development, execution procedures, review triggers, risk assessment, and monitoring regimes.

The EN 17023 standard serves as a domain-specific implementation of the CSM-RA within railway maintenance. When a change to a maintenance plan is proposed, EN 17023 operationalizes CSM-RA principles through three key mechanisms:

- Significant Change Assessment: A structured screening process evaluates whether a maintenance modification (e.g., extending intervals) introduces new hazards.
- Risk Evaluation and Hazard Identification: If a change is deemed significant, a formal risk evaluation is conducted using codes of practice, reference systems, or explicit risk estimation.
- Safety Feedback Loop (Fig. 1): Real-world operational data and workshop defect logs trigger a re-assessment of the maintenance plan, translating high-level legal requirements into traceable technician workflows.

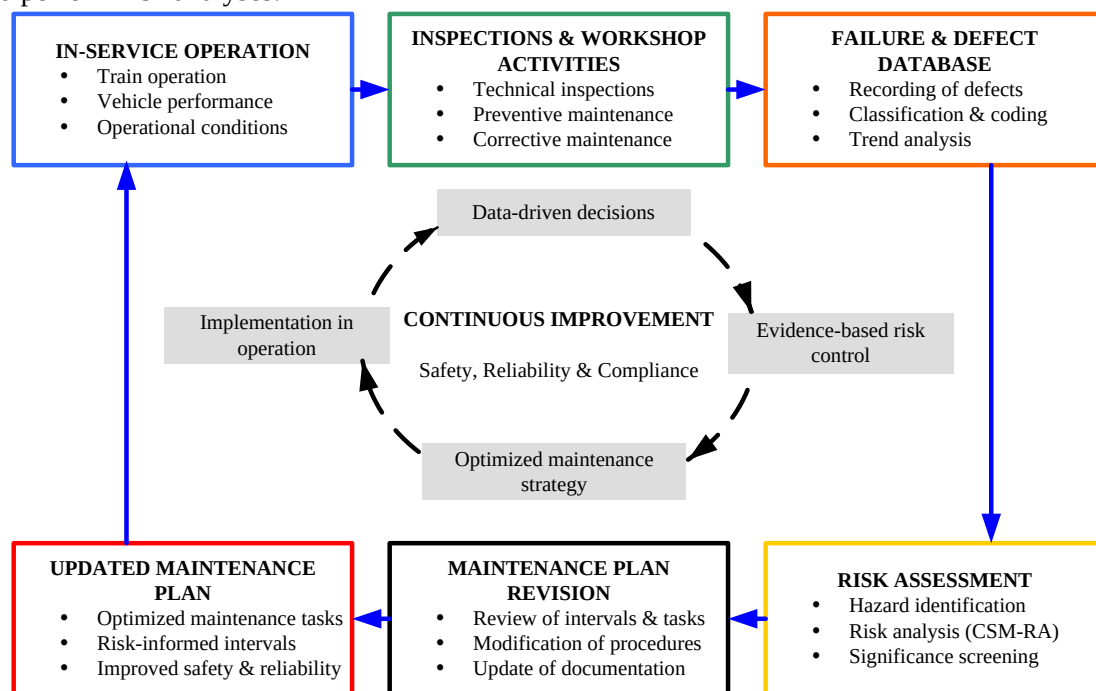


Fig 1. Feedback loop for maintenance plan development and revision in accordance with EN 17023

3. IMPACT OF THE MAINTENANCE PLAN

Risk assessment can be conducted using various methods. For any type of impact requiring a risk assessment, the baseline approach can be utilized by collecting and analyzing the necessary data, which includes operational experience gathered during service and operational experience from a maintenance perspective. Through predictive simulation and investigation of potential risks, combined with the definition of compliance criteria, the risk assessment of hazards arising from the introduction of a proposed change can be evaluated, taking existing safety measures into account [5,6].

3.1. Case Study

Data used in case study were obtained from regular monitoring of freight wagon operated by "Srbija Cargo" at technical wagon inspection (TWI) points at Užice Traction and TWI Section. The data from September 2022 to January 2024 revealed the following operational metrics [7]:

- Out of 5,443 recorded defects, rented wagons accounted for 34% of the total fleet issues.
- For company-owned wagons, the highest defect concentrations occurred within the wagon body (42%) and brake equipment (36%). Rented wagons exhibited a similar distribution, with the highest share of defects attributed to brake equipment

(56%) and the wagon body (23%).

- A defects of brake equipment on company wagons indicated that brake blocks constituted the vast majority of failures at 58%, while pneumatic and mechanical components accounted for 22% and 20%, respectively. Wear-related issues made up 91% of all brake block defects, meaning that brake block wear alone accounted for 48% of the total recorded fleet defects. Rented wagons exhibited the highest number of brake-related defects within the pneumatic system.

These data represent the operational feedback required to trigger a modification of the maintenance plan. Based on this case study, systemic brake block wear on "Srbija Cargo" freight wagons is isolated as the core technical problem, representing nearly half (48%) of all fleet defects. The proposed change to the maintenance plan involves shortening the time or mileage interval between technical brake inspections, to facilitate the replacement of worn brake blocks before they cause wheel damage or brake system failure during operation.

3.2. Risk assessment applying the CSM-RA

By applying the screening algorithm (Tab. 1) outlined in EN 17023, a preliminary analysis was conducted based on evaluation criteria reflecting the core principles of CSM-RA.

Tab. 1. Screening analysis of the proposed maintenance plan change

Criterion	Assessment	Justification
Consequence of failure	High (Safety)	Failure or inefficiency of the brake system due to maximum wear of brake blocks directly jeopardizes railway traffic safety.
Novelty	Low	Replacement of brake blocks modifications to inspection intervals are standard, long-standing operations within railway workshops using mature technologies.
Complexity	Medium	While component replacement is simple, the modification impacts complex fleet logistics, technical inspection scheduling, and operational line capacities.
Monitoring (Oversight)	Easy	The frequency and progression of wear on the newly implemented blocks can be easily monitored via regular TWI records and workshop.
Reversibility	Easy	If the new interval proves to be inefficient or economically unjustified, the system can revert to the baseline maintenance regime without permanent impact.

The consequence of failure receives a "High" assessment because it directly affects a safety-critical train function. According to the EN 17023 algorithm and CSM regulations, a high safety impact is an eliminating factor. Any change relating to safety-critical components (such as the brake system) cannot be introduced via an expedited procedure. Consequently, the proposed change to the maintenance plan is classified as a "significant change". It is mandatory to conduct a detailed risk assessment applying the CSM-RA methodology before the amended maintenance plan is officially validated and implemented.

The detailed risk assessment is structured through

hazard identification and application of risk acceptance principles.

3.3. Defined Safety Measures

To mitigate the identified risks to an acceptable level (As Low As Reasonably Practicable - ALARP), the following mandatory measures must be integrated into the amended maintenance plan:

- Technical Measure (Optimized Interval): Based on data showing block wear accounts for 48% of defects over 16 months, the preventive brake inspection interval for critical wagon series is shortened by half (or an equivalent mileage

threshold).

- Organizational measure (EN 17023 traceability): Each block replacement must be documented through a workshop order, where the serial number and type of block are linked to the wagon ID number and the mechanic who performed the installation.
- Operational measure (TWI control): A mandatory visual inspection of block thickness is introduced at TWI Užice for trains arriving from lines with steep gradients (where braking is more intensive).

In order to operationalize the system and close the loop between the workshop and safety management, Key Performance Indicators (KPIs) were proposed to introduce specific for the brake system maintenance. These indicators would serve as a direct, quantitative input for the CSM for monitoring, enabling early detection of deviations before critical failures occur.

Proposed KPIs for the Brake System:

- Brake reliability metric (KPI_b) - The number of in-service brake system defects per 10,000 train-km. This monitors failure trends to verify the efficacy of the shortened maintenance interval.
- Indicator of premature block wear (KPI_w) - Percentage of brake blocks replaced at TWI stations (unplanned) relative to the number of blocks replaced during regular maintenance in the workshop to detect accelerated material wear or quality issues with supplied components.
- Mean kilometers between failures (KPI_f) - Total fleet operational mileage divided by the number of registered brake defects.

The proposed indicators are directly implemented through defined model of the CSM for monitoring:

- Strategy and planning: Within the SMS, a target value ($KPI_b < 0.05$ defects per 10,000 km) and an alarm threshold (Trigger level) are established.
- Data collection and analysis: Data on replaced blocks from the Užice Section and the completed mileage of freight wagons are entered into the database. The system automatically calculates KPIs on a monthly basis.
- Development of action plans (Response): If KPI_b exceeds the alarm threshold, it serves as a signal to CSM monitoring that the risk control system is not functioning properly. Engineers immediately initiate a technical audit (e.g., verifying the material quality of the blocks or further shortening the interval).
- Reporting and improvement: Performance trends are formally documented and submitted to the national Directorate for Railways, proving that the ECM and railway undertaking actively supervise operational safety.

4. CONCLUSION

Based on the empirical data and risk screening conducted in this study, it can be concluded that the EN 17023 standard is not yet fully operationalized within the observed system. Although defect data is systematically tracked and recorded at TWI stations, the critical step prescribed by the standard to translating field asset data into official, dynamic updates of the maintenance plans, is absent in practice. The logs exist in isolation, breaking the data-driven "learning loop" and weakening the risk control mechanism.

The EN 17023 standard strictly mandates that a maintenance plan must behave as an evolving, safety-responsive document. The absence of an automated feedback loop between observed field failures and documentation updates directly elevates operational risks. A functional "learning loop" implies that real-world wear metrics (such as block wear causing 48% of fleet defects) must systematically trigger the re-evaluation and optimization of maintenance intervals. Without this coupling, the organization remains entirely reactive – remedying failures post-occurrence rather than dynamically adapting the maintenance plan to prevent them.

Future research should validate the proposed methodology on larger railway fleets and investigate the integration of predictive maintenance techniques and digital monitoring technologies into EN 17023 maintenance planning.

REFERENCES

- [1] EN 17023 Railway applications - Railway vehicle maintenance - Creation and modification of maintenance plan, 2018
- [2] Directive (EU) 2016/798 of the EU Parliament and of the Council of 11 May 2016 On Railway Safety (2016)
- [3] Commission Implementing Regulation (EU) 2019/779 of 16 May 2019 laying down detailed provisions on a system of certification of entities in charge of maintenance
- [4] ATMF Annex A to Appendix G of COTIF 1999 – Rules for Certification and Auditing of ECM ("Official Gazette of RS – International Treaties", No. 12 of July 1, 2021)
- [5] Consilvio A., Di Febbraro A., Meo R., Sacco N., Risk-based optimal scheduling of maintenance activities in a railway network, *EURO Journal on Transportation and Logistics*, 8(5), 2019, pp 435-465, ISSN 2192-4376, <https://doi.org/10.1007/s13676-018-0117-z>.
- [6] Gawlak K. Safety critical components (SCC) in the maintenance management system for railway vehicle. *Diagnostyka*. 2022;23(4):2022408. e-ISSN 2449-5220 DOI: 10.29354/diag/156166
- [7] Rogić J., Analysis of Freight Wagon Failures for the Operator "Srbija Cargo" in the Area of the Train Traction Section and TWI Užice, BSc thesis, Academy of Technical and Art Applied Studies Belgrade, Belgrade, 2024.



FREIGHT WAGON FAILURES AS A BASIS FOR SAFETY-ORIENTED MAINTENANCE MANAGEMENT UNDER EUROPEAN RAILWAY REGULATIONS

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Abstract – The technical condition of freight wagons has a direct impact on railway safety and maintenance efficiency. This paper presents an analysis of failures recorded during technical inspections of freight wagons operated by Serbia Cargo and rented wagons over the period from September 2022 to January 2024. A database of recorded defects was analysed using descriptive statistical methods to identify the most failure-prone wagon subsystems and evaluate their significance for safety-oriented maintenance management. The results show that the brake system represents the most critical subsystem, accounting for 36% of failures in Serbia Cargo wagons and 56% in rented wagons. Brake block wear was identified as the dominant failure mode, while failures of pneumatic and mechanical brake components may directly affect braking performance and operational safety. A simplified Failure Mode Analysis (FMA) was performed to assess the risk associated with the most critical brake component failures. The findings indicate that systematic analysis of technical inspection data provides valuable support for risk-based maintenance planning in accordance with the Common Safety Methods (CSM) and the responsibilities of the Entity in Charge of Maintenance (ECM). The proposed maintenance and organizational measures contribute to improving railway safety and harmonizing maintenance practices with European railway regulations.

Keywords – freight wagons, brake system, maintenance management, railway safety, failure analysis, ECM, Common Safety Methods (CSM), risk assessment.

1. INTRODUCTION

The brake system is one of the most safety-critical subsystems of a freight wagon. Therefore, maintaining its operational reliability is essential for railway safety. Continuous monitoring of brake failures provides valuable information for improving maintenance strategies and reducing operational risks. This study analyses failures recorded during technical inspections of freight wagons operated by Serbia Cargo in order to identify the most failure-prone components and propose maintenance improvements.

Based on the failure records of freight wagons operated by "Serbia Cargo" from September 2022, to January 2024, at technical wagon inspection (TWI) points at Užice Traction and TWI Section, an analysis was conducted to identify the subsystems with the highest failure rates [1]. The causes of failures were determined, particularly for safety-critical assemblies such as brakes, and proposals for their mitigation were put forward. Technical non-conformity of vehicles (especially brakes) represents one of the primary sources of risk in the railway system.

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The Common Safety Methods (CSM) objectives and Common Safety Indicators (CSI) are established in accordance with EU directives 2016/798 [2]. This paper focuses on one of the key aspects, the technical reliability of vehicles as a prerequisite for achieving safety targets. Maintenance performed by the Entity in Charge of Maintenance (ECM) shall comply with the Common Safety Methods (CSM) to ensure that maintenance activities remain risk-based, traceable and consistent with European railway safety requirements. While the ECM serves as the entity directly responsible for the technical conformity of railway vehicles, the CSM provides a unified regulatory framework and methods by which this conformity is demonstrated and controlled.

The ECM ensures that the rolling stock is continuously monitored, analyzed, and documented. In doing so, it directly fulfills the requirements of the regulation on common safety methods for monitoring (CSM Monitoring), which mandates performance control and risk management. Through failure analysis and the implementation of corrective measures, the ECM contributes to the continuous improvement of safety. This paper provides an assessment of the impact of identified defects on the safety level of the system, alongside proposed mitigation measures aligned with EU requirements in the field of safety management for CSM and vehicle maintenance for ECM.

2. FAILURE ANALYSIS

To assess the state of functionality and identify the most frequent failures on freight wagons, tracking and logging of freight wagon defects was conducted at TWI points at stations Vreoci, Požega, Prijepolje Teretna, and the border stations of Serbia and Montenegro – Bijelo Polje. The inspections results analysed in this paper were from September 2022 to January 2024 both on company (Serbia Cargo) and rented wagons.

A total of 66% of recorded failures occurred on Serbia Cargo wagons, whereas rented wagons accounted for the remaining 34%. Brake-related failures account for 36% of Serbia Cargo wagons, whereas rented wagons have brake failure 56% [1]. Wagon body failures have 23% on rented wagons whereas on company wagons account for 42% failures (Fig. 1). Other subsystems show low failure rates with the exception of bogies, which account for 9% failure on company wagons. From the perspective of safety-oriented maintenance management, the brake system represents the most safety-critical subsystem. Therefore, the analysis was further expanded to examine brake system defects by components for both company and rented wagons.

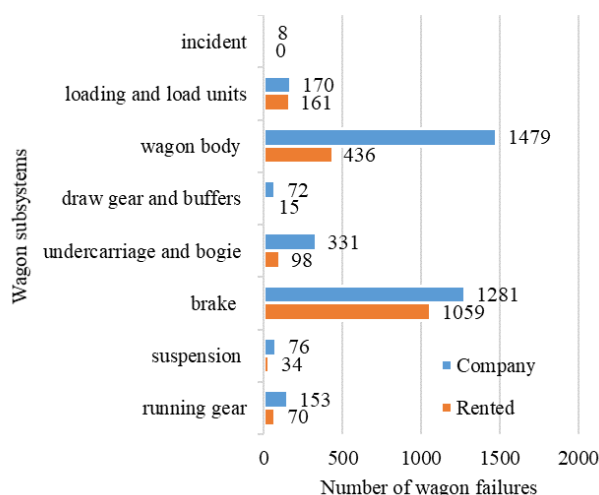


Fig. 1. Distribution of failures by wagon subsystems

The distribution of brake components failure on "Serbia Cargo" freight wagons shows highest rate of brake block failure (58%), while pneumatic component and mechanical component account for significantly less failures (Fig. 2). For rented wagons brake pneumatic components account for the largest share of brake failure (42%), followed by brake blocks (40%). Almost 91% of brake block failure are due to insert wear. This means that brake wear alone accounts for 36 % to 48% of the overall recorded failures. Brake failures predominated in Sgnss and Eanos company wagons and in Eanos and Sgns rented wagons.

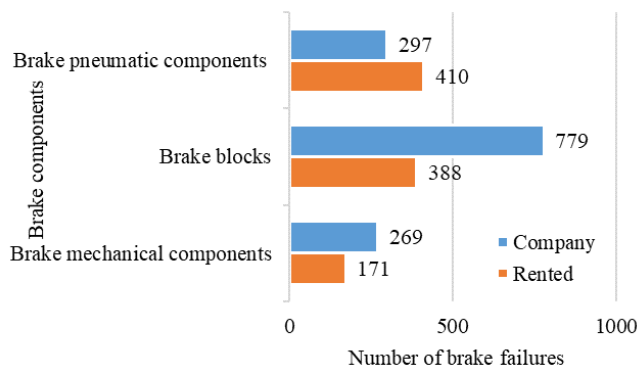


Fig. 2. Distribution of brake failures by component

The majority of failures on the brake pneumatic components can be rectified on-site—without decoupling the wagons—while they are still marshaled in the train formation. Alternatively, depending on the severity of the defect, the wagons can be sent to a workshop. Defects on the mechanical section of the brake system must generally be repaired in a workshop, with the exception of worn brake blocks, which can be replaced on-site.

3. SAFETY IMPLICATIONS AND MAINTENANCE MANAGEMENT

The results indicate that brake block wear represents the most significant maintenance issue.

Although primarily associated with increased maintenance costs, excessive wear may also reduce braking efficiency if replacement intervals are exceeded. Failures affecting pneumatic and mechanical brake components may reduce the effective braking mass of the train. Consequently, the required braking distance may not be achieved, increasing the risk of signal overruns or collisions. The results represent a good basis for CSM risk assessment whereas obtained data can be used as input for CSI. Also ECM should use results of TWI inspection to correct maintenance plans.

The rank of severity (S) and frequency (F) have values between 1 and 5, so the risk evolution in Risk Priority Number (RPN) range from 1 to 25. An overview of risk assessment using Failure Mode Analysis (FMA) for freight wagon failures is given in (Fig. 3). Severity (S) is in accordance with the defined classes of failure given in AVV, Annex 9 (1 – insignificant failures that correspond to low severity and 5 – critical failures that correspond to high severity). Frequency (F) was based on the obtained failure frequency data.

Tab.1. Risk analysis of freight wagon failures

Component	Failure root cause	Failure	Severity (S)	Frequency (F)	Risk Priority Number (RPN)
Brake mechanical components					
Broken or hanging brake rigging components	overload, corrosion, initial crack, material fatigue	fracture or fallout	4	2	8
Defective brake triangle support bracket	overload, corrosion, initial crack, material fatigue	fracture or fallout	4	1	4
Brake distributor isolating cock	external damage, corrosion, initial crack, material fatigue	damage	3	1	3
Brake force changeover device and brake mode selector	blocked valves, rust in the device, clogged nozzles	unusable	3	1	3
Brake release pull wire broken or missing	external damage, corrosion, initial crack, material fatigue	damage	3	1	3
Hand parking brake	external damage, corrosion, initial crack, material fatigue	damage	4	1	4
Brake block					
Cast iron brake block	missing, worn out, cracked	damage	3	4	12
Composite brake block	missing, worn out, cracked, material crushing	damage	3	1	3
Brake block overhanging the wheel tread	displaced	damage	3	1	3
Brake pneumatic components					
Main brake pipe	external damage, corrosion, initial crack, material fatigue	unusable	4	1	4
Brake hose coupling support bracket defective	external damage, tire aging	damage	3	1	3
Air brake inoperative but not isolated	external damage, loosening of the joint	damage	3	2	6
Brake pipe end cock	external damage, corrosion, initial crack, material fatigue does not seal, warped, missing handle	missing or unusable	5	1	5
Derailment detector	external damage, missing,	damage	4	1	4

The analysis of the risk of brake components failure showed that the RPN is the highest for component failure with the consequence of impact or collision due to a failure of brake. Brake failure of one wagon, lead to shortage of braking efficiency and can lead to signal overrun. Limited RPN value was set at 6 according to RNP rate in EN 50126 series standard set. The most critical component failures are

(Fig. 3):

- Broken or hanging brake rigging components - although it does not occur often, the seriousness of the consequences is great, so RPN = 8.
- Cast iron brake block - although it does not occur often, the lack or damage of one or more inserts, together with the high severity of the consequences, gives a high risk, so RPN = 12

- Air brake inoperative but not isolated, the frequency of occurrence is not high, but the severity of the consequences is moderate, so RPN = 6.

The high percentage of brake failures is strongly influenced by operating conditions on the Resnik–Bar railway line. Long descending gradients require intensive braking, resulting in accelerated wear of brake blocks and increased thermal loading of brake components. Wider application of regenerative braking could significantly reduce brake block consumption and improve maintenance efficiency.

Based on the analysis increased controls of certain types of wagons or components are proposed well as failure reporting and analysis system (feedback loop) so that the data from the TWI are used for the revision of maintenance plans (reduction of deadlines for critical components). This will increase safety and improve CSM monitoring. Also specific training for TWI inspectors and train drivers on the recognition of brake failure, which are often not visible during visual inspection, are proposed. The presented failure statistics enable maintenance decisions to be based on measured reliability data rather than fixed maintenance intervals.

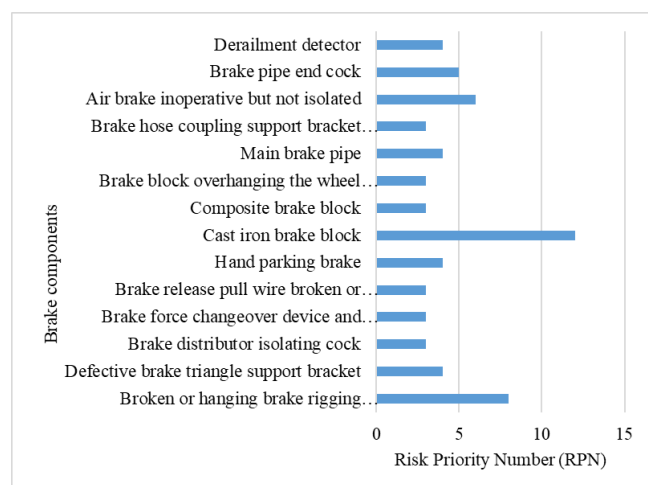


Fig. 3. Risk Priority Number (RPN) for the most critical brake failures

4. CONCLUSION

The highest failure of "Serbia Cargo" freight wagons were detected on wagon body and the brake system. The largest failures (brake block wear)

represents not only an operating cost, but also a potential safety risk if it is not managed adequately (timely replacement, control on the track, etc.). Brake block wear represents the dominant degradation mechanism observed in the analysed fleet and should therefore be considered the primary maintenance indicator for freight wagons operating on mountain railways. Proposed measures like improvement of the feedback loop, targeted controls, application of composite brake blocks represent a step towards harmonizing the maintenance system with the requirements of the EU regulations on ECM and CSM, which directly contributes to raising the level of safety on Serbian railways. Future research should extend the proposed methodology to other railway corridors and evaluate the cost-effectiveness of advanced diagnostic systems and predictive maintenance techniques.

REFERENCES

- [1] Guide for the application of the Commission Regulation (EU) 1078/2012 on CSM for monitoring (2014)
- [2] Final report on the activities of the Task Force Freight Wagon Maintenance (2010)
- [3] Vukšić Popović M., Tanasković J., Krišan I., Technical condition of railway vehicles as a safety factor in traffic, XI International Conference "Heavy Machinery HM 2023", Vrnjačka Banja (2023), pp. 33-38
- [4] Directive (EU) 2016/798 of the EU Parliament and of the Council of 11 May 2016 On Railway Safety (2016)
- [5] Bhadouria A., Braga J., Andrade A., Optimizing maintenance in railway wheelsets from freight wagons: What is the most appropriate lifetime variable?, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit Vo 240, Iss 5 (2025), <https://doi.org/10.1177/09544097251400096>
- [6] Rogić J., Analysis of Freight Wagon Failures for the Operator "Serbia Cargo" in the Area of the Train Traction Section and TWI Užice, BSc thesis, Academy of Technical and Art Applied Studies Belgrade, Belgrade, 2024.
- [7] Grenčík J., Poprocký R., Galliková J., Volna P., Use of risk assessment methods in maintenance for more reliable rolling stock operation, MATEC Web of Conferences 157, 04002 (2018) <https://doi.org/10.1051/matecconf/201815704002>
- [8] AVV, Annex 9



ENERGY HARVESTING TECHNOLOGIES FOR RAILWAY SENSOR SYSTEMS: A COMPARATIVE ANALYSIS BY APPLICATION AND DEPLOYMENT LOCATION

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Abstract – Supplying distributed railway sensor systems is challenging at remote and difficult-to-access locations where wired power is impractical and battery replacement increases maintenance requirements. This paper compares representative energy harvesting systems according to sensor application and deployment location. Piezoelectric, electromagnetic, photovoltaic, thermoelectric, magnetic-field and radiofrequency solutions are considered for different railway deployment locations. The systems are compared using reported power or energy output, operating conditions, sensor application and level of experimental validation. The results show that technology selection depends on source availability, installation constraints and sensor-node energy requirements, with some solutions enabling intermittent batteryless operation, while others supplement battery power or remain at the laboratory-validation stage. Efficient power management and energy storage, long-term field testing, and consistent reporting of energy performance are required for reliable assessment and wider railway deployment.

Keywords – railway sensor systems, energy harvesting, deployment location, wireless sensor nodes, autonomous power supply.

1. INTRODUCTION

Railway condition monitoring uses sensor measurements to support maintenance planning [1]. Applications include bridge strain and displacement monitoring [2], axle-box and bearing temperature monitoring [3], and rail vibration measurement [4]. Supplying these sensors can be difficult where electrical connections are unavailable or battery replacement requires access to remote installations [1, 2].

Energy harvesting offers locally available power for distributed sensing. Reviews cover diverse railway energy sources and conversion technologies [1, 5], but selecting a practical supply also requires relating published results to the intended monitoring task.

This paper examines representative energy harvesting systems for different railway applications and deployment locations. The systems were selected to cover different energy sources and installation

environments for which quantitative performance data and information on experimental validation are available. The analysis connects installation constraints and reported electrical performance with demonstrated sensor functionality, distinguishing evidence from laboratory experiments, field measurements and integrated monitoring systems. The objective is to clarify which conclusions about practical suitability are supported by the available tests.

2. ENERGY SOURCES AND CONVERSION TECHNOLOGIES

Piezoelectric harvesters generate electrical charge when their active elements deform under mechanical loading [6]. In vibration-driven electromagnetic harvesters, relative motion between a magnet and a coil induces a voltage; mechanical transmissions can also drive a generator [7, 8].

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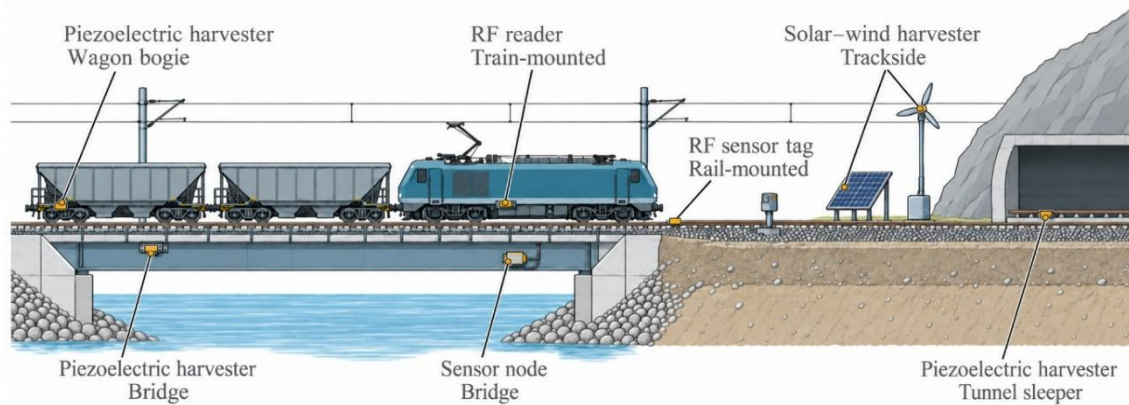


Fig. 1. Schematic illustration of energy harvesters and sensor-system components at representative railway installation locations

Photovoltaic devices convert incident solar radiation into electrical energy [9, 10]. Airflow can drive a turbine coupled to a generator or deform a piezoelectric element [11, 12]. Combining a photovoltaic panel with a wind turbine creates a hybrid system using two energy sources [12].

Thermoelectric generators exploit a temperature difference across their elements [13]. Magnetic-field harvesters use the alternating magnetic field associated with traction return currents [14, 15]. Although they also employ electromagnetic induction, their excitation comes from an externally varying field, without requiring mechanical motion to drive a generator [14].

Radiofrequency (RF) systems receive electromagnetic energy through an antenna and convert it into a DC electrical supply using rectifying circuitry [16]. Ambient RF harvesting uses existing signals, whereas dedicated RF power transfer relies on a transmitter provided for that purpose [16].

Figure 1 schematically illustrates selected energy harvesters and sensor-system components at representative railway installation locations.

3. COMPARISON BY APPLICATION AND DEPLOYMENT LOCATION

The comparison considers installation requirements, the sensor operation supported by the available energy, and experimental validation. Differences in excitation, device design and evaluation methods prevent direct ranking of published outputs [1, 5].

On freight wagons, two piezoelectric systems illustrate different installation conditions. A compact piezoelectric harvester for the restricted space of an axle box was tuned to low-frequency lateral vibrations. It powered commercial wireless sensors in laboratory tests, and its durability was evaluated on a full-scale wagon roller rig [17]. A separate bogie-mounted harvester was field-tested during an eight-hour journey as supplemental power for a node intended to monitor

axle-box and bearing temperature [3]. A photovoltaic wagon node was evaluated through charging measurements, node consumption and almost one year of field monitoring at half-hour intervals [10]. These studies therefore differ in installation location, validation level and whether the harvested energy powers the sensor directly or supplements stored energy.

For track installations, an electromagnetic system demonstrated wireless sensor operation during laboratory replay of recorded railway vibrations [7]. A piezoelectric device for tunnel sleepers was also tested with recorded train excitation, but sensor and radio integration remained future work [18]. The former demonstrates an operational load, while the latter establishes an energy resource requiring further system integration.

On electrified tracks, the magnetic-field device in [15] was evaluated by combining field magnetic measurements with laboratory characterisation to estimate electrical output; an integrated sensor node was not demonstrated in service. In the RF approach, a train-mounted reader supplies energy and receives vibration data from a rail-mounted tag, with tests performed on a scaled railway system [4]. Its operating opportunity is therefore linked to reader-tag interaction.

Bridge monitoring illustrates how energy replenishment determines measurement timing. A piezoelectric system accumulated energy before activating strain and displacement nodes, with approximately 2.6 J required per activation [2]. Its field demonstration supports periodic observations. An airflow harvester proposed for bridge wind barriers was evaluated through wind-tunnel experiments and numerical analysis [11], providing less direct evidence of complete monitoring-node operation.

Table 1 summarises the quantitative results, applications and validation conditions of representative systems.

Tab. 1. Comparison of selected railway energy harvesting systems

Ref.	Location / technology	Reported performance / test conditions	Application / validation
[3]	Wagon bogie / piezoelectric	$\approx 60 \mu\text{W}$; vibrations at 4–10 Hz	Temperature monitoring; battery supplementation; onboard tests
[10]	Freight wagon / photovoltaic	Charging limited to $\approx 40 \text{ mW}$ in direct sunlight; mean node consumption $\approx 2 \text{ mW}$	Condition monitoring; almost one year of field testing
[7]	Track / electromagnetic	Mean power 9.1–29.3 mW; energy 77–167 mJ per replayed train passage	Laboratory vibration replay; wireless sensor demonstrated
[15]	Rail / magnetic field	Laboratory: 184–5178 mW at 100–500 A; estimated $1138 \pm 1603 \text{ mJ/train}$ from field data	Laboratory tests; output estimated from field magnetic measurements
[4]	Rail tag / RF	Activation up to 2.3 m; maximum conversion efficiency 25%	Vibration sensing; dedicated reader; scaled-system tests
[2]	Bridge / piezoelectric	Energy demand $\approx 2.6 \text{ J}$ per activation; mean interval 57–59 min	Strain and displacement monitoring; field demonstration
[18]	Tunnel sleeper / piezoelectric	Mean $260 \mu\text{J}$ per replayed train passage	Laboratory vibration replay; complete node integration pending
[13]	Rail-ground / thermoelectric	Field: 5.8 mW at $\Delta T = 8 \text{ }^\circ\text{C}$; lab: 316.8 mW at $\Delta T = 29.2 \text{ }^\circ\text{C}$	Field and laboratory tests; charging demonstrated
[12]	Trackside / solar-wind	Mean 12.31 W at 17.5 m/s and 1700 W/m^2	Laboratory tests; sensor power supply proposed

Note: Reported power, harvested energy, node demand, and RF transfer characteristics are different metrics and are not directly comparable.

At exposed trackside locations, photovoltaic and hybrid solar-wind devices have been investigated for railway equipment and wireless sensors [9, 12]. The hybrid output was measured under specified laboratory airflow and irradiance conditions and cannot be assumed continuously available [12]. The rail-ground thermoelectric study demonstrated battery charging, with field and laboratory outputs obtained at different temperature differences [13]. These results establish source and charging performance within the tested conditions, rather than a verified sensing schedule.

Across the considered deployment locations, the practical applicability of a technology is determined less by the maximum output power of the energy harvesting system than by whether sufficient energy is available when required and whether system operation has been demonstrated under the complete sensing and communication load.

4. FUTURE RESEARCH DIRECTIONS

Power-management research should address the energy consumed within the supply system itself. Storage leakage can reduce the energy retained between sensor activations [2], making low-loss storage and low standby consumption important design objectives. Future experiments should separately measure losses in rectification, voltage conversion, and storage, and evaluate whether the system can restart after its stored energy has been depleted. Control strategies should also be tested for their ability to adjust

sensing and transmission intervals while meeting the application's minimum monitoring requirements.

Mechanical durability, environmental resistance, and economic feasibility are further priorities for railway deployment [5]. Extended field trials should track changes in output, mounting integrity, and component condition under repeated loading and exposure to temperature variations, moisture, and dust. Economic assessment should include installation and maintenance costs alongside the battery replacements and service visits avoided. This would establish whether a technically functional device offers a practical benefit over its expected service life.

For future evaluations, this review proposes a common reporting framework that specifies the excitation or environmental conditions, the period over which power is averaged, and the point in the electrical circuit where output is measured. Results should additionally state usable stored energy, consumption per complete sensing and communication cycle, and the proportion of scheduled measurements successfully delivered. Recording interruptions and recovery times would provide a measurable basis for assessing the continuity of the monitoring service.

5. CONCLUSION

Energy harvesting can reduce dependence on conventional power supplies in railway sensing, but its contribution varies with the application and installation location. The reviewed systems support different

outcomes, from battery supplementation to intermittent sensor operation, with unequal levels of experimental validation. Technology selection should therefore begin with the required measurements and their timing, followed by an assessment of locally available energy and installation constraints. Demonstrated operation of the complete sensor node provides the clearest basis for judging practical suitability. Consistent reporting of energy availability, system losses, and energy consumption per complete sensing and communication cycle would enable more reliable comparison between technologies. Claims of energy autonomy should remain tied to the operating conditions and monitoring functions actually demonstrated.

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REFERENCES

- [1] J. Zuo, L. Dong, F. Yang, Z. Guo, T. Wang and L. Zuo, "Energy harvesting solutions for railway transportation: A comprehensive review," *Renewable Energy*, vol. 202, pp. 56–87, 2023.
- [2] W. Sheng, H. Xiang, Z. Zhang and J. Wang, "Experimental study and application of a self-powered wireless health monitoring system for railway bridges based on piezoelectric energy harvesting," *Energy*, vol. 317, Art. no. 134583, 2025.
- [3] B. Dziadok, M. Kucharek and J. Starzyński, "Powering the WSN node for monitoring rail car parameters, using a piezoelectric energy harvester," *Energies*, vol. 15, Art. no. 1641, 2022.
- [4] P. Li, Z. Long and Z. Yang, "RF energy harvesting for batteryless and maintenance-free condition monitoring of railway tracks," *IEEE Internet of Things Journal*, vol. 8, no. 5, pp. 3512–3523, 2021.
- [5] R. Wang, J. Zhang, P. Liu, D. Crosbee, Y. Han and S. Zhang, "A review of energy harvesting technologies for railway systems: Principles, applications and challenges," *Energy Conversion and Management: X*, vol. 30, Art. no. 101810, 2026.
- [6] G. Shan, D. Wang, Z. J. Chew and M. Zhu, "A high-power, robust piezoelectric energy harvester for wireless sensor networks in railway applications," *Sensors and Actuators A: Physical*, vol. 360, Art. no. 114525, 2023.
- [7] Z. Hadas, O. Rubes, F. Ksica and J. Chalupa, "Kinetic electromagnetic energy harvester for railway applications-Development and test with wireless sensor," *Sensors*, vol. 22, Art. no. 905, 2022.
- [8] T. Zhang, L. Kong, Z. Zhu, X. Wu, H. Li, Z. Zhang and J. Yan, "An electromagnetic vibration energy harvesting system based on series coupling input mechanism for freight railroads," *Applied Energy*, vol. 353, Art. no. 122047, 2024.
- [9] D. Hao, T. Zhang, L. Guo, Y. Feng, Z. Zhang and Y. Yuan, "A high-efficiency, portable solar energy-harvesting system based on a foldable-wings mechanism for self-powered applications in railways," *Energy Technology*, vol. 9, Art. no. 2000794, 2021.
- [10] S. Cii, G. Tomasini, M. L. Bacci and D. Tarsitano, "Solar wireless sensor nodes for condition monitoring of freight trains," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 5, pp. 3995–4007, 2022.
- [11] X. Xue and H. Xiang, "Performance of a novel piezoelectric energy harvester in railway wind barriers under coupling of train-induced wind and crosswinds," *Engineering Structures*, vol. 349, Art. no. 121872, 2026.
- [12] A. M. Tairab, H. Wang, D. Hao, A. Azam, A. Ahmed and Z. Zhang, "A hybrid multimodal energy harvester for self-powered wireless sensors in the railway," *Energy for Sustainable Development*, vol. 68, pp. 150–169, 2022.
- [13] M. Gao, C. Su, J. Cong, F. Yang, Y. Wang and P. Wang, "Harvesting thermoelectric energy from railway track," *Energy*, vol. 180, pp. 315–329, 2019.
- [14] Y. Kuang, Z. J. Chew, T. Ruan, T. Lane, B. Allen, B. Nayar and M. Zhu, "Magnetic field energy harvesting from the traction return current in rail tracks," *Applied Energy*, vol. 292, Art. no. 116911, 2021.
- [15] Y. Kuang, C. Zuo and X. Gu, "Design, modelling and field test of a track-borne magnetic field energy harvester for electrified railways," *Applied Energy*, vol. 401, Art. no. 126665, 2025.
- [16] S. K. Divakaran, D. D. Krishna and Nasimuddin, "RF energy harvesting systems: An overview and design issues," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 29, Art. no. e21633, 2019.
- [17] Z. Wang, W. Wang, L. Tang, et al., "A piezoelectric energy harvester for freight train condition monitoring system with the hybrid nonlinear mechanism," *Mechanical Systems and Signal Processing*, vol. 180, Art. no. 109403, 2022.
- [18] M. Wischke, G. Biancuzzi, G. Fehrenbach, Y. Abbas and P. Woias, "Vibration harvesting in railway tunnels," in *Proceedings of PowerMEMS 2010*, pp. 123–126, 2010.



PIEZOELECTRIC ENERGY HARVESTERS FOR RAILWAY TRACK VIBRATIONS: A REVIEW OF STRUCTURAL DESIGNS AND PERFORMANCE ENHANCEMENT STRATEGIES

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Abstract – Wireless sensors deployed along railway infrastructure are commonly powered by batteries, whose replacement can be costly, particularly on remote sections. Track vibrations induced by passing trains represent a local source of mechanical energy that can be converted into electrical energy using piezoelectric harvesters. This paper reviews structural configurations for railway track applications, including cantilever beams, piezoelectric stacks, and arched and ring-shaped structures. Methods for improving performance, including resonance tuning, broadband operation, frequency up-conversion, mechanical amplification, and overload protection, are examined. Representative designs are compared in terms of mounting location, excitation conditions, and output power.

Keywords – railway track, piezoelectric energy harvesting, vibration, structural design, performance enhancement.

1. INTRODUCTION

Railway transport is playing an important role in both passenger and freight transportation, while the total length of the global railway network reached approximately 1.15 million kilometres by 2023. [1]. As traffic volumes increase, the need for continuous monitoring of railway infrastructure condition also becomes more pronounced. Traditional manual inspections are labour-intensive and make it difficult to obtain continuous and reproducible data over long distances [2]. Consequently, sensor-based monitoring systems are being widely deployed along railway infrastructure to assess the condition of the track and its components [1].

One of the challenges associated with the broader deployment of such systems is ensuring a reliable power supply. Batteries require periodic replacement and maintenance, whereas wired power supply may be technically complex and economically unjustified on remote railway sections [2, 3]. As an alternative, local energy harvesting from the surrounding environment has been investigated. Passing trains induce periodic deformations and vibrations in rails and other track components, making the resulting mechanical energy a potential source for powering sensor systems [3]. Piezoelectric energy harvesters enable the conversion of mechanical energy from railway track vibrations

into electrical energy. Their compact dimensions, relatively simple design, and suitability for integration within the limited space available along railway tracks make them attractive for railway applications [1, 2].

However, the efficient utilization of railway track vibrations presents a significant design challenge. The excitation characteristics depend on train speed and axle load, axle arrangement, wheel-rail condition, and the mechanical properties of the track. These variations make the selection and design of the harvester important for effective energy conversion. [1-3]. The aim of this paper is to review the structural designs of piezoelectric harvesters proposed for railway track and the methods used to increase their output, and to compare representative solutions by mounting position, excitation and output power.

2. RAILWAY TRACK VIBRATIONS AND PIEZOELECTRIC ENERGY CONVERSION

At frequencies below approximately 30 Hz, vertical track vibration is dominated by the quasi-static response to moving axle loads, while dynamic effects associated with wheel-rail irregularities become more significant at higher frequencies [4]. The periodic arrangement of axles produces characteristic trainload frequencies, whose amplitudes

depend on train geometry, particularly axle and wheel spacing, as well as track properties [4]. Railway vibrations therefore cover a broad frequency range, with significant components reported from approximately 15 to 650 Hz, depending on the train and track conditions [1, 2].

Harvesters exploit the direct piezoelectric effect, where a material becomes polarized and produces electrical energy under mechanical stress [3]. Their operating mode is commonly described by the coefficient d_{ij} , where i and j indicate the directions of the resulting electric field and applied strain, respectively, with 3 denoting the polarization axis [2]. The d_{31} mode, commonly used in bending configurations, enables relatively large deformation under low-amplitude excitation. In the d_{33} mode, the applied force acts along the polarization direction and is commonly employed in multilayer piezoelectric stacks subjected to compression [2]. Lead zirconate titanate (PZT) ceramics are widely used because of their favorable piezoelectric properties and energy output, although their limited tolerance to large strains must be considered in harvester design [1, 2].

3. STRUCTURAL DESIGNS OF PIEZOELECTRIC ENERGY HARVESTERS

Piezoelectric energy harvesters for railway applications have been developed in different structural configurations to adapt the mechanical excitation of the track to the operating characteristics of the piezoelectric element. The representative configurations considered in this review are grouped into cantilever harvesters, piezoelectric stack harvesters, and arched and ring-shaped harvesters, as illustrated in Fig. 1.

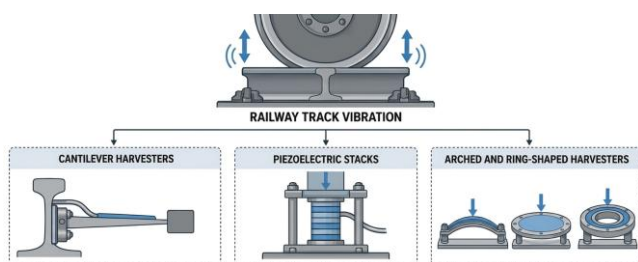


Fig. 1. Piezoelectric energy harvesting from railway track vibration: representative structural configurations

3.1. Cantilever Harvesters

Cantilever harvesters convert track vibration into bending deformation of a piezoelectric beam, typically operating in the d_{31} mode. Since the bending stress is highest near the clamped end and decreases towards the free end, different beam geometries and

proof-mass arrangements have been investigated to improve strain distribution and tune the resonant response [2]. Gao et al. [5] developed a rail-mounted PZT cantilever with a tip mass for low-frequency vibration harvesting, achieving 4.9mW at 7 Hz. To improve the response over a wider frequency range, Yang et al. [6] optimized a bimorph cantilever for the dominant track vibration frequencies, while Dong et al. [7] introduced a dual-mass configuration that allows the first two natural frequencies to be tuned to different components of the track excitation. These studies show the development from simple single-resonance cantilevers towards broadband and multimodal configurations.

3.2. Piezoelectric Stack Harvesters

Piezoelectric stacks consist of multiple piezoelectric layers and generally operate in compression using the d_{33} mode. Their high stiffness allows them to withstand substantial compressive loads, but also makes efficient mechanical excitation and force transfer important. Stack-based harvesters therefore often incorporate mechanisms for frequency up-conversion or force amplification. Shan and Zhu [8] separated the inertial mass and piezoelectric stack into two interacting systems, using impact to excite the stack close to its resonant frequency even when the track excitation occurs at a much lower frequency. The prototype generated a maximum power of 495.74mW and an average power of 43.58mW at 18Hz. A later design [9] combined frequency up-conversion with a mechanical transformer that amplifies the force applied to the stack, producing a maximum power of 568mW under measured railway vibration.

3.3. Arched and Ring-Shaped Harvesters

Arched and ring-shaped structures use their geometry to transfer track loads to piezoelectric elements while reducing direct impact and improving mechanical load distribution. Min et al. [10] proposed an arch-beam piezoelectric stack harvester for low-frequency railway vibration, achieving 193mW. The concept was further developed into a double-arch structure [11], in which the frame cushions the impact and protects the brittle piezoelectric stacks; the complete harvester produced 1.05mW under a 3Hz, 8kN excitation. A different geometric approach was adopted in the doughnut-shaped harvester [12], which uses stacked ring-shaped units and produced 7.23mW under a 3kN, 7Hz laboratory load and 207.67mW under railway track vibration conditions.

4. PERFORMANCE ENHANCEMENT METHODS

Several methods have been developed to broaden the operating frequency range, improve mechanical energy transfer, and protect piezoelectric harvesters from excessive loads.

4.1. Resonance Tuning and Broadband Operation

Resonance tuning can be achieved by modifying the structural parameters of the harvester, particularly the proof masses in cantilever configurations. Dong et al. [7] introduced a dual-mass cantilever in which the tip mass primarily affects the first natural frequency, while the middle mass has a stronger influence on the second. Optimization of the middle mass and its position increased the voltage response at the second dominant track frequency by 32% [7]. Yang et al. [6] addressed the broadband nature of railway vibration through the design of a bimorph harvester adapted to the measured rail response. Other approaches, including multistable structures and arrays of harvesters tuned to different frequencies, can further extend the effective operating bandwidth [2, 3].

4.2. Frequency Up-Conversion and Mechanical Amplification

The relatively low dominant frequencies of railway track vibration can be substantially lower than the resonant frequency of a piezoelectric stack transducer. Frequency up-conversion addresses this mismatch by using low-frequency motion to generate an impact that excites the piezoelectric transducer at its higher natural frequency [8]. In the design of Shan and Zhu [9], an inertial mass system impacts a separate piezoelectric stack system, after which the stack

vibrates freely at its resonant frequency.

Mechanical amplification can additionally increase the force transmitted to the piezoelectric stack. Shan et al. [9] used a mechanical transformer with inclined beams, for which the force amplification factor is determined by the beam angle. The transformer increases the force applied to the stack, while its dimensions must be selected so that mechanical stresses remain within acceptable limits. Arched structures [10, 11] provide another means of transferring and redistributing mechanical loads while protecting the piezoelectric elements.

4.3. Overload Protection

Railway vibration amplitudes can vary considerably with operating conditions, making overload protection important for long-term operation. Shan et al. [13] developed two protection strategies based on mechanical stoppers and impact protection components. Type I restricts inertial-mass displacement and is designed for operation within a 5g ($g=9.81\text{m/s}^2$) acceleration threshold, while Type II dissipates excess energy and enables operation at accelerations up to 15g [13]. These mechanisms reduce the risk of mechanical damage under high vibration levels.

5. COMPARATIVE ANALYSIS

Table 1 reveals substantial differences in the operating principles, excitation conditions, and reported performance of the reviewed harvesters. Cantilever harvesters [5–7] exploit rail vibration through bending and provide relatively simple means of resonance tuning. While the conventional tip-mass configuration [5] is suitable for low-frequency excitation, the broadband [6] and dual-mass [7] designs extend the operating frequency range or

Tab. 1. Comparison of representative piezoelectric energy harvesters for railway track applications

Harvester type (Ref.)	Mounting position	Excitation conditions	Output power	Main advantage
Cantilever with tip mass [5]	Rail web	5–7 Hz, 5g, 100 k Ω	4.9 mW peak	Simple design for low-frequency vibration
Bimorph cantilever, broadband design [6]	Rail web	Random broadband rail vibration	1036.9 $\mu\text{W/Hz}$ and 8.01 $\mu\text{W/Hz}$	Broadband response
Dual-mass cantilever [7]	Rail web	Dominant frequencies: 64 Hz and 721 Hz	65.5 mW and 1.4 mW at the two dominant frequencies	Two tunable natural frequencies
Piezo stack with freq. up-conversion [8]	Rail	18Hz, 0.7g RMS, 150 Ω	495.74 mW peak / 43.58 mW average	Frequency up-conversion (18 to 161 Hz)
Piezo stack with mech. transformer [9]	Rail	21 Hz, 0.7g RMS; measured track vibration signal	511mW peak/24.5mW avg. 568mW peak/7.3mW avg.	Frequency up-conversion and force amplification
Arch beam piezo stack [10]	Under the rail	3Hz, 21kN, 1kN pre-stress	193 mW (211.8 $\mu\text{W/g}$)	Load transfer through arch structure
Double-arch piezo stack [11]	Under the rail	3Hz, 8kN, 340k Ω	1.05 mW total	Impact cushioning and stack protection
Doughnut-shaped harvester [12]	Under the rail	3kN at 7 Hz, 230 k Ω ; track vibration conditions	7.23 mW; 207.67mW under track vibration	Compact stacked-ring structure
Piezo stack with protection [13]	Sleeper	5g (Type I) 15g (Type II)	718mW peak/4.6mW avg. 1365mW peak/11 mW avg.	Overload protection

enable tuning to multiple dominant track frequencies. Their main limitation is the dependence of the output on the relationship between the excitation spectrum and the natural frequencies of the harvester.

Stack-based configurations use different approaches to improve energy conversion. Frequency up-conversion [8] enables low-frequency track motion to excite the piezoelectric stack near its higher natural frequency, while the mechanical transformer [9] additionally amplifies the transmitted force. Both approaches achieved peak powers of approximately 0.5 W, although the corresponding average powers were substantially lower.

Arched and ring-shaped designs [10–12] focus on load transfer and protection of brittle piezoelectric elements. Reported outputs range from 1.05 mW for the double-arch configuration [11] to 207.67 mW for the doughnut-shaped harvester under track vibration [12]. At higher vibration levels, the stopper and impact-protection concepts in [13] provide additional mechanical protection at acceleration levels of 5g and 15g.

Direct performance ranking is difficult because the prototypes were tested under different excitation, electrical load, and mounting conditions. The comparison therefore indicates that railway piezoelectric harvester design involves a trade-off between electrical output, frequency adaptability, mechanical load transfer, and protection. More standardized testing under representative track vibration would enable more reliable comparison of future designs.

6. CONCLUSION

Piezoelectric energy harvesting offers a potential solution for powering low-power railway monitoring systems. The reviewed studies show a development from conventional cantilever harvesters towards broadband, frequency up-conversion, mechanically amplified, and protected stack-based configurations. While these approaches can improve energy conversion under railway vibration, differences in experimental conditions make direct performance comparison difficult. Further long-term testing under representative railway traffic is needed to evaluate practical reliability and energy supply capability.

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REFERENCES

- [1] Ding, D., Fan, J., Wang, H., Jing, G., Guo, Y., *Piezoelectric energy harvesting in railways: Current status and future challenges*, Energy Strategy Reviews, Vol. 61, 101869, 2025.
- [2] Jing, G., Zhang, R., Connolly, D. P., Hou, W., Aela, P., *Piezoelectric energy harvesters for railways: recent trends and future opportunities*, Multiscale and Multidisciplinary Modeling, Experiments and Design, Vol. 8, 325, 2025.
- [3] Zuo, J., Dong, L., Yang, F., Guo, Z., Wang, T., Zuo, L., *Energy harvesting solutions for railway transportation: A comprehensive review*, Renewable Energy, Vol. 202, pp. 56-87, 2023.
- [4] Cleante, V. G., Brennan, M. J., Gatti, G., Thompson, D. J., *On the target frequency for harvesting energy from track vibrations due to passing trains*, Mechanical Systems and Signal Processing, Vol. 114, pp. 212-223, 2019.
- [5] Gao, M. Y., Wang, P., Cao, Y., Chen, R., Liu, C., *A rail-borne piezoelectric transducer for energy harvesting of railway vibration*, Journal of Vibroengineering, Vol. 18, Issue 7, pp. 4647-4663, 2016.
- [6] Yang, F., Gao, M., Wang, P., Zuo, J., Dai, J., Cong, J., *Efficient piezoelectric harvester for random broadband vibration of rail*, Energy, Vol. 218, 119559, 2021.
- [7] Dong, L., Zuo, J., Wang, T., Xue, W., Wang, P., Li, J., Yang, F., *Enhanced piezoelectric harvester for track vibration based on tunable broadband resonant methodology*, Energy, Vol. 254, 124274, 2022.
- [8] Shan, G., Zhu, M., *A piezo stack energy harvester with frequency up-conversion for rail track vibration*, Mechanical Systems and Signal Processing, Vol. 178, 109268, 2022.
- [9] Shan, G., Wang, D., Chew, Z. J., Zhu, M., *A high-power, robust piezoelectric energy harvester for wireless sensor networks in railway applications*, Sensors and Actuators A: Physical, Vol. 360, 114525, 2023.
- [10] Min, Z., Hou, C., Sui, G., Shan, X., Xie, T., *Simulation and Experimental Study of a Piezoelectric Stack Energy Harvester for Railway Track Vibrations*, Micromachines, Vol. 14, 892, 2023.
- [11] Min, Z., Chen, Y., Shan, X., Xie, T., *A novel double-arch piezoelectric energy harvester for capturing railway track vibration energy*, Energy, Vol. 312, 133636, 2024.
- [12] Min, Z., Du, X., Zhang, X., Wu, W., Shan, X., Xie, T., *Picking up railway track vibration energy using a novel doughnut-shaped piezoelectric energy harvester*, Energy, Vol. 310, 133183, 2024.
- [13] Shan, G., Wang, D., Zhu, M., *Piezo stack energy harvesters with protection components for railway applications*, Sensors and Actuators A: Physical, Vol. 373, 115454, 2024.

Strategy and policy



THE MISSING INSTITUTION IN EUROPEAN RAIL FREIGHT CORRIDOR GOVERNANCE: LESSONS FROM AVIATION AND ELECTRICITY

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Abstract – Recent research has shown that the application of cooperative game theory in European rail freight corridor governance, as a tool for enhancing cooperation among governments and infrastructure managers, can improve corridor performance and revenue generation through cooperative game solution concepts. However, the practical application of such a model depends on a critical institutional assumption: the existence of a governance body able to centrally collect track access charges or, at minimum, organize financial transfers between corridor participants. This paper addresses this institutional void. It examines the current governance structure of Rail Freight Corridors under Regulation (EU) No 913/2010 and argues that existing corridor bodies function primarily as coordination platforms rather than entities with fiscal authority. To identify a feasible path forward, the paper compares rail with electricity and aviation sectors, where these issues are already addressed. On this basis, it proposes a practical corridor-level institutional model capable of operationalizing cooperative revenue allocation, improving corridor performance, and strengthening the competitiveness of rail freight in the European transport market.

Keywords – railway corridors, electricity, aviation, governance, revenue allocation

1. INTRODUCTION

Rail freight corridors (RFCs) represent one of the clearest examples of the tension between the transnational logic of transport markets and the nationally bounded structure of infrastructure governance in Europe. Although international freight services operate across several countries as a single transport chain, the underlying infrastructure remains managed, priced, and financially accounted for by separate national infrastructure managers (IMs). Despite more than a decade of development, RFC governance bodies remain coordination platforms without financial competences. None of the existing corridor bodies is empowered to collect, settle, redistribute, or compensate corridor-related infrastructure charges. As a result, railway undertakings still face a system in which track access charges are paid separately to each IM along the route, while broader corridor objectives continue to depend largely on voluntary cooperation among participating states and IMs. This institutional asymmetry significantly constrains the capacity of RFCs to

function as integrated economic and governance spaces.

This paper builds directly on previous research by the same author(s), including the published cooperative game model in Prokić and Bošković (2025) and the broader analytical and empirical work developed in Prokić (2026). That research started from the premise that many of the persistent inefficiencies observed on international rail freight corridors stem from insufficient coordination and cooperation among governments and IMs along the corridor. On that basis, a cooperative game framework was developed and demonstrated, including on the Alpine–Western Balkan Rail Freight Corridor, showing that corridor-level cooperation may generate higher collective track access charges revenues than nationally optimized charging structures. By applying cooperative game theory, particularly the Shapley Value together with two corridor-specific solution concepts, the model provided a mathematical basis for allocating the gains from cooperation among corridor participants [1], [2].

The significance of that earlier work is twofold.

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First, it demonstrated that corridor-level cooperation is not only normatively desirable but can also be economically rational. Second, it showed that RFCs may be understood not merely as platforms for coordination, but as potential spaces of joint economic governance in which performance improvements and revenue gains can be distributed according to transparent rules. However, that same research also revealed a decisive institutional limitation: cooperative revenue allocation cannot be implemented without a mechanism capable of collecting payments, calculating entitlements, and arranging financial transfers among participating IMs. Such a mechanism is currently absent from RFC governance.

This is the central problem addressed in the present paper. While the economic and mathematical foundations of corridor-level cooperation have already been established, the institutional framework required to operationalize them is still missing. Regulation (EU) No 913/2010 created a framework for coordination, capacity-related cooperation, and stakeholder consultation, but it did not establish a corridor-level fiscal or settlement mechanism. In this respect, the existing institutional design is not merely incomplete, it is structurally incapable of implementing cooperative revenue allocation in practice [3].

To assess whether such an institutional arrangement could be developed in the railway sector, this paper turns to other European network industries characterized by transnational flows and nationally organized infrastructure. Electricity and aviation provide particularly relevant points of comparison because, in both sectors, the growth of cross-border flows led to institutional mechanisms extending beyond coordination alone to include charging, compensation, and revenue redistribution. This broader question is not absent from European railway policy debates. The European Union Agency for Railways has already raised the idea of a “Eurocontrol for rail,” pointing to the need for stronger pan-European institutional capacity in traffic management, path allocation, and cost recovery [4].

Against this background, the present paper asks what kind of institutional design would be required to operate cooperative revenue allocation in European rail freight corridors. More specifically, it examines whether the experience of the electricity and aviation sectors can inform the creation of a rail-specific body or department capable of supporting centralized track access charge collection and redistribution. The contribution of the paper is therefore not to propose a new mathematical allocation rule, but to shift the debate from allocation theory to institutional design. The central question is no longer only how the cooperation surplus should be divided, but which

institution should have the authority and capacity to collect, manage, and redistribute it.

2. STATE OF PLAY IN EUROPEAN ELECTRICITY SECTOR

The electricity sector provides a particularly relevant institutional analogy for RFCs because it combines cross-border flows with nationally organized infrastructure management. Like the railway sector, it underwent liberalization and structural reform, through which vertically integrated national monopolies were unbundled and infrastructure management was separated from competitive market activities. In that process, Transmission System Operators (TSOs) emerged as the entities responsible for operating, maintaining, and developing the high-voltage transmission grid, in a role broadly comparable to that of IMs in the railway sector [5], [6]. This parallel is important because in both sectors infrastructure remains nationally organized, while system use increasingly acquires a transnational character. As cross-border electricity trade expanded, the physical and economic interdependence of national grids became increasingly difficult to manage through domestic institutions alone. Nationally optimal decisions often diverged from what would be optimal at the European level, particularly in areas such as system operation, investment planning, and tariff design [7]. In response, the European Union progressively developed a multi-level governance framework capable of reconciling national competences with broader system objectives. At the European level, the Agency for the Cooperation of Energy Regulators (ACER) was established to strengthen coordination among national regulators and reduce the risk of fragmentation within the internal energy market [7]. [8]. At the level of infrastructure management, the European Network of Transmission System Operators for Electricity (ENTSO-E) was established in 2009 as a supranational, not-for-profit association representing TSOs across Europe and providing a common institutional platform for cooperation in network planning, market integration, adequacy assessment, technical standard-setting, and the development of shared tools and data platforms [5], [9]. A particularly important lesson for the railway sector lies in the evolution of regional cooperation in electricity. Initially, coordination among TSOs was largely voluntary and took place through joint offices and technical coordination centres. Over time, however, it became evident that voluntary cooperation was not sufficient to sustain an increasingly integrated market and to safeguard cross-border system performance. This led first to the creation of Regional Security Coordinators and later, with a stronger legal basis, to

the establishment of mandatory Regional Coordination Centres from July 2022 onward [10]. In other words, what began as voluntary cooperation gradually evolved into a more formalized and partly mandatory structure, supported by supranational institutions and clearer European rules. This institutional trajectory is highly relevant for RFCs, where cooperation remains predominantly voluntary and where corridor governance bodies still lack the authority and instruments needed to ensure effective collective action. Another key feature of the electricity sector, and one largely absent from the railway sector, is the existence of a European-level mechanism for charging and compensating transit flows. As the internal electricity market developed, traditional transit charges became increasingly problematic because they led to tariff pancaking, that is, the accumulation of multiple transmission charges as electricity transactions crossed several national borders. This created a barrier to efficient cross-border trade because charges reflected the number of jurisdictions crossed rather than the logic of an integrated network. In response, the sector moved toward the so-called single system paradigm, under which the European electricity network would increasingly be treated, for tariff purposes, as if it were one integrated system rather than a sequence of separate national systems [11]. The abolition of separate transit charges, however, immediately created a redistribution problem. TSOs hosting cross-border flows continued to bear transmission losses and infrastructure-related costs, but they could no longer recover those costs through national transit tariffs. The response was the creation of the Inter-Transmission System Operator Compensation (ITC) mechanism, first introduced in 2002 and subsequently formalized in European legislation, notably Regulation 714/2009 and Commission Regulation 838/2010 [11], [12]. Rather than establishing a single pan-European transmission tariff, the parties opted for a compensation mechanism covering both the use of external networks and the losses generated by cross-border transactions and loop flows [13]. Today, the ITC mechanism forms part of Europe's broader electricity infrastructure cost-sharing framework. It compensates TSOs for the costs of hosting cross-border transit flows, including transmission losses and infrastructure availability costs. The mechanism is financed through the ITC Fund, with participating TSOs or groups of TSOs receiving compensation according to the transits they carry and contributing to the fund on the basis of their net imports and exports. Its implementation and clearing are carried out by ENTSO-E under the ITC Clearing and Settlement Multi-Year Agreement, while ACER oversees implementation and reports annually to the European

Commission on the functioning of the mechanism and the management of the fund [14].

3. STATE OF PLAY IN EUROPEAN AVIATION SECTOR

Since the 1950s, the rapid expansion of civil aviation, driven in particular by the introduction of jet aircraft, has led to a substantial increase in air traffic volumes and, consequently, to a significant rise in the complexity of air traffic management. This development required European countries to invest in increasingly advanced automated systems, while the costs of providing air navigation services grew considerably. At the same time, countries became aware that, with the expansion of international civil aviation, they were effectively providing services free of charge to airlines from other countries unless a common charging framework was established.

It was in this context that the European Organisation for the Safety of Air Navigation (Eurocontrol) was founded in 1960. The original Member States decided to adopt a common policy for en-route charging, establish a joint system for the calculation, billing, and collection of en-route charges, and entrust Eurocontrol with the administration of this system. This institutional development led to the establishment of the Central Route Charges Office (CRCO) in 1971, which became responsible for operating a centralized system for the collection of route charges. In essence, aircraft operators are charged for the use of airspace in order to contribute to the costs incurred by countries and air navigation service providers in the provision of en-route services. Within the Eurocontrol area, a harmonized route charging system was thus developed, under which the CRCO is responsible for billing, collecting, and disbursing route charges to Member States. Eurocontrol also provides similar services for terminal navigation charges, communication charges, and certain charging functions for non-Member States under the relevant legal arrangements [15], [16].

From an institutional perspective, this is highly significant. Eurocontrol was not established merely as a coordination forum, but as an organization with operational and financial functions at supranational level. Its broader objective has been to promote the development of a seamless pan-European air traffic management system and to harmonize strategies in the field of air traffic management while preserving safety. A key legal foundation of this system is the Multilateral Agreement relating to Route Charges, signed in 1981, under which the Contracting States agreed to adopt a common policy and create a joint system for the calculation, billing, and recovery of route charges, using Eurocontrol for this purpose [17]. Through the CRCO, Eurocontrol bills and collects en-

route charges on behalf of its Member States, thereby performing precisely the type of centralized financial function that is missing in the governance of European rail freight corridors.

The relevance of the aviation sector was further reinforced by the evolution of EU law. On 6 December 2006, the European Commission adopted Regulation (EC) No 1794/2006, laying down a common charging scheme for air navigation services, applicable from 1 January 2007. This Regulation was fully consistent with the Eurocontrol Multilateral Agreement, but at the same time constituted an important step in the implementation of the Single European Sky. Its purpose was not only to strengthen enforcement of the existing route charging system, but also to further harmonize air navigation service charges across European airspace. According to the European Commission's objectives, the system was intended to ensure that charges were fair, transparent, and reflective of the real costs of services, while also encouraging the safe and efficient provision of air navigation services and strengthening consultation mechanisms with airspace users [17].

The operational logic of the route charging system is relatively straightforward. A route charge is levied for each flight performed within Eurocontrol airspace, which is divided into charging zones defined by the Member States. The charge is calculated on the basis of three core elements: the distance factor for each charging zone, the aircraft weight factor, and the unit rate of charge applicable in the respective charging zone [18].

The system is based on the principle of full cost recovery. Forecast data are used to define the annual unit rates for each charging zone, with the unit rate expressed in euro and calculated as the ratio between the forecast en-route cost base of the charging zone and the forecast number of service units for the same period, plus an administrative fee applied uniformly

across zones in order to cover the costs of the CRCO. The unit rates are defined annually by each Member State and, where relevant, adjusted monthly when national currencies other than the euro are involved [19].

This charging architecture is especially relevant for the argument of the present paper because it clearly separates service provision from financial administration. Air navigation services remain provided by national or designated Air Navigation Service Providers (ANSPs), but the financial interface with airlines is centralized through Eurocontrol. This means that an airspace user does not need to pay each provider separately for each segment of a multi-country flight. Instead, the CRCO performs the functions of centralized calculation, billing, collection, and disbursement. In institutional terms, Eurocontrol acts as the "banker" of the system.

4. COMPARISON BETWEEN SECTORS

The comparison with the electricity and aviation sectors shows that cross-border infrastructure systems can be supported by institutions that perform not only coordination functions, but also financial settlement functions.

In the electricity sector, cross-border use is addressed through a compensation mechanism between network operators, whereas in aviation Eurocontrol provides centralized billing, collection, and redistribution of charges.

RFCs currently have neither of these arrangements. They lack both a formal clearing mechanism between IMs and a centralized body able to collect and redistribute revenues across jurisdictions.

The main institutional differences among the three sectors are summarized in Table 1.

Tab 1. Comparative institutional features of railway, electricity, and aviation

Dimension	Rail Freight Corridors (current model)	Electricity sector	Aviation sector
Nature of network use	International freight trains use infrastructure across several countries	Cross-border electricity flows pass through several national grids	Flights use airspace and air navigation services across multiple countries
Infrastructure operators	National infrastructure managers	Transmission System Operators	National or designated Air Navigation Service Providers
Current charging relationship with user	Railway undertaking pays each infrastructure manager separately along the train path	Network users are not charged through a fully corridor-like central mechanism, but TSOs are compensated for hosting cross-border flows	Airlines receive a centralized bill through Eurocontrol's CRCO
Cross-border coordination structure	Executive Board, Management Board, C-OSS, advisory groups	ACER, ENTSO-E, RCCs, national regulators	Eurocontrol's CRCO and other relevant departments
Degree of	Limited, mostly coordination-	Strong coordination and	Strong coordination plus

supranational coordination	based	compensation framework	centralized financial administration
Financial settlement mechanism	No centralized TAC collection or redistribution body	ITC mechanism compensates TSOs for hosting cross-border flows	CRCO centrally bills, collects, and redistributes route charges
Legal basis for cross-border financial mechanism	No dedicated supranational fiscal mechanism under RFC governance	EU legislation and regulatory framework formalizing ITC	Multilateral Agreement relating to Route Charges and related EU legislation
Main institutional function	Capacity coordination and stakeholder consultation	Compensation for transit-related infrastructure and loss costs	Centralized calculation, billing, collection, and disbursement
Closest relevance for rail	Baseline problem: fragmented charging along one train path	Model for side-payments and compensation between infrastructure operators	Model for single billing and centralized redistribution
Main lesson for rail	Current model lacks a corridor-level financial institution and mandatory cooperation and coordination principle	Cooperation can be supported through an inter-operator compensation mechanism with mandatory cooperation principle on the regional level	A supranational body can lawfully act as the financial intermediary for a transnational network

5. PROPOSED INSTITUTIONAL FRAMEWORK FOR RFCS

The comparative analysis suggests that the main institutional lesson for RFCs is not the need to replicate the electricity or aviation sectors in full, but rather to recognize that supranational bodies can be created to guide decision-making beyond purely national priorities, organize cross-border financial flows, and support common charging principles at network level. In both comparator sectors, the existence of a supranational institutional layer has made it possible to align operational and financial arrangements with broader system objectives. For RFCs, this points to the need for a corridor-level institutional framework that combines strategic coordination, charging oversight, and financial settlement.

Accordingly, the most appropriate solution would be the establishment of a RFC's Settlement and Charging Department within each corridor governance body, with clearly defined corridor-level competences (Fig. 1). As illustrated in the figure, the idea is that every corridor governance body should include a dedicated department responsible for these functions. Such a reform would require either a new regulatory instrument or an amendment to Regulation (EU) No 913/2010, through which the purpose, competences, minimum institutional capacities, and governance arrangements of this department would be clearly defined.

Its role would be to ensure that the transnational use of corridor infrastructure is governed not only through the coordination of capacity and operational planning, but also through a structured framework for charging, collection, and revenue redistribution. In this respect, such a department would constitute the

missing institutional layer between nationally organized infrastructure managers and the transnational economic logic of corridor traffic.

The proposed department should perform three interconnected functions. First, it should provide a common corridor-level framework for determining access charge principles, including guidelines that would orient national charging practices toward corridor-wide objectives rather than purely national priorities. This would not necessarily imply the immediate full harmonization of track access charges across all participating countries, but it would require a supranational framework capable of defining common principles, reducing distortions, and increasing transparency in the treatment of corridor traffic. In this way, the department would help guide decision-making toward broader system goals, including improved corridor performance, more efficient use of infrastructure, and stronger rail freight competitiveness.

Second, the department should perform a central financial settlement function. Instead of maintaining the current fragmented structure in which railway undertakings pay each infrastructure manager separately along the train path, the corridor framework should enable centralized collection of access charges for corridor traffic and the subsequent redistribution of revenues among participating infrastructure managers according to an agreed methodology. The comparative experience of Eurocontrol demonstrates that such centralized collection is institutionally feasible in a transnational network industry, while the electricity sector shows that common clearing and settlement arrangements can be organized even in institutionally fragmented systems. For RFCs, this would create a much closer alignment between the

operational unity of a corridor train path and its financial treatment.

Third, the proposed department should ensure regulatory oversight, transparency, and compliance. Its role would therefore extend beyond financial intermediation alone.

charges is institutionally feasible, and that common guidelines for determining charges can be defined at corridor level.

For the railway sector, the central challenge is therefore not whether such an arrangement is conceptually possible, but how to provide it with an appropriate legal mandate and political support within the European railway...

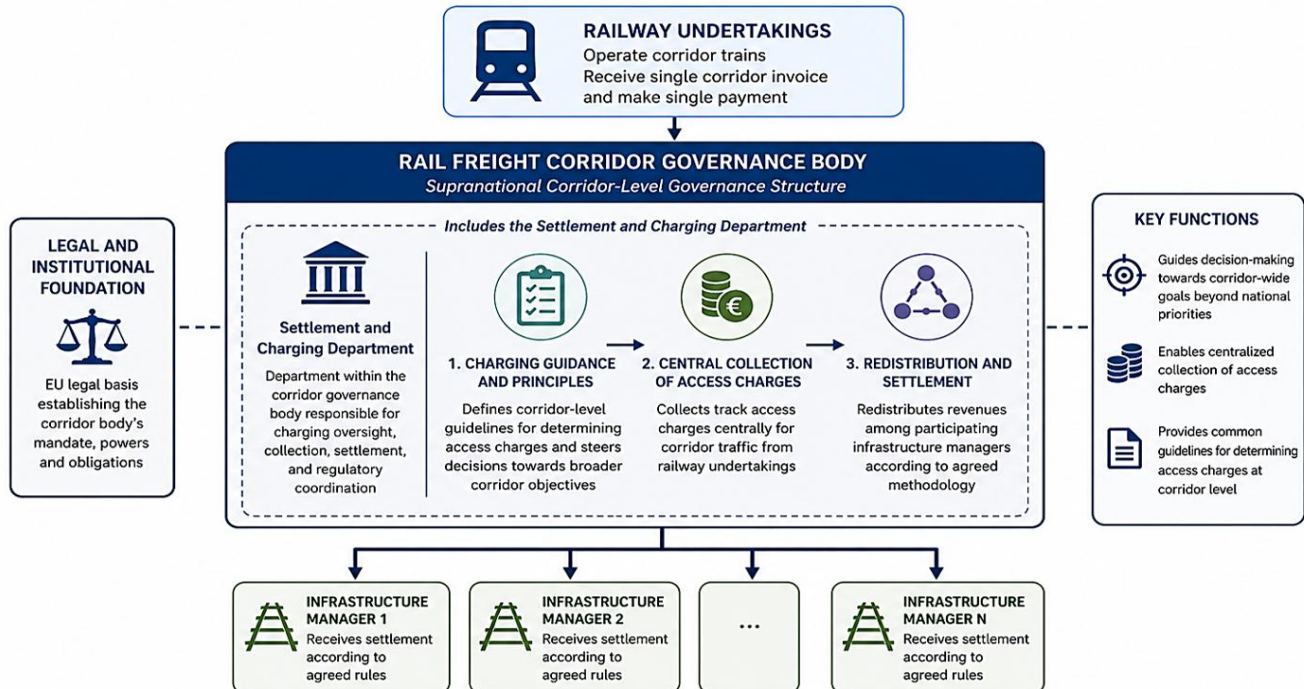


Fig 1. Proposed institutional framework for European Rail Freight Corridors

It should also provide the institutional safeguards necessary to ensure that the charging and redistribution process is transparent, predictable, and credible for railway undertakings, infrastructure managers, and governments. This would require clearly defined governance rules, operator participation, common reporting standards, and a legal basis capable of ensuring the enforceability of decisions and settlements at corridor level.

Under such a framework, the corridor would no longer function merely as a coordination platform. It would become an institutional space in which broader transnational objectives could be translated into concrete financial and regulatory practice. The proposed department would not replace infrastructure managers as owners and operators of national network segments. Rather, it would complement them by performing those functions that cannot be effectively carried out within purely national frameworks.

In this sense, the proposed institutional framework adapts the main insights derived from the electricity and aviation sectors to the specific realities of RFCs, namely that supranational bodies can legitimately steer decision-making toward broader network objectives, that centralized collection of access

governance framework.

6. CONCLUSION

The paper proposes that each RFC governance body should include a dedicated Settlement and Charging Department with corridor-level competences. Such a department would provide three essential functions: guidance on corridor-level charging principles, centralized collection and redistribution of access charges, and oversight of transparency and compliance. In this way, it would fill the current gap between nationally organized infrastructure management and the transnational economic logic of corridor traffic. Rather than replacing national IMs, it would complement them by performing those functions that cannot be effectively carried out within purely national frameworks.

The comparative analysis shows that this type of institutional reform is both necessary and feasible. The aviation sector provides the closest institutional analogy to the problem addressed in this paper. Eurocontrol and its CRCO demonstrate that, in a transnational network industry, a supranational

body can centralize billing, collection, and redistribution of charges while leaving service provision in the hands of national operators. For RFCs, this is the most relevant precedent, since it shows that a corridor-level financial function can be separated from the underlying management of national infrastructure. The electricity sector is relevant in a complementary but important sense. Namely, it shows that even in institutionally fragmented systems, financial compensation and settlement between national infrastructure managers can be organized through common rules, supranational coordination, regulatory oversight, and, crucially, a transition from voluntary to mandatory forms of regional cooperation. Unlike RFCs, where cooperation remains largely voluntary, the electricity sector demonstrates that effective cross-border governance ultimately required mandatory regional cooperation supported by a supranational institutional framework. Together, these examples confirm that strengthening RFC governance does not require a complete transfer of national competences, but rather the creation of a corridor-level institutional layer capable of aligning national actors with broader corridor objectives.

The central conclusion is therefore that the next step in the evolution of RFCs must be institutional rather than mathematical or purely economic. The key challenge is no longer only how to define a fair allocation of the gains from cooperation, but how to create an institutional framework capable of implementing it. In this respect, the proposed reform is not simply a technical adjustment to charging practices, but a broader governance reform aimed at strengthening the capacity of RFCs to function as effective transnational policy and management spaces.

If RFCs are to move beyond their current role as coordination platforms, they require an institutional mechanism able to connect operational coordination with financial settlement and strategic corridor-level objectives. A Settlement and Charging Department within each corridor governance body would provide precisely this missing link. Its establishment would strengthen RFC governance by reducing fragmentation, supporting more coherent charging practices, and creating the conditions for more effective, transparent, and competitive rail freight corridors in Europe. At the same time, such a framework would enable the gradual development of market-based allocation mechanisms, clearer allocation rules, and corridor-level guidance for the introduction and evolution of corridor access charges. In this way, institutional reform would not only improve the governance of RFCs, but also create the foundations for a more integrated and

economically consistent system of corridor management. The ongoing integration of RFCs into the broader European Transport Corridors framework may provide an additional opportunity for introducing such corridor-level financial functions in future governance reforms.

REFERENCES

- [1] Prokić, M., Bošković, B., Enhancing railway corridor governance: Cooperative game model, *Journal of Rail Transport Planning & Management*, 36, 100549, 2025.
- [2] Prokić, M., *Povećanje konkurentnosti međunarodnih železničkih teretnih koridora u modelu kooperativne igre*, Doktorska disertacija, 2026.
- [3] Regulation (EU) No 913/2010 of the European Parliament and of the Council, concerning a European rail network for competitive freight, *Official Journal of the European Union*, L 276, 22–32, 2010.
- [4] ERA, *Cross-border Rail Transport Potential*, European Union Agency for Railways, Publications Office of the European Union, Luxembourg, 2022.
- [5] Tolstrup, K., Framework of market coupling, in A. Estermann, M. Schrade, and L. Anderson, eds., *European electricity market coupling: A practitioner's guide*, Springer, 3–29, 2025.
- [6] Langsdorf, S., *EU energy policy: From the ECSC to the Energy Roadmap 2050*, 2011.
- [7] Victor, P. Y., *Definition of the current regulations, investments and efficiency of TSOs in Europe to assess the causes and impacts of the network expansion*, Louvain School of Management, 2021.
- [8] ACER, *ACER practice report on transmission tariff methodologies in Europe*, 2019.
- [9] ENTSO-E, *ENTSO-E market report 2022*, 2022.
- [10] Glegota, J. W., Regional coordination centres and their role in European market coupling, in A. Estermann, M. Schrade, and L. Anderson, eds., *European electricity market coupling: A practitioner's guide*, Springer, 99–118, 2025.
- [11] Pototschnig, A., Conti, I., *An Inter-TSO compensation mechanism for renewable and low-carbon gases*, European University Institute, 2022. <https://data.europa.eu/doi/10.2870/113871>
- [12] Ruester, S., Von Hirschhausen, C., Marcantonini, C., He, X., et al., *EU involvement in electricity and natural gas transmission grid tariffication – Final report, topic 6*, Publications Office of the European Union, 2012. <https://data.europa.eu/doi/10.2870/35676>
- [13] Camacho, L. O., Pérez-Arriaga, I. J., Comparison of several inter-TSO compensation methods in the context of the internal electricity market of the European Union, *Energy Policy*, 35(4), 2379–2389, 2007.
- [14] ACER, *Report on the implementation of the inter-transmission system operators compensation mechanism in 2024*, 2025. <https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER-2025-report-ITC-mechanism-2024.pdf>
- [15] Delgado, L., European route choice determinants, *Proceedings of the 11th USA/Europe Air Traffic*

Management Research and Development Seminar, 2015.

[16] EUROCONTROL, *CRCO customer guide to charges*, 2026.

<https://www.eurocontrol.int/sites/default/files/2026-04/eurocontrol-customer-guide-to-charges.pdf>

[17] Castelli, L., Ranieri, A., Air navigation service charges in Europe, *Proceedings of the Seventh USA/Europe Air Traffic Management Research and Development Seminar*, 2007.

[18] EUROCONTROL, *Central Route Charges Office (CRCO)*, 2026. <https://www.eurocontrol.int/crco>

[19] Castelli, L., Labbé, M., Violin, A., A network pricing formulation for the revenue maximization of European air navigation service providers, *Transportation Research Part C: Emerging Technologies*, 33, 2013.



BALANCING CAPACITY, FLEXIBILITY AND RESILIENCE: LESSONS FROM AUTOMATED METRO SYSTEMS FOR FUTURE RAILWAYS

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Abstract – Railway and metro systems are traditionally designed to maximize capacity under normal operating conditions. However, increasing automation, reduced headways and higher infrastructure utilization make system behavior under disturbed conditions an increasingly important issue. While conventional railways and automated metro systems pursue the same objective of high capacity, degraded operating conditions manifest differently due to their different levels of operational flexibility. This paper examines the relationship between capacity, degraded operations, operational flexibility and resilience in automated rail systems, using automated metro networks as a representative example of highly optimized rail operations. Particular attention is given to infrastructure-based flexibility mechanisms, especially pocket tracks, which support service recovery and operational adaptation during disturbances. The analysis is based on a comparison of degraded operating conditions in metro and conventional railway systems and on the mechanisms used to maintain service continuity. The analysis shows that degraded operating conditions provide a new perspective for understanding the balance between capacity, operational flexibility and resilience. They further suggest that future railways may increasingly face challenges already encountered in automated metro networks, whose experiences offer valuable lessons for a future design in which balancing capacity, operational flexibility and resilience may become as important as capacity optimization itself.

Keywords – operational flexibility, degraded operations, resilience, automated metro systems, future railways.

1. INTRODUCTION

Rail transport systems are increasingly expected to provide high capacity, reliability and service quality while operating in environments characterized by growing demand and increasing levels of automation. In both conventional railways and metro systems, capacity enhancement remains one of the primary design objectives. This objective is achieved through infrastructure optimization, reduction of headways, advanced signaling systems and an increasing degree of operational automation.

Recent developments such as Communications-Based Train Control (CBTC), Grade of Automation 4 (GoA4) metro systems, Automatic Train Operation over ETCS (ATO over ETCS), Moving Block signaling, Digital Automatic Coupling (DAC) and

emerging concepts of autonomous freight trains illustrate a common trend towards highly automated and highly optimized railway systems. While these developments significantly increase capacity and infrastructure utilization, they simultaneously reduce the operational margins available for disturbance management. As a result, future railway systems may increasingly face a trade-off between maximizing capacity and maintaining resilience under disturbed operating conditions.

However, railway systems are not operated exclusively under normal operating conditions. Infrastructure failures, rolling stock malfunctions, operational incidents, maintenance activities and external events may force the system to operate under degraded operating conditions. As operational

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margins become smaller and system interdependencies increase, the ability to manage degraded operating conditions is emerging as a critical performance requirement alongside traditional capacity objectives. This evolution suggests that degraded operating conditions should no longer be regarded solely as exceptional operational situations, but increasingly as a fundamental consideration in the design of future automated railway systems.

Although conventional railways and metro systems pursue similar operational objectives, they have evolved under fundamentally different design constraints. Conventional railways traditionally rely on the inherent operational flexibility of extensive network layouts, multiple routing options and heterogeneous traffic management. Automated metro systems, by contrast, operate within closed and highly optimized networks where infrastructure redundancy is intentionally limited in order to maximize capacity and operational efficiency. Consequently, operational flexibility cannot be assumed as an inherent property of the system but must be deliberately incorporated through infrastructure design, operational concepts and traffic management strategies.

These differences become particularly evident during degraded operating conditions. While conventional railways often absorb disturbances through the inherent flexibility of the network, metro systems depend on predefined operational procedures and dedicated infrastructure solutions to maintain service continuity. Infrastructure elements such as pocket tracks, crossovers and turnback facilities therefore perform a strategic role by enabling rapid operational recovery and maintaining acceptable levels of service under disturbed operating conditions.

Against this background, degraded operating conditions provide a valuable analytical framework for understanding the evolving relationship between capacity, operational flexibility and resilience in future railway systems. Rather than treating degraded operation solely as an operational issue, the analysis presented in this study explores its broader implications for infrastructure planning and system design. Automated metro systems are adopted in this paper as the reference model because they represent the most mature operational environment in which the interaction between capacity, operational flexibility and resilience can already be observed.

The remainder of the paper is organized as follows. Section 2 introduces the concept of degraded operating conditions and defines the theoretical framework adopted in this study. Section 3 discusses the relationship between capacity, operational flexibility, robustness and resilience. Section 4 compares conventional railway and automated metro systems under degraded operating conditions. Section

5 examines the role of infrastructure design in creating operational flexibility, while Section 6 presents pocket tracks as an example of infrastructure-based resilience. Finally, Section 7 discusses the implications of current automation trends for future railway systems, followed by concluding remarks.

2. CAPACITY-ORIENTED DESIGN PHILOSOPHY IN RAIL SYSTEMS

Capacity has traditionally been regarded as one of the most important performance indicators of both railway and metro systems. Historically, rail systems have been designed, planned and evaluated primarily under normal operating conditions. Infrastructure capacity, timetable construction, fleet sizing and signaling performance are typically determined assuming a stable operating environment in which trains run according to the planned service pattern. In other words, system performance is generally assessed for a “normal day” scenario. [1]

The continuous growth of transport demand has further strengthened this capacity-oriented design philosophy. To increase throughput and improve infrastructure utilization, rail operators and infrastructure managers have introduced a wide range of measures, including headway reduction, timetable optimization, advanced signaling systems and increasing levels of automation. On conventional railways, this trend is reflected through the implementation of ETCS, Moving Block concepts and Automatic Train Operation (ATO), while metro systems increasingly rely on CBTC technology and high Grades of Automation (GoA).

The primary objective of these developments is to maximize the utilization of existing infrastructure and increase system capacity. However, the performance achieved under normal operating conditions does not necessarily reflect system behavior under disturbed conditions. Infrastructure failures, rolling stock malfunctions, operational incidents and external events remain unavoidable regardless of the level of automation applied.

Consequently, modern automated rail systems should not be evaluated exclusively through their performance under normal operating conditions. While automation and optimization significantly increase system capacity, they may simultaneously reduce the operational margins available for disturbance management. As a result, the more a rail system is optimized for normal operation, the more sensitive it may become to disturbances and the more complex its management becomes under degraded conditions. This observation highlights that maximizing capacity alone cannot fully characterize system performance under disturbed operating conditions and points towards the need for a balanced

consideration of capacity, operational flexibility and resilience.

3. DEGRADED OPERATIONS, RESILIENCE AND OPERATIONAL FLEXIBILITY

Railway systems are traditionally assessed through indicators such as capacity, reliability, safety and interoperability. While these concepts provide valuable insights into system performance, they offer only a partial understanding of how rail systems behave under disturbed conditions. A complementary perspective can be obtained by viewing the railway as a complex socio-technical system capable of operating in different states, each characterized by specific operating conditions, constraints and performance levels.

From this perspective, understanding the relationship between capacity, degraded operations and resilience requires a clear definition of both operational states and performance-related concepts that describe system behavior in the presence of disturbances.

Three principal operational states can be distinguished. Normal operation represents the state in which all intended functions are performed within predefined performance limits and operating conditions [2, 3]. In railway systems, this corresponds to the planned realization of train services with all infrastructure, signaling and rolling stock subsystems functioning as intended.

Degraded operation refers to a state in which the system continues to perform its essential functions despite the loss, reduction or malfunction of one or more components, subsystems or operational capabilities [4, 5]. Within railway systems, degraded operation implies that safety remains preserved, while performance is reduced through capacity restrictions, speed reductions, timetable modifications, rerouting or modified operating procedures.

Emergency operation represents a state triggered by major disruptions or hazardous events requiring exceptional operating measures to protect passengers, personnel, assets or the environment [6]. Such conditions may involve service suspension, evacuation procedures, emergency traffic management or other extraordinary actions aimed at preserving system safety.

In addition to operational states, several performance-related concepts are essential for analyzing system behavior under disturbed conditions.

Capacity may be defined as the maximum number of trains, passengers or freight units that can be accommodated by a railway system within a specified period while satisfying predefined operational requirements [7, 8]. Traditionally, capacity has been one of the dominant criteria used to evaluate railway

performance.

Reliability expresses the probability that a system will perform its required functions without failure for a specified period under stated conditions [3, 4]. In the railway context, reliability reflects the consistency with which infrastructure, rolling stock and operational processes deliver planned services.

Closely related to reliability is the concept of robustness, which describes the ability of a system to withstand disturbances without significant degradation of performance. While a robust railway system continues to function with limited consequences following a disturbance, a resilient railway system emphasizes the ability to adapt, maintain service and recover functionality once significant disruption has occurred.

Resilience extends beyond reliability by addressing system behavior after a disturbance has occurred. It is commonly defined as the capability of a system to anticipate, absorb, adapt to and recover from disruptive events while maintaining an acceptable level of functionality [9, 10]. In railway systems, resilience is reflected in the ability to preserve service continuity and restore operational performance following disruptions.

Unlike capacity, reliability and resilience, operational flexibility does not have a universally accepted definition within railway literature. The concept is interpreted differently across research domains, including infrastructure design, traffic management, operations planning and resilience studies. For the purposes of this paper, operational flexibility is defined as the capability of a railway system to modify train operations, service patterns or infrastructure utilization in response to disturbances while maintaining an acceptable level of service.

The concepts introduced above are closely interconnected. The manifestation of degraded operations depends largely on the inherent operational flexibility of the system, while resilience reflects its ability to maintain and recover functionality under such conditions. Operational flexibility may therefore be viewed as the mechanism through which degraded operating conditions are managed and resilience is achieved. This relationship is particularly relevant when comparing conventional railways and automated metro systems, whose structural and operational characteristics result in fundamentally different responses to disturbances.

4. DIFFERENT INTERPRETATIONS OF DEGRADED STATE IN METRO AND CONVENTIONAL RAIL SYSTEMS

Although conventional railways and metro systems pursue the same objective of maximizing capacity, degraded operating conditions do not affect them in

the same way. As discussed in the previous section, the manifestation of degraded operations depends largely on the operational flexibility available within the system. Consequently, two rail systems exposed to a similar disturbance may experience significantly different operational consequences.

This distinction becomes particularly evident when comparing automated metro systems and conventional railways. Automated metro systems operate within highly controlled and isolated environments characterized by homogeneous rolling stock, fixed service patterns, dedicated infrastructure and intensive infrastructure utilization. These characteristics enable exceptionally high levels of automation, short headways and high transport capacity. However, they simultaneously limit the range of operational responses available during disturbances.

This creates an apparent paradox of automated metro systems. The same characteristics that maximize efficiency and capacity under normal operating conditions may reduce the system's ability to adapt when disturbances occur. Metro systems generally provide limited opportunities for rerouting, overtaking, train reordering or alternative service patterns. Consequently, even relatively minor disturbances may significantly affect service continuity and rapidly lead to partial service

suspension or substantial reductions in operational performance.

Conventional railways present a different operational paradigm. They are characterized by a greater diversity of operational resources and traffic management possibilities. Multiple train categories, station tracks, overtaking facilities, alternative routes and traffic regulation measures provide a level of inherent flexibility that allows the system to adapt to disturbances without necessarily interrupting service. As a result, degraded operation in railway systems often manifests itself through capacity reductions, timetable modifications, train reordering, rerouting or other operational compromises rather than through direct service interruption.

From this perspective, the fundamental difference between metro systems and conventional railways is not the occurrence of disturbances but the ability to respond to them. Railway flexibility is largely inherent, emerging from the structure and organization of the network itself. Metro flexibility, in contrast, must be deliberately designed through dedicated operational procedures and infrastructure solutions.

Tab 1 summarizes the principal characteristics influencing the manifestation of degraded operations in both systems.

Tab 1. Comparison of metro and conventional railway characteristics affecting degraded operations

Feature	Metro	Conventional Railway	Impact on Degraded Operations
Automation level	Very high	Medium to high	Influences dependence on system functionality
Capacity utilization	Very high	High	Affects sensitivity to disturbances
Operational flexibility	Low	High	Determines adaptation capability
Alternative routing	Very Limited	Available	Influences service continuity
Traffic regulation options	Very Limited	Extensive	Affects disturbance management
Disturbance recovery	Challenging	More flexible	Influences recovery time

Consequently, degraded operation manifests differently in metro and conventional railway systems. In conventional railways, disturbances are frequently absorbed through operational adaptation. In automated metro systems, the same disturbances may produce more severe consequences because fewer adaptation options are available. Therefore, understanding degraded operations requires not only analyzing the disturbance itself but also examining the operational flexibility available within the system.

This observation provides the foundation for understanding why automated metro systems have developed dedicated infrastructure-based mechanisms to support operational flexibility and resilience during degraded operating conditions. These mechanisms illustrate how operational flexibility contributes to

achieving an appropriate balance between capacity and resilience and are discussed in the following section.

5. DESIGNED FLEXIBILITY IN AUTOMATED METRO SYSTEMS

Automated metro systems may be viewed as laboratories for studying degraded operations and resilience. Their high degree of automation, intensive infrastructure utilization and strict operational requirements have led to the development of dedicated mechanisms specifically intended to support service continuity under disturbed conditions. Consequently, the management of degraded operating conditions becomes an integral part of system design rather than merely an operational issue.

In contrast to conventional railways, where many adaptation options emerge naturally from network structure and traffic management practices, metro systems must deliberately incorporate flexibility into their architecture. In other words, flexibility in metro systems is not inherited from the network structure; it is deliberately designed into the system. This flexibility is not primarily intended to improve performance under normal operating conditions. Instead, it is designed to provide alternative operational options when planned service patterns can no longer be maintained.

To achieve this objective, metro systems employ a range of infrastructure elements specifically intended to support operational adaptation and service recovery. Typical examples include crossovers, turnback facilities, storage tracks and pocket tracks. Although these elements differ in their physical configuration and operational function, they share a common purpose: enabling the system to continue operating when disturbances prevent the execution of the planned service pattern.

Tab 2 summarizes the principal infrastructure mechanisms used to support degraded operations in automated metro systems.

Tab 2. Infrastructure mechanisms supporting degraded operations in automated metro systems

Infrastructure element	Primary function in degraded operation
Crossovers	Route changes and traffic diversion
Turnback tracks	Short-turning and service regulation
Storage tracks	Temporary train holding and fleet management
Pocket tracks	Service recovery, incident isolation and partial line operation

These infrastructure elements may be interpreted as physical manifestations of resilience embedded within the network itself. Rather than increasing capacity, their primary purpose is to preserve operational functionality when normal operating conditions can no longer be sustained. In this sense, resilience is not achieved solely through operational procedures but is also incorporated into the infrastructure during the design phase.

Consequently, the solutions developed in metro systems provide valuable insights into how operational flexibility interacts with infrastructure design to support resilience under degraded operating conditions. Among these solutions, pocket tracks represent one of the most comprehensive mechanisms for restoring operational flexibility because they simultaneously support train regulation, service recovery, incident isolation and partial line operation. For this reason, they are examined in greater detail in

the following section

6. POCKET TRACKS: FROM DEGRADED OPERATIONS TO RESILIENCE

A pocket track is an additional track, typically located between the running tracks, which allows trains to reverse direction, be temporarily removed from service or be held without obstructing mainline operations. Although relatively simple from an infrastructure perspective, pocket tracks play an important role in supporting railway operations when planned service patterns can no longer be maintained.

The significance of pocket tracks cannot be fully explained through normal operating requirements. Their primary value becomes evident when disturbances occur and the system enters a degraded operating state. Under such conditions, operators are required to adapt train services to changing circumstances while preserving an acceptable level of service. Pocket tracks provide additional operational options that would otherwise not be available.

Several operational functions can be supported using pocket tracks. These include short turning of trains, temporary train storage, train regulation, incident isolation and partial line operation. By enabling trains to reverse direction before reaching a disrupted section, operators can continue serving unaffected parts of the network while minimizing the impact of disturbances on passengers and system performance.

From this perspective, pocket tracks represent an infrastructural response to an operational problem. They serve as technical tools for organizing train operations under disturbed operating conditions and provide operators with additional opportunities to modify service patterns when the planned operating concept can no longer be sustained.

Pocket tracks may therefore be viewed as mechanisms for restoring operational flexibility. Their purpose is not to improve operational flexibility during normal operation, but rather to create flexibility when disturbances reduce the range of available operational options. In this way, they help transform a rigid operating structure into a system capable of adapting to changing conditions.

At the same time, the benefits provided by pocket tracks are not achieved without cost. Their implementation requires additional track infrastructure, turnouts, signaling equipment, control functions and maintenance activities. Consequently, the decision to incorporate pocket tracks reflects a deliberate trade-off between investment costs and the ability to maintain service during service disruptions and disturbed operating conditions.

The importance of pocket tracks extends beyond their specific operational functions. They illustrate a

broader engineering principle: the ability of a transport system to operate effectively under degraded conditions is not determined solely by operational procedures but is also influenced by infrastructure design decisions. In this sense, pocket tracks represent a tangible example of how degraded operation management and system resilience can be incorporated into the physical architecture of a rail system.

The significance of pocket tracks therefore extends beyond a single infrastructure element, illustrating a broader systems-engineering philosophy that is becoming increasingly relevant as conventional railways evolve towards higher levels of automation.

7. TOWARDS FUTURE AUTOMATED RAILWAYS: EVOLUTION, CHALLENGES AND LESSONS FROM METRO SYSTEMS

For almost two centuries, conventional railways and metro systems have followed different evolutionary paths. Conventional railways have evolved as open transport systems characterized by extensive networks, heterogeneous traffic and relatively high inherent operational flexibility. In contrast, automated metro systems have been developed as highly optimized, closed systems designed to maximize capacity within constrained urban environments. Today, however, increasing automation is gradually bringing these two evolutionary paths closer together.

This convergence is reflected in the progressive introduction of automation technologies into conventional railway systems. Concepts such as Automatic Train Operation over ETCS (ATO over ETCS), Moving Block signaling, higher Grades of Automation (GoA3 and GoA4), Digital Automatic Coupling (DAC), advanced digital traffic management systems and autonomous freight train concepts all pursue the same objective: increasing capacity, improving operational efficiency and maximizing infrastructure utilization. Recent studies indicate that automation is progressively extending beyond urban rail towards regional, mainline and freight railway applications, where ATO is increasingly integrated with ETCS-based signaling systems and digital traffic management concepts [11–13].

Several of these technologies have already progressed beyond the conceptual stage and entered operational implementation. In Germany, the Digital S-Bahn Hamburg project successfully demonstrated highly automated train operation based on ETCS, while the Digital Node Stuttgart and the ARTE programme represent the next steps towards higher Grades of Automation [12]. In Finland, Siemens Mobility successfully demonstrated ATO over ETCS

Level 2 under real mainline operating conditions, whereas in the Czech Republic AŽD Praha conducted the first autonomous train demonstrations on a regional railway line [16,17]. Outside Europe, Rio Tinto's heavy-haul railway in Western Australia became the world's first fully autonomous freight railway network, while the French National Railway (SNCF) has demonstrated autonomous passenger and freight train technologies supported by artificial intelligence [13,14, 15]. At the urban rail level, fully automated GoA4 metro systems are already operating in more than sixty cities worldwide, including Copenhagen, Paris, Milan, Vancouver and Sydney, confirming that fully automated rail operation has become an established engineering solution rather than a future concept [11,13].

Taken together, these developments demonstrate that the transition towards highly automated railway operation is no longer a future vision but an ongoing engineering reality. More importantly, they suggest that conventional railways are progressively entering a stage of technological and operational development that automated metro systems have already experienced for several decades.

Beyond technological progress, this transformation is also operational and organizational. Higher levels of automation reduce operational headways, increase infrastructure utilization and strengthen the integration between infrastructure, rolling stock and traffic management systems. At the same time, they reduce operational margins and increase the dependence of railway operation on digital communication, automated control and decision-support systems. Consequently, disturbances that could previously be managed through local operational interventions increasingly become system-level events requiring coordinated operational responses.

As a result, future railway systems will increasingly need to consider degraded operating conditions as one of the fundamental design scenarios. Infrastructure layout, operational concepts, traffic management strategies and operational flexibility mechanisms must therefore be planned not only for normal operation but also for maintaining acceptable system performance under disturbed operating conditions.

From this perspective, automated metro systems may be regarded as laboratories for the future of highly automated railways. Over several decades, they have accumulated practical experience in developing infrastructure solutions, operational procedures and traffic management concepts specifically intended to maintain service continuity under degraded operating conditions. Rather than relying on inherent operational flexibility, metro systems systematically integrate operational flexibility into the system architecture through infrastructure design, operational planning and

traffic management strategies. Consequently, they provide a unique opportunity to observe how highly automated railway systems behave under disturbed operating conditions and how resilience can be systematically incorporated into the system.

These developments may be interpreted through the conceptual framework presented in Figure 1. As railway systems evolve towards higher levels of automation, increasing capacity is likely to be accompanied by reduced operational flexibility unless appropriate resilience mechanisms are incorporated into system design. Future railway systems will therefore need to achieve an appropriate balance between capacity, operational flexibility and resilience rather than maximizing any one of these objectives independently.

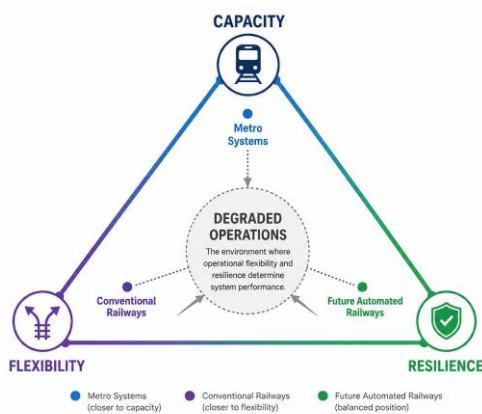


Fig 1. Conceptual framework illustrating the balance between capacity, operational flexibility and resilience under degraded operating conditions

Note: Degraded operating conditions provide the environment in which the balance between capacity, operational flexibility and resilience becomes visible

The most important lesson that future railway systems can learn from automated metro systems is therefore not a particular technology or infrastructure element, but a different design philosophy. Degraded operating conditions should no longer be regarded as exceptional operational situations to be addressed only after disturbances occur. Instead, they should become one of the fundamental design scenarios influencing infrastructure planning, operational concepts and traffic management strategies from the earliest stages of railway system development.

8. CONCLUSIONS

This paper examined the relationship between capacity, operational flexibility and resilience through the perspective of degraded operating conditions in conventional railway and automated metro systems. The analysis demonstrates that degraded operating conditions provide a valuable framework for understanding railway system behavior beyond

normal operation, revealing interactions between design objectives that often remain hidden under nominal operating conditions.

The comparison between conventional railways and automated metro systems shows that the ability to manage degraded operating conditions is fundamentally influenced by the level of operational flexibility embedded within the system. Conventional railways have traditionally relied on the inherent flexibility of their network structure to absorb disturbances through operational adaptation. Automated metro systems, by contrast, compensate for their limited inherent flexibility by deliberately incorporating operational flexibility into infrastructure design, operational concepts and traffic management strategies. Infrastructure elements such as pocket tracks illustrate how resilience can be embedded into the physical architecture of the system rather than achieved solely through operational procedures.

The ongoing evolution of railway automation suggests that this distinction will gradually become less pronounced. The introduction of technologies such as ATO over ETCS, higher Grades of Automation, Moving Block signaling and autonomous train operation is progressively increasing infrastructure utilization while simultaneously reducing operational margins. As conventional railways become operationally more similar to automated metro systems, issues of operational flexibility, degraded operating conditions and resilience are expected to become increasingly important design and operational challenges.

The principal contribution of this paper extends beyond the analysis of degraded operating conditions or individual infrastructure solutions. It argues that, as railway systems become increasingly automated, degraded operating conditions are no longer merely an operational issue but are progressively evolving into a design paradigm for future automated railway systems. The findings of this study suggest that degraded operating conditions should no longer be regarded simply as exceptional operational events requiring predefined procedures, but as fundamental design scenarios that influence infrastructure planning, operational concepts and traffic management from the earliest stages of railway system development.

From this perspective, the significance of automated metro systems extends far beyond urban transport. They are, in effect, laboratories for the future of railways. Their experience demonstrates that the long-term challenge of railway engineering is not to maximize capacity alone, nor to prioritize operational flexibility or resilience independently, but to achieve an appropriate balance between these three objectives. As conventional railways continue their

transition towards higher levels of automation, the ability to maintain acceptable performance under degraded operating conditions will increasingly depend on successfully balancing capacity, operational flexibility and resilience. Achieving this balance is likely to become one of the defining characteristics of future railway systems.

REFERENCES

- [1] Goverde, R., Corman, F., D'Ariano, A., *Railway line capacity consumption of different railway signaling systems under scheduled and disturbed conditions*. Journal of Rail Transport Planning & Management, 3(3), 78-94, 2013.
- [2] International Organization for Standardization, ISO 55000:2024 Asset management - Vocabulary, overview and principles, ISO, Geneva, 2024.
- [3] International Electrotechnical Commission, IEC 60050 International Electrotechnical Vocabulary, IEC, Geneva, 2020.
- [4] European Committee for Electrotechnical Standardization, EN 50126-1:2017+A1:2024 Railway applications - The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 1: Generic RAMS process, CENELEC, Brussels, 2024.
- [5] International Electrotechnical Commission, IEC 61508-1:2010 Functional safety of electrical/electronic/programmable electronic safety-related systems - Part 1: General requirements, IEC, Geneva, 2010.
- [6] International Organization for Standardization, ISO 22320:2018 Security and resilience - Emergency management - Guidelines for incident management, ISO, Geneva, 2018.
- [7] International Union of Railways, UIC Code 406: Capacity, 2nd ed., UIC, Paris, 2013.
- [8] Hansen, I. A., Pachl, J. (eds.), *Railway Timetabling and Operations: Analysis, Modelling, Optimisation, Simulation, Performance, Evaluation*, Eurailpress, Hamburg, 2014
- [9] Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., et al., *A framework to quantitatively assess and enhance the seismic resilience of communities*, Earthquake Spectra, 19(4), 733–752, 2003.
- [10] Hollnagel, E., *Resilience engineering and the built environment*, Building Research & Information, 42(2), 221–228, 2014.
- [11] Djordjević, B., Fröidh, O., Krmac, E., *Determinants of autonomous train operation adoption in rail freight: knowledge-based assessment with Delphi-ANP approach*, Soft Computing, 27, 7051–7069, 2023.
- [12] Automatic Train Operation [Internet], Digitale Schiene Deutschland, [cited 2026 Jun 25]. Available from: <https://digitale-schiene-deutschland.de/en/Automatic-Train-Operation>
- [13] Singh, P., Dulebenets, M. A., Pasha, J., Gonzalez, E. D. R. S., Lau, Y. Y., Kampmann, R., *Deployment of autonomous trains in rail transportation: current trends and existing challenges*, IEEE Access, 9, 91427–91461, 2021.
- [14] Briginshaw, D., Rail is on the way to autonomous trains [Internet], International Railway Journal, 2019 [cited 2026 Jun 25]. Available from: <https://www.railjournal.com/opinion/rail-autonomous-trains>
- [15] Kimiagar, Y., What are the artificial intelligence applications in rail transit? [Internet], American Public Transportation Association, 2019 [cited 2026 Jun 25]. Available from: https://www.apta.com/wp-content/uploads/What-are-the-Artificial-Intelligence-Applications-in-Rail-Transit_Yousef_Kimiagar.pdf
- [16] Community of European Railway and Infrastructure Companies (CER), Rail Freight Forward (RFF), 30 by 2030 – How rail freight achieves its goals [Internet], International Union of Railways, 2020 [cited 2021 Aug 13]. Available from: https://www.railfreightforward.eu/sites/default/files/downloadcenter/rff_cer_position_paper.pdf
- [17] Finland: Nordic region's first ATO over ETCS [Internet], EUROPE SAYS, 2026 Mar 10 [cited 2026 Jun 25]. Available from: <https://www.europesays.com/2836316/>



INTERMODAL RAIL-AIR TRAVEL – RECOMMENDED FUTURE SERVICES

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Abstract – When travelling by plane, people often use private cars or taxis as a means of transport to the airport, or short-haul flights for longer distances. There are two main reasons why public transport or the train are often not used: 1) For many people, taking luggage to the airport is more complicated than using a car or a short-haul flight. 2) Many people are used to the ‘world of aviation’ but feel overwhelmed when using ‘unfamiliar’ systems (e.g. public transport in other countries). The AirWorld-Door2Door exploratory project investigated whether AI-based services could enable a seamless ‘aviation experience’ from door to door, utilising sustainable transport modes for the pre- and post-flight journey. Given the diversity of application areas and the complexity of AI usage, an initial exploratory analysis was conducted to identify existing gaps in appeal and appropriate measures. Based on this, systems were designed, such as facilities to facilitate baggage transport (e.g. through baggage drop-off on the feeder train) or a virtual escort service along the entire travel chain, which provides information tailored to personal needs at every stage of an intermodal journey. Real-time information is particularly important in the event of disruptions (e.g. service disruptions or delays) and targeted instructions on what to do to still reach the flight on time.

Keywords – intermodal transport, air-rail-services, baggage handling.

1. INTRODUCTION

When travelling by plane, people often use private cars or taxis as a means of transport to the airport, or short-haul flights for longer distances. There are two main reasons why public transport or the train are often not used:

- 1) For many people, taking luggage to the airport is more complicated than using a car or a short-haul flight.
- 2) Many people are used to the ‘world of aviation’ but feel overwhelmed when using ‘unfamiliar’ systems (e.g. public transport in other countries).

Most air travellers prefer feeder flights to feeder trains, for example on medium-distance routes. This applies in particular to people who live near regional airports and therefore have comparable alternatives. The same applies to the first and last mile to and from airports, which is often covered by taxi/rental car or private car rather than sustainable public transport. Cooperation between rail and aviation companies, such as AIRail in Austria, enables through-ticketing from the railway station and offers a connection guarantee in the event of delays. However, pre- and post-journey stages, including access to information, booking to and from the station, baggage handling, orientation during the journey, uncertainty about delays, ticketing, and navigation on the first and last mile, still often present major hurdles to using rail as a feeder service and/or public transport for the first and last mile.

The aim of the AirWorld-Door2Door project was to explore future organisational and technical possibilities, for example by using new technologies such as artificial

intelligence, and to identify measures that could be particularly suitable for offering air travellers a seamless door-to-door travel experience. The goal was to remove systemic barriers outside the traditional aviation environment, such as those affecting the first and last mile, and to significantly increase willingness to use sustainable alternatives for travel to and from airports. The members of the project consortium were: netwiss (project lead), TU Wien, N+P Experience Design, Flughafen Wien, Austrian Airlines, ÖBB, FH JOANNEUM Graz, Hilfgemeinschaft.

Desk research served as the foundation for all subsequent steps. Building on this, the following additional methods were applied:

1. Networking workshops and focus groups: An important task in the project was to bring together various stakeholders (travellers, passenger representatives, tourism representatives, public transport operators, railways, aviation, disability associations). The aim was to gain an in-depth understanding of the current challenges facing intermodal rail-to-air travel, both from the perspective of travellers and companies.

2. Surveys: Passengers were surveyed via Austrian Airlines and Vienna Airport about their reasons for (not) using sustainable mobility options when travelling by air and their requirements for future systems, using paper questionnaires and online surveys.

3. Internal concept workshops & system design: Within the consortium, the findings were discussed in depth in three workshops, during which services were conceived and defined to close current gaps using new

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technologies. Working groups within the consortium designed specific suitable systems, the potential suitability of which was continuously reviewed by the stakeholders in the consortium.

2. STATE OF THE ART

There are various approaches to improving the continuity of intermodal air travel chains, but so far no truly seamless service has been established in Europe that has generated correspondingly high demand. [1]

2.1. Cooperation models between railways and airlines

High-speed rail allows railways to compete directly with air travel on distances of up to 750 km. [2] This has led to cooperation between railways and airlines, which offer services such as check-in, baggage transport and ticketing. [3] Depending on the degree of cooperation, the offers are classified as follows: [4]

Low: Quick arrival/departure to/from the airport, e.g. via Rail&Fly. [5,6] Through tickets are issued, e.g. from Vienna Airport to/from the Austrian provincial capitals, which can be used for arrival/departure from any stop in the respective province. However, there is no seamless baggage handling and no "connection guarantee".

Moderate: There are codeshare agreements between railways and airlines, and the respective train is also assigned its own flight number. The advantage for travellers is that in the event of delays, necessary measures such as rebooking are taken care of by the airline or railway company (e.g. AIRail in Austria (ÖBB/Austrian), Lufthansa Express Rail in Germany (DB/Lufthansa) and tgvair in France (SNCF/AirFrance). However, there is no seamless baggage handling.

High: The so-called integration also provides for luggage transport, among other things. An example of this was the AIRail cooperation between Lufthansa and DB, where until 2007 travellers could check in their luggage at the check-in counters in Cologne and Stuttgart. [7] However, this service was discontinued due to a lack of appeal and profitability. Travellers now check in their luggage at the AiRail terminal in Frankfurt and collect it there on their return journey. [8]

In some cases, there are additional services for baggage transport. In Switzerland, for example, there is the SBB's "Fluggepäck" service, [9] which allows baggage to be dropped off at railway stations or even at an address. It is then transported to the destination airport, and the service also works in the opposite direction. The disadvantage is that in most cases, luggage must be registered at least one day in advance or will be delivered one day later on the return journey.

In several countries, e.g. Japan, it is possible to have luggage delivered to your hotel. However, when travelling to the airport, a lead time of up to two days is also required. [10] In several European cities, including Vienna, the company Airportr [11] offers the option of having luggage delivered directly to an address or picked

up from there in cooperation with Austrian and British Airways. In Vienna, when using the CityAirportTrain, it is possible to drop off luggage at the station in station Wien Mitte. [12] This can be done up to 75 minutes before departure, but only works for departures and not in the opposite direction.

In the TerminalAufSchiene research project, a system was developed whereby luggage can be dropped off immediately after boarding the feeder train for through AIRail bookings. The advantage is that, in Austria, all Railjet stops can be used, no station infrastructure is required for baggage handling, travellers do not have to be at the station early, and short transfer times can be achieved at the airport when changing to the aircraft, as baggage drop-off is no longer necessary. However, trial operations by Austrian and ÖBB [13] showed that the manual baggage unloading and transfer process to the airport sorting facility is cost-intensive and was therefore not pursued further, even though the system would be technically and operationally feasible.

Particular challenges in baggage transport on intermodal travel chains arise from travellers having to handle bulky luggage themselves, from the treatment of special items in external unaccompanied baggage services (such as bicycles or ski bags), and from legal requirements such as customs checks on entry.

2.2. Consistent provision of information and booking

Apart from rail or long-distance bus connections that are booked as part of the flight (e.g. AIRail, Rail&Fly, Lufthansa Express Bus/Rail), there are practically no connecting travel bookings or information available as part of the flight booking.

In tourist regions in Europe, often multi-day flat-rate tickets covering all modes of public transport can be purchased – sometimes free of charge. Information on this is often available online, with varying degrees of reliability, including on Google Maps. However, using such offers requires doing your own research, downloading several apps and registering, which can be daunting for the uninitiated due to the complexity and variety of booking systems.

2.3. Lack of planning security and deviations

Intermodal travel with many transfers and touchpoints (e.g. border controls, check-in, baggage drop-off) carries risks such as long waiting times, delays and missed connections. If you miss your flight through your own fault, you will not receive any assistance, such as rebooking. The complexity and risk make this option unattractive, especially for those unfamiliar with it, who either avoid the journey or leave too early, which increases travel time and reduces the appeal.

3. SYSTEMIC CHALLENGES IN EUROPE

The implementation of seamless intermodal mobility solutions in Europe is associated with considerable systemic, regulatory and technological challenges.

Compared to successful individual examples outside Europe, institutional fragmentation, heterogeneous market structures and complex legal frameworks are particularly inhibiting factors here. Key barriers can be divided into cooperation, regulatory, infrastructure and integration problems. At the cooperation level, diverging business models, fare logic and competitive interests make integration difficult. In air transport in particular, aggressive pricing models and dynamic fare structures mean that selective, low-cost flight offers are preferred over intermodal solutions. Different booking and distribution systems also prevent the establishment of uniform platforms. From a regulatory perspective, data protection requirements – particularly under the GDPR – pose significant barriers to cross-system data exchange. However, intermodal travel chains require precisely this data linkage to enable ticketing, information and service coordination. In addition, national transparency requirements and differing legal provisions lead to a fragmented legal situation that complicates cross-border solutions. Physical and infrastructural deficits also have a limiting effect. Uncoordinated timetables, a lack of integrated luggage systems, inadequate information services and insufficient barrier-free access impair usability. Deficits in charging infrastructure and bicycle parking facilities further reduce the attractiveness of sustainable options. The "last mile problem" thus remains a key obstacle to acceptance.

To overcome these barriers, seven areas of technological action were identified in the AirWorld – Door2Door project. Digital luggage solutions – such as:

- Automated drop-off points
- RFID tracking (Radio-Frequency Identification)
- Autonomous logistics and
- Biometric verification-address a key obstacle to convenience.
- Information and navigation systems based on
 - AR (Augmented Reality)
 - NLP (Natural Language Processing) and
 - Beacon technologies improve orientation and reduce cognitive barriers, especially for people who are unfamiliar with the system or have limited mobility.

Integrative booking and fare systems, such as one-stop-shop platforms with CO₂ transparency, dynamic pricing and open interfaces, can simplify travel chains, but face regulatory and economic constraints. AI-based forecasting models, multimodal re-routing and real-time communication offer relevant potential for dealing with irregularities. Accompanying and assistance systems enable personalised support along the entire travel chain, for example via digital travel companions and user-centred profiles. For the last mile, demand-responsive transport, ride pooling and autonomous micro-mobility are gaining in importance, but their availability varies from region to region. There are recurring challenges across all technologies: data protection, lack of interoperability, infrastructure requirements and unresolved responsibilities in terms of operation and

liability. The analysis shows that many technological building blocks already exist. The central challenge lies less in the development of new technologies than in their integration, standardisation and scaling. Common interface standards, robust data models and new forms of cooperation between transport companies and technology providers are crucial to success. The results thus form a viable basis for further system concepts and pilot projects.

4. SYSTEM DESIGNS

Based on the findings from the needs and technology analysis, different system concepts were developed that address various weak points along intermodal travel chains. These fall into three overarching development areas: Luggage logistics as the key to reducing congestion; Digital support, assistance and information; and System integration & connection logic.

4.1. Luggage logistics as the key to reducing congestion

A central focus was on separating passengers and luggage along the travel chain. The ideas range from early luggage drop-off at drop-off stations in rural and urban areas, to luggage rental models, smart luggage racks on trains, and autonomous door-to-door luggage services. Particularly noteworthy is the use of a smart luggage rack on trains, which can be unloaded directly at the airport and exchanged for an empty one. The rack would be designed so that it could be easily pushed out of the train by on-board staff in the low-floor carriage area. An autonomous and digitally networked transport vehicle (AGV) then can take over the onward transport across the platform to the airport's baggage handling system. This system would make it possible to check in baggage digitally during the train journey without the need for additional staff on the railway or airport side. In combination with end-to-end baggage tracking systems, this could create a high degree of transparency, security and control along the entire travel chain. At the same time, partial automation would make processes more efficient. For users, this would not only mean a more comfortable travel experience, but also a noticeable simplification of multimodal transfers.

4.2. Digital support, assistance and information

The second group comprises digital travel companion services, such as a VR/AR-based (Virtual / Augmented reality) assistant, uniform information interfaces and transparent booking tools. The aim of the concept is to provide in future travellers – especially those who are unfamiliar with the system or belong to vulnerable groups – with more consistent and accessible support.

Real-time navigation, situation-specific information and central booking interfaces could reduce uncertainty along the travel chain and noticeably improve service quality. Technically savvy unaccompanied minors would also benefit from these solutions, for example through interactive interfaces, simplified operating logic or

automatic notifications to caregivers – an additional benefit that could build trust and promote independence. Predictive travel planning could extend this approach by using individual preferences, routines and past behaviour patterns to intelligently plan future journeys – even when changing modes of transport or dealing with complex processes. The use of gamification elements will also become increasingly relevant in this context in order to strengthen user loyalty to digital services. Playful interactions, reward systems or progress indicators could enrich the travel experience emotionally, promote the use of digital tools and increase reuse – for example, through travel achievements, CO₂ savings targets or personalised recommendations. This could create new incentives to interact with sustainable mobility options.

In addition, the concept of a digital one-stop shop would be promising, where the entire door-to-door travel chain could be planned and booked centrally. Travellers would not only receive an integrated overview of available options, but could also transparently compare individual factors such as carbon footprint, travel price and duration. This would provide a sound basis for making sustainable travel decisions – tailored to personal priorities. The one-stop shop could also offer the potential to seamlessly integrate additional services such as travel insurance, support services along the travel chain or luggage options, thus making access to sustainable mobility significantly more accessible and user-friendly.

4.3. System integration & connection logic

A third area of development concerns the smart connectivity of individual mobility services, for example through a connection guarantee in public transport. In theory, digital travel data, real-time tracking and defined conditions could be used to ensure a reliable connection – for example, in the event of delays in upstream transport. A promising approach could lie in the use of existing real-time tracking technologies, such as those already used by ÖBB in SimplyGo for automated fare calculation. These technologies could be expanded to record the actual journey, not for billing purposes, but as proof in the event of a guarantee claim. This would allow passengers to travel with existing tickets (e.g. a yearly pass) and still benefit from a guaranteed rebooking in the event of a delay in the connecting service. The interface – for example, with the airline or an insurance partner – would define the time by which the point of departure must be left in order to trigger the guarantee. This would enable a transparent and automated system without additional effort for users and would build on existing infrastructure. In practice, however, it is clear that such concepts fail less because of technical limitations than because of organisational, regulatory and political constraints. A genuine connection guarantee in public transport is currently difficult to implement because responsibilities, fare responsibilities and liability issues are not uniformly regulated. The transfer of sensitive travel data between transport operators has also not yet been standardised

across the board. There is a considerable need for action here in order to make the technical potential systematically usable.

5. CONCLUSION

The system concepts developed were described at a conceptual level within the project and subjected to a qualitative assessment of their feasibility, potential impact, and scalability. This shows that:

- Many of the solutions presented are based on existing technologies or require only moderate further development.
- Obstacles are often not technical, but systemic – for example, in the cooperation between different actors, data transfer or regulatory issues.
- Pilotability exists above all where individual services can be tested in isolation (e.g. luggage drop-off, travel assistant, information interfaces).
- A particular lever lies in the intelligent combination of several system ideas, such as linked luggage racks, hybrid escort services or user-centred platforms.

The system concepts developed and the assessments of feasibility illustrate that the vision of a seamless, sustainable door-to-door aviation experience is conceptually and technically feasible – provided that the appropriate conditions for cooperation, data integration and governance are created. The ideas developed provide a sound basis for further pilot projects, demonstrators or in-depth planning in selected regions or use cases. Specifically regarding the topics of ‘automated baggage drop-off’ on trains and ‘end-to-end mobility support services for intermodal journeys’, the project consortium has already devised two concrete development projects and submitted them to the Austrian Federal Ministry for Innovation, Mobility and Infrastructure for funding.

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REFERENCES

- [1] AirWorld-Door2Door, Research project, FFG, Final report 2025
- [2] Yang, Hangjun; Zhang, Anming: Effects of high-speed rail and air transport competition on prices, profits and welfare, in: Transportation Research, Part B 46, 2012, p. 1331.
- [3] Schulz, Axel; Baumann, Susanne; Wiedenmann, Simone: Airport Management, Munich, 2010, p. 181.
- [4] Chiambareto, Paul; Decker, Christopher: Air-rail intermodal agreements: Balancing the competition and environmental effects, in: Journal of Air Transport Management, Volume 23, 2012, p. 37ff.
- [5] <https://www.bahn.de/service/informationen-buchung/bahn-flug/rail-fly> (16.2.2024)
- [6] <https://www.oebb.at/de/regionale-angebote/ueberregionale-angebote/anreise-zum-flughafen/railandfly> (16.2.2024)
- [7] Chiambareto, Decker, 2012, p. 38
- [8] <https://www.bahn.de/p/view/service/buchung/flug/airail.shtml> (17.1.2021)
- [9] <https://www.sbb.ch/de/billette-angebote/reservation-gepaek/fluggepaek.html>
- [10] <https://www.jrailpass.com/blog/transporting-luggage-forwarding> (17 January 2021)
- [11] <https://airportr.com/de/>
- [12] <https://www.cityairporttrain.com/de/home#city-check-in>
- [13] <https://www.austrianairlines.ag/2021/08/19/unbeschwert-reisen-austrian-airlines-testet-airail-gepaekaufgabe-im-zug/>

Other Railway Aspects



APPLICATION OF PHYSICS AI IN RAILWAY VEHICLE DESIGN – A REVIEW

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Abstract – Modern railway vehicle design must satisfy numerous requirements related to safety, reliability, weight reduction, energy efficiency, and performance. Numerical methods such as FEM and multibody system models provide reliable results, but their application to complex problems and numerous operating conditions can require significant computational time and resources. Physics AI combines artificial intelligence with physical knowledge and offers a promising way to overcome these limitations. This paper reviews its applications in railway engineering, including collisions and braking, vehicle dynamics and control, structural analysis and fatigue, wheel–rail and vehicle–track interaction, aerodynamics, pantograph–catenary systems, and maglev systems. The reviewed studies show that incorporating physical knowledge into AI models can improve accuracy, robustness, physical consistency, and generalization while reducing data requirements and computational cost. These results highlight the significant potential of Physics AI for future railway system design, analysis, monitoring, and control.

Keywords – Physics AI, Railways, Physics-Informed Machine Learning, Railway Vehicle Design, Physics-Informed Neural Networks.

1. INTRODUCTION

When designing modern railway vehicles, it is necessary to meet multiple engineering requirements, including structural weight reduction, energy efficiency, passenger safety, and environmental sustainability [1]. Particularly in passenger railway vehicles, one of the most important issues is passenger safety, which is achieved through adequate vehicle crashworthiness [2]. In addition, increasingly complex requirements related to multi-system capabilities, vehicle crash behavior, and passenger comfort can lead to an increase in structural mass [3]. The fatigue life of bogie frames is also directly related to the reliability and safety of railway vehicles. At the same time, in high-speed and heavy-haul railway vehicles, there is a need to reduce the mass of components in order to decrease energy consumption and increase

speed and payload, while these same components are subjected to severe vibration loads that can increase the risk of fatigue [4]. All of the aforementioned requirements, which must be fulfilled and are often mutually conflicting, make the design process of railway vehicles highly complex. In recent years, computer simulation of railway vehicle behavior in motion has become an almost standard task in the design process within the railway industry [5]. Such tools enable static analyses of railway vehicle components, as well as dynamic analyses of multibody systems. For static analyses, the finite element method is most commonly applied, while multibody system models are used to analyze the dynamic behavior of railway vehicles [6]. Although detailed numerical simulations can provide highly accurate results, they may require considerable computational time and substantial computational

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resources. This issue becomes particularly pronounced when detailed models are used or when vehicle behavior needs to be analyzed under a large number of different load cases, operating conditions, or design variants [7]. As an example of such computational demand, a 1000 ms collision simulation of two trains, each consisting of four vehicles, may require more than 100 hours of computation on a typical high-performance workstation [8]. For this reason, there is a need for approaches that reduce computational time while maintaining the required accuracy in predicting railway vehicle behavior. One such approach is the application of Physics AI methods. Artificial intelligence offers a solution to this problem through the application of fast data-driven surrogate models [9]. In particular, combining machine learning with prior physical knowledge has proven effective for addressing limited training data, improving generalization, and ensuring the physical consistency of results [10]. For these reasons, the combination of artificial intelligence and physical knowledge has great potential in railway engineering.

This paper aims to present the potential applications of Physics AI methods in railway engineering through the analysis of existing approaches and published research.

2. PHYSICS AI APPLICATIONS IN RAILWAY ENGINEERING

The literature review shows that Physics AI methods are applied in various areas of railway engineering. Based on the conducted review, existing studies can be classified into applications related to collisions, crashworthiness, braking, and safety; railway vehicle dynamics and control; structural analysis, fatigue, and reliability; wheel–rail and vehicle–track interactions; and aerodynamics. Other significant applications include pantograph–catenary and maglev systems.

2.1. Crashworthiness, Braking and Safety

The high costs of acquiring data from full-scale train collision experiments limit the application of purely data-driven machine learning methods in train collision simulations. Therefore, Tang et al. [11] applied a Parallel Physics-Informed Neural Network (PPINN) to solve the multibody dynamics equations of train collisions. In the PPINN approach, the governing physical equations of the system are incorporated into the training process, while the considered computational time domain is divided into several subdomains that are solved in parallel, thereby reducing the computational cost. A full-scale numerical train collision model was developed and four collision scenarios were analyzed, considering dynamic responses, collision forces, absorbed energy,

and vertical wheel rise. The obtained results showed good agreement with FEM and conventional numerical methods, indicating the potential of the PPINN approach for accelerating complex dynamic simulations of railway vehicles. In contrast, He et al. [12] proposed a variable-fidelity surrogate model (VFSM) for optimizing the parameters of energy-absorbing elements in train collisions. The approach combines a large number of fast 1D simulations with a smaller number of more accurate 3D simulations connected through transfer learning. From the perspective of Physics AI, the use of an LSTM network with Motion Constraints (LSTM-MC) is particularly important, as it incorporates physical knowledge of system motion into the prediction process. This enables highly accurate predictions of displacement, velocity, and acceleration with significantly lower computational cost than using 3D models alone. The model was then applied to optimize the parameters of energy-absorbing elements with the aim of reducing train acceleration during a collision. One of the most important parameters, particularly from a safety perspective, is the stopping distance of a train. Sepahvand et al. [13] proposed a physics-informed Bayesian framework for its virtual prediction. The idea is to first estimate the stopping distance using physical equations that describe the train braking process and then further adjust this estimate based on experimental data using a Gaussian Process model and a Bayesian approach, which estimates and corrects model discrepancies based on the available data. In this way, physical knowledge is directly incorporated into the prediction process. Such a model enables not only the prediction of stopping distance but also the estimation of the uncertainty associated with that prediction, which can reduce the need for a large number of costly experiments and enable more reliable virtual testing of braking system performance.

The presented studies demonstrate the potential of Physics AI for train collision and braking analysis, while reducing computational time, resource demands, and the need for costly experiments.

2.2. Railway Vehicle Dynamics and Control

Although artificial intelligence represents a promising technology for solving dynamic response problems in real time, it has limitations in terms of generalization capability and prediction reliability. Han et al. [14] proposed a physics-informed neural network framework for railway dynamics problems. To improve prediction reliability and generalization, the dynamic equations of the vehicle–track system were incorporated into the network loss function as physical constraints. The authors also introduced a self-adaptive method for weighting these constraints and a SAT architecture, forming the SATPINN

model. Using both data and physical constraints, the model predicts dynamic responses such as displacement and velocity, achieving higher accuracy and better generalization than the baseline models. In addition to predicting dynamic responses, Physics AI can also be applied in the field of railway vehicle control. One of the important problems in this area is trajectory-following control for virtual rail trains (VRTs). Traditional model-based control methods have difficulties dealing with nonlinear dynamics and require highly accurate system models, while deep learning methods based solely on data lack sufficient physical interpretability and robustness. Ji et al. [15] proposed a physics-informed deep learning approach in which the Lagrangian equations of dynamics are incorporated into a neural network, forming a Deep Lagrangian Neural Network (DLNN). In this way, the network can learn the complex dynamics of the vehicle from data while simultaneously preserving the fundamental physical laws of the system. The developed model is used to determine the control inputs required for following a predefined trajectory and has demonstrated higher accuracy, better generalization, and greater robustness compared with conventional data-driven models. A similar approach has also been applied to the control of virtually coupled trains, where, in addition to trajectory tracking, differences in the dynamics of individual trains need to be taken into account. Liu et al. [16] developed a physics-informed neural network model for train dynamics (PINN-TDM), which incorporates the Davis formula to determine the parameters of basic train resistance. The model was then integrated into a Model Predictive Control (MPC) system for virtually coupled trains, improving trajectory tracking accuracy and train-set stability under different wheel-rail contact conditions.

The presented studies demonstrate the potential of Physics AI in railway vehicle dynamics and control, particularly for rapid dynamic response prediction, trajectory tracking, and advanced control.

2.3. Structural Analysis, Bogie Frames, Fatigue and Reliability

Accurate and efficient prediction of the fatigue state of bogie frames is important for structural optimization and rapid iterative design of railway vehicles. Yang et al. [17] developed an approach for rapid fatigue assessment of welded bogie frame joints based on full-field stress tensor reconstruction. Instead of directly predicting the maximum principal stresses, the approach uses physically defined stress tensor components and a multivariate Gaussian Process to approximately reconstruct the stress field while accounting for the physical coupling between its components. In this way, physical knowledge of the structural stress state is incorporated into the

prediction process. The reconstructed stress field is then used for fatigue assessment, achieving high accuracy while reducing the computation time from approximately 30 minutes to 0.1 s. In addition to bogie frames, fatigue behavior is also of great importance for other load-bearing components of railway vehicles, such as axles. Induction-hardened S38C steel axles used in high-speed trains are characterized by high static strength, but fatigue failure still represents a significant safety concern. The gradient in microstructure and mechanical properties resulting from induction hardening, with the properties changing from the surface toward the core, further complicates accurate prediction of their fatigue life. To address this problem, Deng et al. [18] proposed a machine learning model incorporating physical information related to the gradient. Since a conventional neural network only searches for mathematical relationships in the data, the authors first evaluated the importance of gradient-related physical quantities and then developed an explicit formula for fatigue life prediction using symbolic regression and dimensional analysis, whose predictions were incorporated into the loss function. Based on this, a Layered Input Deep Learning (LIDL) model was developed, which takes into account the interactions between adjacent layers. The developed model demonstrated high prediction accuracy and good generalization capability in predicting axle fatigue life. In addition to fatigue life prediction, Physics AI approaches can also be applied to the condition assessment and maintenance of railway vehicle wheelsets. The maintenance of high-speed train wheelsets in China is mainly carried out according to a planned schedule based on service mileage or operating time. Such an approach is often overly conservative and may lead to excessively frequent repairs, while wheel tread damage occurring between maintenance intervals may remain undetected and compromise operational safety. Although FEM enables detailed analysis of damage evolution in wheel-rail contact, its high computational cost and limited ability to cover a wide range of operating conditions make its application for rapid prediction difficult. Xiao et al. [19] developed a novel hybrid physics-data framework for rapid and intelligent risk prediction. Within this approach, the results of high-fidelity FEM simulations of rolling contact and crack propagation are used to generate the database. The simulations are coupled with an automated algorithm for tracking the growth of three-dimensional surface cracks under different operating conditions. A Gaussian Process Regression model was then trained on the generated data to rapidly predict the risk index, enabling efficient condition assessment of wheelsets with considerably lower computational cost.

Such approaches can significantly facilitate and accelerate the process of structural analysis, fatigue assessment, and reliability evaluation, while also improving the obtained results.

2.4. Wheel–Rail Interaction, Wear and Vehicle–Track Interaction

Among various safety concerns, derailment prevention represents one of the fundamental priorities in railway systems. Accurate estimation of wheel–rail forces (WRFs) is important for assessing vehicle stability and derailment risk. Direct measurement using instrumented wheelsets is expensive and requires structural modifications, making it unsuitable for vehicles in regular operation. Zhang et al. [20] proposed an approach that combines a physics-informed Force–Moment Equilibrium (FME) model with deep learning-based correction networks for the indirect estimation of wheel–rail forces. The FME model first provides initial estimates of the lateral and vertical forces, after which neural networks learn to correct errors in the physical model caused by complex and nonlinear effects under real operating conditions, since the behavior of a real vehicle cannot be fully represented by an idealized physical model. The corrected forces are then used to determine the derailment coefficient. The proposed approach demonstrated high accuracy under different track conditions and showed potential for real-time monitoring of wheel–rail forces. In addition, geometric deviations, i.e., track irregularities, increase the probability of derailment. At the same time, the growing safety requirements in railway transport have increased the need for efficient identification of track irregularities using data from trains in regular operation. However, physics-based models depend on accurately known system parameters, while data-driven approaches often have limited interpretability. Dai et al. [21] proposed a novel Physics-Informed Kolmogorov–Arnold Network (PIKAN) for identifying vertical track irregularities based on bogie acceleration signals during straight-track operation. The KAN is directly embedded into the vehicle inverse dynamics model, so that the model follows the physical laws of the system during prediction while simultaneously learning from data without requiring prior knowledge of vehicle parameters. Based on the measured bogie accelerations, PIKAN identifies track irregularities and demonstrated higher accuracy and robustness than conventional data-driven neural networks. Another problem that occurs is wheel polygonal wear, which causes pronounced periodic vibrations at the wheel–rail interface, thereby compromising ride safety and increasing maintenance costs. Diagnostic solutions based solely on deep learning often have limited generalization capability under changing operating conditions and depend

heavily on large datasets, mainly because they neglect the frequency-dependent physical characteristics and the coupling between multiple wheels in wheel–rail dynamics. Xu et al. [22] applied the physics-guided neural network Co-FRF-NN, in which physical knowledge of wheel–rail dynamics is incorporated through a MIMO FRF-Net architecture. In this way, the model directly accounts for frequency-dependent vibration behavior and interactions among multiple wheels. The network was used to diagnose wheel polygonal wear based on vibration signals, achieving higher accuracy, better generalization across different speeds, and a reduced need for large amounts of data compared with conventional data-driven models.

Incorporating physical knowledge into AI models improves prediction accuracy, robustness, and reliability in complex vehicle–track interaction problems.

2.5. Aerodynamics

Physics-informed neural networks (PINNs) represent an increasingly important approach in flow simulation because they enable the simultaneous incorporation of physical laws and measured data when solving the Navier–Stokes equations and their variants. Zeng et al. [23] proposed a physics-informed data-driven strategy for reconstructing the time-averaged flow field around a train under crosswind conditions. Data and physics residuals are simultaneously incorporated into the PINN loss function, allowing physical knowledge to directly guide the reconstruction process. The authors also determined an optimal distribution of available data, while the reconstructed flow field showed good agreement with reference numerical simulations. Chen et al. [24] proposed a Neural Physics approach for high-fidelity train aerodynamic simulations, using CNNs whose weights are defined by classical numerical discretization schemes rather than learned through training. Applied to a freight train under calm and crosswind conditions, the method showed good agreement with numerical and experimental results.

Physics AI is highly relevant for railway vehicle aerodynamics, enabling accurate flow-field reconstruction with improved data efficiency and lower computational demands.

2.6. Other Significant Applications

From the perspective of pantograph–catenary interaction, Physics AI approaches have also been increasingly applied to the prediction, monitoring, and state assessment of these highly dynamic systems. Cheng et al. [25] developed a physics-informed surrogate model for the pantograph–catenary system that combines physical knowledge with deep neural networks. The physical equations are incorporated into the loss function, while a neural operator based

on Transformer and convolutional structures learns the complex relationships within the system. The model was successfully applied to response prediction and state identification using both simulation and real-world data. Chu et al. [26] proposed a model called FENet for this problem, which combines physical information with a data-driven approach. The model uses a Temporal Convolutional Network to extract short-term features and an attention-based LSTM to capture long-term dependencies, while constraints derived from the equations of motion are incorporated into the loss function so that physical principles can guide the learning process. In this way, fast and accurate prediction of the long-term dynamic response of the system under different external excitations is achieved with very low computational cost. Yan et al. [27] developed a machine-vision-driven physics-informed neural network (VIPINN) for state detection of the pantograph–catenary system. The model combines physics-guided feature extraction with analysis in both the time and frequency domains, while data loss and physics loss are simultaneously incorporated into the training process. VIPINN demonstrated higher detection accuracy and greater robustness to noise under complex operating conditions. Another approach was presented by Wang et al. [28]. They developed a surrogate model based on the Koopman Neural Operator approach for rapid prediction of the high-frequency dynamics of the pantograph–catenary system. The model was trained using data generated by a fully flexible FEM model, while physical consistency was incorporated into the loss function. FEM-level accuracy was achieved with a significant reduction in computational time.

Physics AI can also be applied to maglev systems. Ni et al. [29] applied Physics-Informed Neural Networks (PINNs) and Bayesian Physics-Informed Neural Networks (B-PINNs) to identify the parameters and states of a maglev levitation system from a small amount of noisy data. Incorporating physical laws enabled reliable problem solving even in the presence of measurement noise and external disturbances. In another study, Ni et al. [30] applied a residual-augmented PINN for probabilistic prediction of the response of a maglev levitation system under uncertain parameters. The model significantly improved accuracy and achieved approximately 440 times faster computation compared with the finite difference method. Another application of Physics AI was presented by Zhang et al. [31], who developed a multi-domain physics-informed digital twin for a hydrogen-powered maglev train. Physical constraints from the electrical, mechanical, magnetic, and energy domains were incorporated into the PINN model, enabling accurate real-time simulation of the complex system with low computational cost.

3. CONCLUSION

Based on the conducted literature review, it can be concluded that Physics AI has significant potential for application in various areas of railway engineering. The analyzed studies demonstrate different approaches and application possibilities, ranging from the prediction of dynamic and structural responses to condition monitoring, control, and system reliability assessment. Physical knowledge can be incorporated into artificial intelligence methods in different ways, thereby improving the accuracy, robustness, and physical consistency of the obtained results. In addition, such approaches can significantly reduce the time required for numerical calculations and simulations, as well as the overall computational demand. They are particularly important in problems where collecting large amounts of experimental data is expensive or difficult, since incorporating physical knowledge can reduce the dependence of models on data and improve their generalization capability. Based on the presented results, further development and wider application of Physics AI approaches can be expected in the design, analysis, monitoring, and control of modern railway systems.

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REFERENCES

- [1] Ari, M. E., Bilgi, C., Demir, B., Composite Materials in Railway Vehicles: Performance and Application Perspectives—A Review, *Arabian Journal for Science and Engineering*, 2026.
- [2] Sun, V. Q. C., Lang, C., Sun, Y. Q., Multi-body dynamic modelling and simulations for train crashworthiness design analysis, *Australian Journal of Mechanical Engineering*, Vol. 23, No. 2, pp. 378–390, 2025.
- [3] Ulbricht, A., Development and technological realisation of an innovative lightweight rail vehicle in composite design, *ZEVrail*, Vol. 143, No. 6–7, pp. 220–227, 2019.
- [4] Xiu, R., Spiryagin, M., Wu, Q., Yang, S., Liu, Y., Fatigue life assessment methods for railway vehicle bogie frames, *Engineering Failure Analysis*, Vol. 116, Article 104725, 2020.
- [5] Schupp, G., Simulation of Railway Vehicles: Necessities and Applications, *Mechanics Based Design of Structures and Machines*, Vol. 31, No. 3, pp. 297–314, 2003.
- [6] Dizo, J., Blatnický, M., Skocilasova, B., Computational Modelling of the Rail Vehicle Multibody System Including Flexible Bodies, *Communications - Scientific Letters of the University of Zilina*, Vol. 17, No. 3, pp. 31–36, 2015.
- [7] He, J., Xu, P., Xing, J., Yao, S., Wang, B., Zheng, X.,

- Optimization of energy-absorbing parameters for train crash energy management using a variable-fidelity neural network surrogate model, *Engineering Structures*, Vol. 334, Article 120242, 2025.
- [8] Deng, G., Peng, Y., Hou, L., Li, Z., Li, B., Yu, C., Simms, C., A Novel Simplified FE Rail Vehicle Model in Longitudinal and Lateral Collisions, *Machines*, Vol. 10, No. 12, Article 1214, 2022.
- [9] Azizzadenesheli, K., Kovachki, N., Li, Z., Liu-Schiaffini, M., Kossaifi, J., Anandkumar, A., Neural operators for accelerating scientific simulations and design, *Nature Reviews Physics*, Vol. 6, pp. 320–328, 2024.
- [10] Meng, C., Griesemer, S., Cao, D., Seo, S., Liu, Y., When physics meets machine learning: a survey of physics-informed machine learning, *Machine Learning for Computational Science and Engineering*, Vol. 1, Article 20, 2025.
- [11] Tang, Z., Dong, S., Yang, X., Zhang, J., Application of a parallel physics-informed neural network to solve the multi-body dynamic equations for full-scale train collisions, *Applied Soft Computing*, Vol. 142, Article 110328, 2023.
- [12] He, J., Xu, P., Xing, J., Yao, S., Wang, B., Zheng, X., Optimization of energy-absorbing parameters for train crash energy management using a variable-fidelity neural network surrogate model, *Engineering Structures*, Vol. 334, Article 120242, 2025.
- [13] Sepahvand, K., Schwarz, C., Urspruch, O., Guenther, F., Physics-Informed Bayesian Inference for Virtual Testing and Prediction of Train Performance, *Machines*, Vol. 14, No. 2, Article 211, 2026.
- [14] Han, C., Qu, S., Yang, Y., Gao, M. Y., Dong, L., Yang, F., Ma, T., Yang, Y., Zhai, W., A self-adaptive transformer-enhanced physics-informed neural network for railway dynamics system, *Engineering Applications of Artificial Intelligence*, Vol. 164, Part B, Article 113291, 2026.
- [15] Ji, Y., Huang, Y., Yang, M., Leng, H., Ren, L., Liu, H., Chen, Y., Physics-informed deep learning for virtual rail train trajectory following control, *Reliability Engineering & System Safety*, Vol. 261, Article 111092, 2025.
- [16] Liu, Y., Yang, L., Zhang, S., Kang, Y., Xun, J., Sun, Z., Parameter identification and platoon control for virtually coupled train set with physics-informed neural network dynamics model, *Vehicle System Dynamics*, Vol. 63, No. 1, pp. 71–92, 2025.
- [17] Yang, X., Hu, H., Bi, C., Real-time fatigue strength assessment of bogie frame welds based on a novel full-field stress tensor reconstruction method, *Engineering Structures*, Vol. 359, Article 122723, 2026.
- [18] Deng, X., Hu, Y., Wang, Z., Kan, Q., Zhang, X., Kang, G., Fatigue life prediction of induction-hardened S38C axle by a machine learning model integrating gradient physical information, *International Journal of Fatigue*, Vol. 201, Article 109140, 2025.
- [19] Xiao, Q., Xu, Z., Chang, C., Deng, X., Fang, J., Lin, F., A hybrid physics-data framework for multi-scale crack propagation assessment in high-speed train wheel treads, *Engineering Fracture Mechanics*, Vol. 335, Article 111929, 2026.
- [20] Zhang, P., Zhang, S., Liu, C., Liu, Y., Wang, R., Luo, P., Zhang, H., A hybrid physics-informed framework for indirect wheel–rail force measurement via FME modeling and CNN-LSTM-based correction, *Measurement*, Vol. 276, Article 121476, 2026.
- [21] Dai, B., Xu, Y.-L., Li, Q., Zhang, Z., Vertical track irregularity identification based on a physics-informed Kolmogorov-Arnold Network with bogie accelerations of in-service trains, *Mechanical Systems and Signal Processing*, Vol. 245, Article 113845, 2026.
- [22] Xu, W., Wen, Z., Tao, G., Wu, X., Yang, C., Xie, Y., Cai, W., Liu, J., Chi, M., Liang, S., A physics-guided neural network with embedded multi-wheel FRF for robust wheel polygonal wear diagnosis, *Measurement*, Vol. 270, Article 120847, 2026.
- [23] Zeng, G. Z., Chen, Z. W., Ni, Y. Q., Rui, E. Z., Investigating embedded data distribution strategy on reconstruction accuracy of flow field around the crosswind-affected train based on physics-informed neural networks, *International Journal of Numerical Methods for Heat and Fluid Flow*, 2024.
- [24] Chen, B., Liu, Z., Guo, Z., Heaney, C. E., Pain, C. C., Accelerated physics-based simulations of train aerodynamics using machine learning libraries, *Journal of Central South University*, Vol. 32, No. 12, pp. 4636–4659, 2025.
- [25] Cheng, Y., Yan, J., Zhang, F., Li, M., Zhou, N., Shi, C., Jin, B., Zhang, W., Surrogate modeling of pantograph-catenary system interactions, *Mechanical Systems and Signal Processing*, Vol. 224, Article 112134, 2025.
- [26] Chu, W., Wang, H., Song, Y., Liu, Z., FENet: A Physics-Informed Dynamics Prediction Model of Pantograph-Catenary Systems in Electric Railway, *IET Intelligent Transport Systems*, Vol. 19, No. 1, 2025.
- [27] Yan, J., Zhou, N., Cheng, Y., Zhang, F., Wang, H., Wang, M., Jin, B., Li, M., Lu, Q., Zhang, W., Application of machine-vision-driven physics-informed neural networks in pantograph–catenary system state detection, *Mechanical Systems and Signal Processing*, Vol. 257, Article 114577, 2026.
- [28] Wang, X., Song, Y., Yang, H., Yao, J., Wang, H., Liu, Z., Koopman Neural Operator-based surrogate modelling for high-frequency dynamics of high-speed rail pantographs, *Mechanical Systems and Signal Processing*, Vol. 258, Article 114780, 2026.
- [29] Ni, F., Dai, Y., Zheng, Q., Jia, W., Physics-informed machine learning for robust inverse problem solving in maglev train levitation systems under noisy measurement, *Nonlinear Dynamics*, Vol. 113, No. 20, pp. 26981–26999, 2025.
- [30] Ni, F., Fan, L., Zheng, Q., Jia, W., Probabilistic density evolution of maglev train levitation systems using residual-augmented physics-informed neural networks, *Reliability Engineering & System Safety*, Vol. 269, Article 112053, 2026.
- [31] Zhang, Y., Zhang, S., Dinavahi, V., Multi-Domain Physics-Informed Machine Learning Based Real-Time Digital-Twin Emulation for a Hydrogen-Powered Maglev Transportation System, *Green Energy and Intelligent Transportation*, Article 100441, 2026.



OPERATIONAL VALIDATION OF SPACE-ENABLED RAIL BUCKLING RISK MONITORING IN THE SPATRA RAILWAY PILOT

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Abstract - SPATRA project developed and demonstrated a Railway Pilot (RWP) that combines Earth Observation (EO)-derived land-surface temperature, meteorological forecasts, in-situ rail and environmental measurements, and track data to predict rail-track temperature and heat-related buckling risk. This paper summarises the integrated rail-pilot results. The RWP was operated from 1 July to 31 August 2025 on a 22 km Red Cross-Jasenovik section of the Niš-Svrljig line. The reported pilot results showed that 15 of 17 rail-temperature predictions were within ± 5 °C of in-situ measurements. Retrospective analysis of 22 hot-weather slow-order days indicates that risk-based restriction windows would reduce slow-speed operation from 264 to 146 h, a reduction of 118 h (about 45%). The system also identified the documented 24 July 2025 buckling location as high risk in advance. After interface refinements, all user-oriented KPIs exceeded 90% satisfaction, with section scores between 4.64 and 4.90/5. The results support more targeted speed restrictions, inspection prioritisation and traceable hot-weather decision-making, while wider deployment requires sustained sensor coverage, up-to-date asset data and integration with Railway Infrastructure Manager procedures.

Keywords - Railways, heat-related buckling, Earth Observation, rail track temperature, decision support.

1. INTRODUCTION

Increasing summer temperatures create a growing operational challenge for continuous welded rail, because high rail temperature can increase compressive thermal forces and the probability of lateral instability. Conventional hot-weather procedures are intentionally conservative, but they are often based on forecast air temperature and broad rules that have limited spatial and temporal resolution. The SPATRA project (Space-Based Applications for Transport Monitoring and Management) [1] addresses this gap by combining satellite-derived information with local measurements and operational data in decision-support services for land transport. Its

Railway Pilot (RWP) focuses on prediction and management of heat-related rail buckling risk [2].

This paper summarises the rail workstream pilot results, which evaluates the end-to-end behaviour, integrated performance and user acceptance of the pilot under operational conditions [2]. The evaluation builds on the pilot plan and KPI framework defined in [2], the integrated component validation reported in [4], and the user and system requirements defined in [5]. The objective is not to repeat module-level algorithm validation, but to present the evidence most relevant to railway infrastructure management: prediction performance, ability to localise high-risk periods and segments, potential impact on slow-speed orders, end-user acceptance, and prerequisites for

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wider deployment.

2. RAILWAY PILOT SETUP AND EVALUATION

2.1 Pilot corridor and integrated service

The RWP was demonstrated on a 22 km section of the Niš-Svrljig-Knjazevac-Prahovo corridor between Red Cross (Crveni Krst, Niš) and Jasenovik stations. The corridor combines high summer temperatures, small-radius curves, mixed cut-and-embankment geometry and strongly varying shading conditions. Eight representative sites were characterised by curvature, sleeper and fastening configuration and micro-climatic exposure. For risk assessment, the test track was divided into 234 homogeneous segments (Fig. 1). In-situ stations provided rail temperature, lateral displacement and local environmental measurements, while additional track and asset parameters were used to characterise segment susceptibility [1]

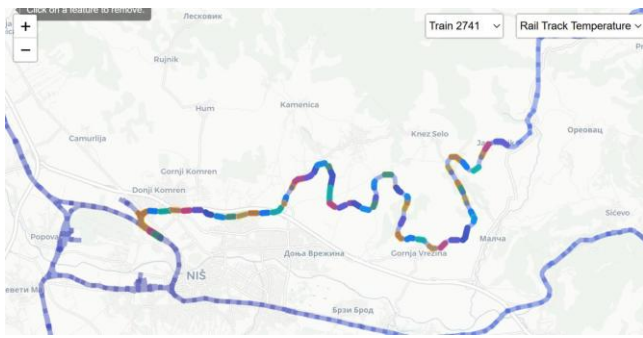


Fig. 1. Pilot demonstration track between stations Red Cross (Niš) and Jasenovik.

During the 1 July-31 August 2025 campaign, the integrated back-end operated in production-like mode. The processing chain combined a high-resolution EO-based Land-Surface-Temperature (LST) processor, Rail Track Temperature Prediction (RTTP), classical buckling-risk estimation using a Zarembski–Grissom–Lees-type buckling-risk index [6], which combines the rail-temperature increase above the neutral temperature with supplementary track-related risk factors, and an ANN-based lateral-displacement assessment. EO-derived LST and meteorological inputs provide spatial coverage, while in-situ measurements provide local calibration and ground truth [7]. Hourly RTT, risk and lateral-displacement outputs were delivered to Serbian Railway Infrastructure (ISR) users through the RWP WebGUI, where staff could inspect maps, segment-level time series, threshold exceedances and alerts [2].

2.2 Operational reference data and KPIs

Pilot interpretation used ISR operational records for the same summer period. Twenty-eight hot-140

weather telegrams were issued for the demonstration track, while the retrospective slow-order efficiency comparison reported covers 22 days with the standard 12-hour restriction window. One buckling incident was officially documented on Section 153 at km 9+040 on 24 July 2025, providing a real-world reference case. The key integrated KPIs addressed RTT prediction accuracy, buckling-risk assessment, efficiency of slow-order application and user satisfaction with the WebGUI, visual analytics and alerts [2].

3. PILOT RESULTS

3.1 Rail-temperature prediction and buckling-risk indication

For the pilot retrospective comparison, predicted and measured RTT values were examined for 17 dates in July associated with ISR slow-order telegrams. Fifteen of the 17 observations (about 88.2%) were within the ± 5 °C tolerance used for the integrated comparison. The two exceedances remained limited, at approximately 5.1 °C and 5.9 °C absolute error. RWP Results and Analysis Report therefore concluded that the RTT model performed reliably under the vast majority of observed pilot conditions.

The documented 24 July 2025 buckling case is the most important operational reference. The RWP identified the affected segment as high risk before the incident and predicted buckling risk above 70% during the late morning and early afternoon. In [2], the high-risk period is reported around 10:00-15:00, whereas Train 2743 entered the section at 17:05 and the deformation was then reported. The case demonstrates that the RWP could provide an earlier, segment-specific warning layer to complement field inspection and existing hot-weather rules. Risk values are nevertheless sensitive to local parameters such as rail-neutral temperature, track quality and fastening type, so the output is intended as decision support rather than an automatic safety decision [2].

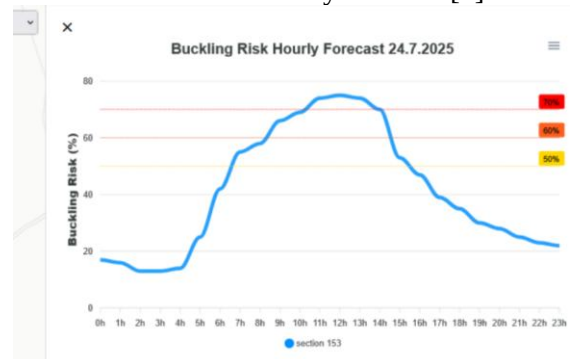


Fig. 2. Buckling-risk forecast for Section 153 on 24 July 2025 (adapted from [2], Fig. 8).

3.2 Potential reduction of heat-related slow-speed operation

Current ISR hot-weather practice applies precautionary slow-speed orders when forecast air temperature exceeds an internal threshold of approximately 33 °C. On the analysed days, restrictions were generally imposed from 10:00 to 22:00. Study reported in [2] compares this conservative 12-hour window with a risk-based approach in which reduced speed is associated with periods when the RWP buckling-risk indicator exceeds 70%. Across the 22 analysed days, the conventional approach corresponds to 264 hours of slow-speed operation, whereas the RWP-derived high-risk windows total 146 hours. The difference is 118 hours, or approximately 45%. On most days, the risk-based windows were 4-7 hours shorter than the standard block [2].

The results also indicate that timing can be refined in both directions. For example, on 1 July the standard 10:00-22:00 slow order could, according to the retrospective RWP result, have been focused on 10:00-16:00. Conversely, a vulnerable segment may require action earlier than a generic standard window if its risk rises rapidly. The operational value is therefore not simply shorter restrictions: it is the possibility to target where and when risk is elevated, while retaining ISR responsibility and established safety procedures.

3.3 Integrated KPI summary

Taken together, the integrated results presented in [2] show five points of direct operational relevance. First, 15 of 17 RTT observations in the retrospective sample were within ± 5 °C. Second, the risk-based slow-order windows totalled 146 h compared with 264 h under the standard 12 h windows, a reduction of about 45%. Third, the documented 24 July 2025 incident location was identified as high risk in advance. Fourth, after GUI refinements all user-oriented KPIs exceeded the 90% satisfaction targets. Finally, system logs reported threshold exceedance detection within 30 s and completion of processing within 1 min in more than 95% of cases.

3.4 User acceptance and operational relevance

ISR staff used the WebGUI during the summer campaign and in structured workshops. The first questionnaire round was already positive, but users requested clearer risk scales, better explanation of thresholds and greater visibility of live sensor data. The project consequently added intermediate risk thresholds, integrated live in-situ information and refined alert presentation. In the second round, all

user-oriented KPIs were reported as achieved: overall satisfaction 4.67/5 (93.4%), data visualisation and analysis 4.73/5 (94.6%), alerts and notifications 4.64/5 (92.8%), and interface usability 4.90/5 (98%) [2].

Feedback shows that the main operational benefits are the ability to localise critical segments in space and time, prioritise inspections, and document the rationale for hot-weather measures. ISR experts considered a two-stage workflow natural: first review a daily line-level risk map, then drill down into hourly RTT, risk and sensor traces for flagged segments. They also highlighted the value of archived risk maps and alert histories as a traceable record for post-event analysis, threshold refinement and longer-term climate-adaptation planning [1].

4. OPERATIONAL IMPACT FOR RAILWAY INFRASTRUCTURE MANAGEMENT

4.1 Inspection planning and recurrent thermal hotspots

The same segment-level information used to refine slow-speed orders can support inspection and maintenance planning. During the campaign, short curves and transition sections repeatedly reached higher risk levels than adjacent track under comparable meteorological forcing. SPATRA results therefore propose using recurrent high-risk segments as thermal hotspots in asset-management practice. Such locations can be assigned higher inspection frequency during the hottest months and can be prioritised for ballast cleaning, tamping, sleeper renewal or additional stabilisation measures where justified by field condition. On individual hot days, the hourly risk forecast can also help route patrol teams first to segments expected to enter the high-risk regime earliest, rather than relying only on uniform patrol patterns and static vulnerable-section lists [2].

4.2 Traceable risk history and decision rationale

A further result of the integrated service is systematic digital documentation. For each hot day, the RWP can retain predicted RTT and buckling risk by segment and hour, together with threshold exceedances, active alerts and recorded operational responses. ISR feedback identified this as an important complement to current documentation, which is largely textual and distributed across different systems. A georeferenced risk archive can provide traceable justification for past restrictions and non-actions, support post-incident and near-miss analysis, and create a data source for refining thresholds and identifying repeatedly critical locations for climate-adaptation and reinvestment planning [2].

4.3 Requirement coverage and maturity at pilot scale

[2] assesses the main functional and non-functional requirement groups as fully or largely met at pilot scale. The core processing chain is fully implemented: thermal downscaling, RTT prediction, buckling-risk and lateral displacement assessment, quality control, threshold monitoring and WebGUI delivery all operated as an integrated service. User-facing workflows for map exploration, segment time series and alert review were also demonstrated. Performance and usability were considered adequate for the pilot, while the principal open issues concern parameter sensitivity, extension of the lateral-displacement model to different track typologies, richer configuration and explanations, and deeper integration with ISR control-room tools. The overall demonstration therefore supports the SPATRA project conclusion of TRL6 and technical readiness for pre-operational use, not yet network-wide autonomous operation.

5. LESSONS AND DEPLOYMENT REQUIREMENTS

The SPATRA rail pilot confirms that EO and in-situ data are complementary rather than interchangeable. Satellite and meteorological products provide spatial continuity over the corridor, while local stations provide ground truth and measurements, such as lateral displacement, that cannot be obtained directly from EO. [2] and [4] also report that the complete RWP chain operated reliably at pilot scale; threshold exceedances were detected within 30 s and processing completed within 1 min for more than 95% of cases in the validation logs, supporting near-real-time use during heatwaves.

At the same time, network-wide use requires conditions that go beyond the successful pilot. A sparse but representative sensor network is needed for different climatic and track typologies, together with regular maintenance of rail-neutral temperature, geometry, fastening, ballast and track-quality data. Risk alerts should be integrated into ISR dispatch, traffic-management and asset-management environments so that they appear alongside existing operational information. Formal procedures must define responsibilities and threshold-to-action mappings, and users require concise training on interpretation of risk indices and confidence levels [2].

SPATRA final report [2] therefore recommends a phased transition: formalise RWP-supported operating procedures; standardise role-specific WebGUI views and legends; link alerts directly to the affected

segment and time context; use the digital archive systematically in safety reviews; incrementally extend reference sensors; and, in the medium term, integrate the service with ISR operational and asset databases. Multi-year data should then be used to refine site-specific thresholds and sustain model calibration as part of normal service lifecycle management.

6. CONCLUSION

The SPATRA Railway Pilot demonstrated an end-to-end EO-enabled service for heat-related rail buckling risk under realistic operating conditions on the Niš-Svrljig demonstration corridor. The project integrated evidence reported shows reliable rail-temperature prediction in the pilot sample, correct identification of the documented 24 July 2025 high-risk segment, a substantial potential reduction in the duration of heat-related slow-speed operation, and very high user acceptance after interface refinement. The principal operational contribution is not automated replacement of existing Railway Infrastructure Manager procedures, but a more spatially and temporally specific evidence layer for speed restrictions, inspection planning and documentation. The pilot achieved the project target of TRL6, while progression towards sustained operational use depends on sensor and asset-data governance, formal workflow integration, model maintenance and continued validation on additional lines and seasons.

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REFERENCES

- [1] SPATRA project. <https://spatra-project.eu/>
- [2] SPATRA Consortium, Deliverable D4.3, Pilot Results and Analysis Report, Grant Agreement 101129658
- [3] SPATRA Consortium, Deliverable D4.1, Pilot Plan and Protocol Specification, Grant Agreement 101129658.
- [4] SPATRA Consortium, Deliverable D4.2, Integration and Validation Report, Grant Agreement 101129658
- [5] SPATRA Consortium, Deliverable D2.1, Requirements and Use Cases, Grant Agreement 101129658
- [6] Zarembski, A. M., Grissom, G. T., Lees, H. M. Jr., "Assessing the Risk of Track Buckling," *Railway Track & Structures*, Vol. 101, No. 2, pp. 23–26, 2005.
- [7] D. Ristić-Durrant et al., "Novel Use of EO Satellite Data and AI in Railways: A Concept for Rail Buckling Risk Estimation in the SPATRA Project," 2025 20th European Dependable Computing Conference Companion Proceedings (EDCC-C), Lisbon, Portugal, 2025, pp. 80-83, doi: 10.1109/EDCC-C66476.2025.00036



MANAGEMENT OF AI SMART MONITORING IN RAILWAY SYSTEMS: A REVIEW OF PREDICTIVE MAINTENANCE, RISK-INFORMED DECISION SUPPORT, AND OPERATIONAL RESILIENCE

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Abstract – Artificial intelligence, data-driven condition monitoring and digital twins are increasingly used to anticipate railway degradation, yet their managerial value depends on whether predictions are converted into defensible maintenance actions. This paper provides a structured narrative review of recent peer-reviewed evidence on railway predictive maintenance, focusing on maintenance management rather than algorithmic performance alone. The synthesis examines condition assessment, failure anticipation, maintenance prioritization, scheduling and resource allocation, and closed-loop performance feedback across infrastructure and rolling-stock applications. Recent studies show that machine-learning models can identify high-risk track sections, provide explainable real-time fault warnings, and optimize tamping schedules under operational constraints. However, a persistent translation gap remains between accurate diagnosis and network-level management because of limited field validation, weak interoperability, uncertainty, black-box models, and fragmented system integration. A monitoring-to-management framework is therefore proposed, linking sensing, diagnosis, prognosis, criticality assessment, prioritization, scheduling, intervention and feedback, supported by explainability, data governance and lifecycle costing. The review positions AI monitoring as a decision-support capability embedded within railway asset-management processes.

Keywords – railway maintenance; maintenance management; predictive maintenance; artificial intelligence; decision support.

1. INTRODUCTION

Railway maintenance management is fundamentally a decision problem: managers must determine where, when and how to intervene across heterogeneous assets while balancing safety, service availability, possession time, workforce, machinery and lifecycle cost. Predictive maintenance is supported by sensors, machine learning and digital twins, and recent reviews document rapid growth of these technologies across railway subsystems [1,2]. Yet the practical value of prediction is not determined by diagnostic accuracy alone. A model becomes useful to maintenance management only when its output changes priority, schedule, resource allocation,

renewal choice or operational restriction. This distinction exposes a recurring gap in literature. Technical studies commonly optimize detection, classification or remaining-life estimation, whereas railway managers require decisions under uncertainty and operational constraints. Predictions may arrive without sufficient lead time, without explicit criticality, without transparent reasoning, or without integration with maintenance planning systems. Conversely, studies now connect condition data to prioritization, scheduling and prescriptive analytics, creating a basis for a more management-oriented synthesis. The objective of this paper is to review how recent AI railway monitoring progresses from

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condition information to actionable maintenance management. The contribution is a structured narrative synthesis organized by decision function and a monitoring-to-management framework that identifies the stages and enabling conditions required to translate predictive outputs into operational action.

2. REVIEW APPROACH

A structured narrative review was adopted to fit the conference format while retaining a transparent analytical logic. The evidence base comprises recent peer-reviewed studies published in 2025-2026 and selected because they explicitly connect monitoring or prediction with at least one management function: condition assessment, failure anticipation, prioritization, scheduling, resource allocation, decision explainability, or lifecycle asset management. Candidate studies were identified through targeted Scopus searches using combinations of railway, predictive maintenance, artificial intelligence, machine learning, digital twin, maintenance management, decision support, scheduling and asset management. Final selection was purposive, retaining studies that demonstrated an explicit link between a monitoring or predictive output and a maintenance-management decision, operational outcome or implementation barrier. Review papers were used to identify field-level gaps, while empirical studies were used to examine how technical outputs are converted into decisions. The synthesis is organized by decision function rather than by algorithm family; it is interpretive and comparative, not a pooled-effect meta-analysis.

3. FROM PREDICTION TO MAINTENANCE DECISIONS

Recent evidence shows that prediction is becoming more directly linked to intervention needs. Morais et al. proposed a framework in which heterogeneous performance indicators are processed and forecast to support railway-track maintenance management over time [3]. In a Western Balkans case study, Trajkova et al. used inspection, infrastructure, operational and maintenance variables to predict Track Quality Index on the Kolashin-Podgorica line [4]. Random Forest outperformed multiple linear regression ($R^2 = 0.69$ versus 0.57), and the model achieved 86.4% sensitivity for high-risk segments. Importantly, the output was interpreted as a basis for prioritizing tamping, renewal and targeted interventions rather than merely as a prediction score. The choice of management variable can be as important as the predictive algorithm. For freight-wagon wheelsets, Bhadouria et al. compared time, mileage and gross-ton mileage through regression, survival analysis and reinforcement learning, identifying gross-ton mileage

as the most reliable lifetime variable for maintenance decisions [5]. Toribio et al. addressed another management requirement: lead time. Their two-stage framework combined forecasting and anomaly detection for metro trains and maintained effective detection at one- and three-hour horizons, giving maintenance teams time to prepare interventions rather than react only after deviations become visible [6].

Decision support in safety-critical maintenance requires not only a warning but also a credible basis for action. Using real data streams from the Porto metro operator, García-Méndez et al. developed an online predictive-maintenance pipeline with visual and natural-language explanations, reporting more than 98% F-measure and 99% accuracy [7]. The contribution is managerial as well as technical: explanations allow decision-makers to relate an alert to the underlying sensor behavior and respond more rapidly. Sayed et al. reached a complementary conclusion for track-geometry defects [8]. Their SMOTE-SHAP workflow improved minority-defect recall for several classifiers and exposed the influence of physically meaningful variables, but precision trade-offs and moderate overall discrimination led the authors to position the models as screening and prioritization aids rather than stand-alone operational decision systems. Together, these studies show why explainability should be treated as part of decision quality, especially when false alarms consume scarce maintenance capacity.

The strongest transition from prediction to management occurs when models optimize a maintenance action. MajidiParast et al. presented a prescriptive analytics framework using graph convolutional networks and historical maintenance data to support optimal railway-track maintenance scheduling while representing spatial interdependencies [9]. Ge et al. moved further toward operational planning by integrating stochastic track deterioration, maintenance-window constraints and cost into a deep-reinforcement-learning model for tamping [10]. Validation on a real 50 km ballasted-track section produced feasible schedules and reduced labor, material and machinery-use costs by 27.8%, 8.3% and 16.9%, respectively. These results illustrate a central management principle: predictive accuracy becomes operational value when the objective function also represents possession, timeliness, cost, resource use and expected maintenance benefit.

Digital twins provide a potential architecture for connecting monitoring, simulation and maintenance decisions. Bianchi et al. combined a digital twin of bonded insulated rail joints with AI classifiers to support predictive structural-health monitoring [11], and a subsequent physics-informed DT-AI framework

extended this logic to coupled joint and sleeper degradation, creating a decision-oriented workflow for automated condition assessment and future prioritization [12]. At a broader level, Kazemi et al. found that DT applications can improve monitoring and decision support, but most implementations remain conceptual or pilot-scale and face interoperability, scalability, data-governance and validation barriers [13]. Mutlu and Kaewunruen similarly identified a 'Digital Twin Gap': many railway systems remain unidirectional digital representations rather than fully synchronized decision environments [2]. Rolling-stock work integrating BIM, PdM and continuously updated digital representations further demonstrates the potential for lifecycle-oriented asset management, while also underscoring the need for robust interoperability [14].

4. MONITORING-TO-MANAGEMENT FRAMEWORK

The reviewed evidence supports a decision-maturity sequence in which each technical output must answer a progressively more managerial question. Condition data establish what is happening; diagnosis identifies the health state; prognosis estimates what is likely to happen and when; criticality assessment adds consequence and uncertainty; prioritization determines where intervention is most valuable; scheduling determines when the work can be executed; resource allocation determines with what crew, machinery and budget; and feedback verifies whether the intervention restored the expected condition. Fig. 1 summarizes this monitoring-to-management logic.

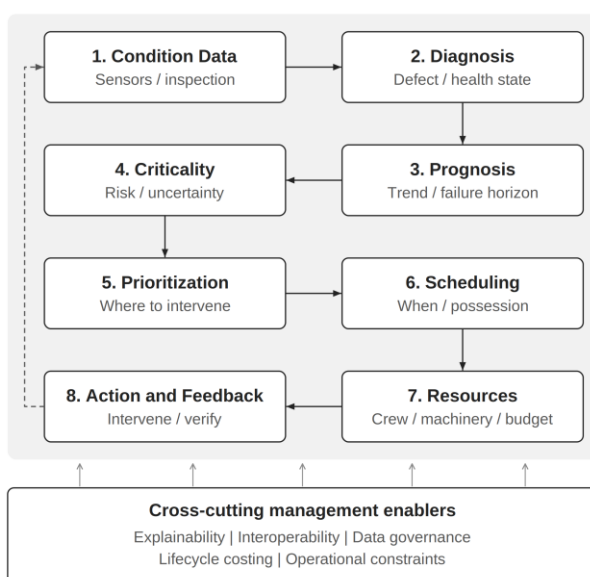


Fig. 1. Monitoring-to-management framework for AI-enabled railway maintenance

Three cross-cutting requirements determine

whether this chain is reliable. First, decision traceability requires interpretable indicators, confidence information and a documented link between a prediction and the proposed intervention. Second, constraint-aware optimization requires technical conditions to be evaluated together with maintenance windows, costs, resources and service effects. Third, closed-loop validation requires post-intervention data to be returned to the asset record and used to test whether predicted benefits were achieved. This shifts performance assessment away from model accuracy alone toward management outcomes such as avoided failures, intervention lead time, possession hours, resource utilization, cost per maintained asset, false-alarm burden and post-maintenance condition recovery.

5. DISCUSSION

A consistent pattern is seen across the literature: railway research is strongest at detection and prognosis, while evidence becomes thinner as the decision moves toward network-level prioritization, integrated scheduling and closed-loop management. Systematic reviews report concentration on selected assets and limited practical validation [1], while DT reviews show that many implementations remain subsystem-specific prototypes [2,13]. The implication is not that more complex algorithms are always needed; rather, railway maintenance systems require stronger integration between analytics and the management processes that convert evidence into executable work. Viewed through the proposed framework, the literature can be interpreted in four decision-maturity levels: condition visibility, prediction of degradation or failure, prescriptive support for prioritization or scheduling, and closed-loop management in which intervention results update subsequent decisions. For deployment, this means that technical validation should be accompanied by decision validation. A high-performing model that cannot express uncertainty, explain an alert, accommodate possession constraints or exchange data with asset-management systems may add little operational value. By contrast, the most management-relevant studies in the reviewed set explicitly linked prediction to prioritization [4,8], actionable lead time [6,7], prescriptive scheduling [9,10], or lifecycle integration [11-14]. Future work should test integrated solutions across multiple asset classes and operating conditions, report lifecycle cost and service outcomes, and evaluate whether recommendations remain stable when data quality, traffic, weather and resource constraints change.

6. CONCLUSION

AI monitoring is expanding the technical basis of

railway predictive maintenance, but its management value is realized only when diagnostic and prognostic outputs are translated into decisions that can be prioritized, scheduled, resourced and verified. Recent studies demonstrate credible progress: high-risk track segments can be identified, warnings can be produced with useful lead time and explanations, and maintenance schedules can be optimized under practical constraints. At the same time, field validation, interoperability, uncertainty treatment and system-level integration remain major barriers. The proposed monitoring-to-management framework places predictive models inside an asset-management cycle that links condition data to criticality, prioritization, scheduling, intervention and feedback. This management perspective provides a practical basis for evaluating railway AI not only by what it predicts, but by the quality and measurability of the maintenance decisions it enables.

REFERENCES

- [1] El Hor, D., Bannari, R., Bannari, A., A Systematic Review and Unified Framework for Predictive Maintenance in the Railway Domain, *Vehicles*, 8, 220, 2026. <https://doi.org/10.3390/vehicles8090220>
- [2] Mutlu, U., Kaewunruen, S., Digitalised Predictive Maintenance in Railways: A Systematic Review of AI, BIM, and Digital Twins, *Infrastructures*, 11, 87, 2026. <https://doi.org/10.3390/infrastructures11030087>
- [3] Morais, M.-J., Sousa, H.S., Matos, J.C., Araújo, M., Algorithm to Forecast Railway Track Assets Performance in Europe, *Applied Sciences*, 16, 4754, 2026. <https://doi.org/10.3390/app16104754>
- [4] Trajkova, I.N., Zafirovski, Z., Dimitrijevic, J., Ristov, R., Gacevski, V., Data-Driven Prediction of Track Quality Index: A Comparative Study of Statistical and Ensemble Learning Models—A Case Study of the Kolashin–Podgorica Railway, *Infrastructures*, 11, 258, 2026. <https://doi.org/10.3390/infrastructures11080258>
- [5] Bhadouria, A.S., Braga, J.A.P., Mishra, R.P., Andrade, A.R., Optimizing maintenance in railway wheelsets from freight wagons: What is the most appropriate lifetime variable?, *Proc. IMechE Part F: J. Rail Rapid Transit*, 2025. <https://doi.org/10.1177/09544097251400096>
- [6] Toribio, L., Veloso, B., Gama, J., Zafra, A., A two-stage framework for early failure detection in predictive maintenance: A case study on metro trains, *Neurocomputing*, 670, 132506, 2026. <https://doi.org/10.1016/j.neucom.2025.132506>
- [7] García-Méndez, S., de Arriba-Pérez, F., Leal, F., Veloso, B., Malheiro, B., Burguillo-Rial, J.C., An explainable machine learning framework for railway predictive maintenance using data streams from the metro operator of Portugal, *Scientific Reports*, 15, 27495, 2025. <https://doi.org/10.1038/s41598-025-08084-1>
- [8] Sayed, M.M.M., Rind, T.A., Ahmed, S., Khan, M.A., Mangnejo, D.A., Shah, M.F., Explainable AI for Railway Track Maintenance: Integrating SMOTE and SHAP in Class-Imbalanced Predictive Models, *Journal of Engineering*, 2026, 1944007, 2026. <https://doi.org/10.1155/je/1944007>
- [9] MajidiParast, S., Neamatian Monemi, R., Gelareh, S., A graph convolutional network for optimal intelligent predictive maintenance of railway tracks, *Decision Analytics Journal*, 14, 100542, 2025. <https://doi.org/10.1016/j.dajour.2024.100542>
- [10] Ge, H., Wang, J., Wang, W., Zaheer, Q., Liao, L., Sun, Y., Li, Y., Qiu, S., Optimization of heavy railway maintenance machinery tamping scheduling based on deep reinforcement learning, *Applied Soft Computing*, 201, 115689, 2026. <https://doi.org/10.1016/j.asoc.2026.115689>
- [11] Bianchi, G., Freddi, F., Giuliani, F., La Placa, A., Implementation of an AI-based predictive structural health monitoring strategy for bonded insulated rail joints using digital twins under varied bolt conditions, *Railway Engineering Science*, 33, 703-720, 2025. <https://doi.org/10.1007/s40534-024-00371-3>
- [12] Bianchi, G., Freddi, F., Giuliani, F., AI–Digital Twin framework for automated predictive maintenance of bonded insulated rail joints, *Automation in Construction*, 190, 107102, 2026. <https://doi.org/10.1016/j.autcon.2026.107102>
- [13] Kazemi, M.J., Rashidi, M., Kang, W.-H., Siahkouhi, M., Toward Smart Railway Infrastructure Predictive and Optimised Maintenance Through Digital Twin (DT) System, *Sensors*, 26, 2333, 2026. <https://doi.org/10.3390/s26082333>
- [14] Coutinho, J.M., Raposo, H., Farinha, J.M.T., Marques Cardoso, A.J., BIM and PdM of Railway Rolling Stock with Automatic Upgrading Based on GenAI, *Machines*, 14, 535, 2026. <https://doi.org/10.3390/machines14050535>



FROM RAILWAYS ACT 1993 TO GREAT BRITISH RAILWAYS: EVOLUTION OF UK RAIL REFORM AND RETURN TO PUBLIC OWNERSHIP (1993–2026)

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Abstract – This paper analyzes the long-term reform trajectory of the United Kingdom railway system from the implementation of the Railways Act 1993 to the legislative confirmation of public ownership of Great British Railways (GBR) in 2026. The study examines the transformation from a vertically integrated public railway system (British Rail) into a fragmented, market-oriented structure based on privatization, franchising, and infrastructure separation. It further evaluates the operational, financial, and safety consequences of this model, including coordination inefficiencies, rising transaction costs, and systemic safety challenges highlighted by major infrastructure failures and accidents. Special attention is given to the collapse of Railtrack and subsequent re-nationalization of infrastructure through Network Rail, as well as the gradual reintegration process culminating in the Williams–Shapps reform agenda and the Passenger Railway Services (Public Ownership) Act 2024. The paper concludes that while privatization achieved partial improvements in traffic growth and service innovation, it failed to ensure system integration, financial sustainability, and clear accountability. The 2026 amendment legally securing GBR in public ownership is interpreted as a strategic reversal toward centralized governance of railway infrastructure and operations.

Keywords – Railway reform, Railways Act 1993, Great British Railways, privatization, public ownership.

1. INTRODUCTION

The United Kingdom railway reform represents one of the most complex structural transformations in modern European transport history. The legislative change introduced by the Railways Act 1993 initiated a systemic transition from a publicly owned, integrated railway model to a fully fragmented, market-driven structure. Over the following three decades, the system evolved through multiple phases of privatization, institutional failures, partial re-nationalization, and finally reintegration under the concept of Great British Railways (GBR). The amendment of 10 June 2026, which legally guarantees GBR remains in public ownership, marks the culmination of this long reform cycle.

1.1. Historical Context of UK Railway Reform

The reform of the UK railway system emerged from broader economic and political changes in the late 20th century, characterized by a shift toward market liberalization and reduced state intervention. These conditions created the policy environment that led to the Railways Act 1993 and the restructuring of British Rail.

2. STATE OF THE UK RAILWAYS BEFORE 1993

Before the Railways Act 1993, the railway system

was operated by British Rail, a vertically integrated state-owned enterprise. It managed infrastructure, passenger and freight services, rolling stock, maintenance, signaling systems, and national timetable planning within a single organizational structure.

Although operational responsibility was centralized, the system faced several structural limitations:

- high dependency on state subsidies
- aging infrastructure and rolling stock
- slow administrative and investment processes
- limited commercial flexibility

Despite these challenges, safety levels remained relatively stable, and the system maintained national coordination and strategic coherence.

3. OBJECTIVES OF THE RAILWAYS ACT 1993

The Railways Act 1993 was introduced as part of a broader political and economic agenda of liberalization in the United Kingdom. Its main objectives were:

- reduction of public expenditure on railways
- improvement of operational efficiency through competition
- attraction of private investment into infrastructure and services
- restructuring of the railway into market-based entities

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- separation of regulatory and operational functions

The underlying assumption was that market mechanisms would deliver higher efficiency, better service quality, and reduced financial burden on the state.

3.1. Core ideas of the reform model

Structural separation

- Infrastructure: Railtrack (later Network Rail)
- Operations: multiple franchised train operating companies
- Rolling stock: leasing companies (ROSCOs)

Franchise-based competition

Competition was introduced through bidding for service contracts rather than direct operational competition on the same routes.

Market governance model

The system was designed around contractual relationships, performance monitoring, and financial incentives.

Reduced direct state operation

The state shifted from operator to regulator and contract manager

4. SYSTEM DEVELOPMENT AND OUTCOMES (1993–2026)

Initial phase (1993–2000)

The early years showed:

- increased passenger numbers
- new rolling stock investment
- improved service innovation

However, the system became highly fragmented.

Structural crisis phase (2000–2010)

A key turning point was the collapse of Railtrack in 2001, replaced by Network Rail. Major safety incidents (Southall, Ladbroke Grove, Hatfield) exposed weaknesses in infrastructure management and coordination.

Expansion with coordination problems (2010–2018)

Passenger growth continued, but systemic inefficiencies increased:

- delays and disruptions
- complex fare structures
- unclear accountability

System failure recognition (2018–2021)

Large-scale timetable disruptions in 2018 confirmed structural dysfunction. The Williams–Shapps Plan (2021) officially identified fragmentation as the core system problem.

Reintegration phase (2024–2026)

The Passenger Railway Services (Public Ownership) Act 2024 initiated gradual renationalization of operations. The 2026 amendment legally secured GBR as a permanently public entity.

5. REASONS FOR THE 2026 AMENDMENT

The amendment was driven by several systemic factors:

- excessive fragmentation of operational responsibilities
- lack of unified accountability
- rising transaction and coordination costs
- continued dependence on public funding
- need for long-term infrastructure planning
- political desire for institutional stability

5.1. Consequences of the 1993 reform

Positive outcomes:

- increased passenger demand
- modernization of rolling stock
- improved service standards in certain areas
- introduction of commercial discipline

Negative outcomes:

- systemic fragmentation
- increased administrative complexity
- weak accountability structure
- high coordination costs
- infrastructure safety challenges
- persistent reliance on state financial support

6. CONCLUSION

The period from 1993 to 2026 demonstrates that railway privatization in the UK produced mixed results. While it succeeded in increasing passenger usage and introducing market-oriented practices, it failed to maintain system integration, financial independence, and clear operational accountability.

The establishment of Great British Railways and the legal requirement for its public ownership in 2026 represent a strategic correction of earlier reform assumptions. The UK railway experience highlights that railway systems function most effectively when governed through integrated planning, centralized accountability, and stable long-term public ownership of critical infrastructure.

REFERENCES

- [1] Shaw, J., *The Railways Act and UK Transport Policy, Transport Policy Review*, London, 2005. Proceedings, Conference, Place, Year.
- [2] A Glaister, S., *UK Railways: Privatization and Regulation*, Oxford University Press, Oxford, 2010.
- [3] Office of Rail and Road, *Rail Statistics 2024–2025*, London, 2025.
- [4] UK Parliament, *Passenger Railway Services (Public Ownership) Act 2024*, The Stationery Office, London, 2024.
- [5] UK Parliament, *Railways Bill – Commons Amendments securing Great British Railways in Public Ownership*, House of Commons, London, 2026.
- [6] Department for Transport, *Williams–Shapps Plan for Rail*, UK Government, London, 2021.

The Graduates and the Future of Railway



FAILURE ANALYSIS OF TYPE R FREIGHT WAGONS ON THE SERBIAN RAILWAY NETWORK

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Abstract – The subject of this research is to investigate the occurrence and characteristics of failures of Type R freight wagons operating on the railway network of the Republic of Serbia. The type "R" wagons are four-axle flat wagons with high payload capacities, designed for the transport of heavy general cargo and containers. The research is based on failure and maintenance records provided by national company "Serbia Cargo", comprising 2,427 recorded failure events collected during the period from January 1, 2021, to April 26, 2024. The study applies statistical data processing, classification methods, and data visualization to identify dominant failure patterns and assess the reliability performance of the analysed wagon fleet. An analysis of failure causes, frequencies, and categories was conducted, with particular emphasis on the identification of the most failure-prone components and systems. Failures were classified according to their type, location of occurrence, and time of occurrence, enabling a comparative assessment of failure frequencies across different years and maintenance locations. The main findings of the analysis show that the majority of failures are related to technical malfunctions, indicating that the technical condition and maintenance system are the most critical segments. Besides the insights provided into the reliability characteristics of Type R freight wagons, the obtained results can also contribute to improved organization of preventive maintenance planning, aiming to reduce life-cycle costs of this type of wagon.

Keywords – freight wagons, type R wagons, failure frequencies, maintenance, analysis, classification of failures

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ANALYSIS OF FAILURES OF TYPE “Z” FREIGHT WAGONS ON SERBIAN RAILWAYS

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Abstract – The aim of the thesis is to analyze the failures occurring on freight wagons of the "Z" type operating on the Serbian railway network, with a particular focus on identifying critical components and operational conditions that contribute to their occurrence. Based on the obtained results, the thesis seeks to propose preventive measures and maintenance strategies aimed at reducing the frequency of future failures, improving wagon reliability and safety, and optimizing the overall efficiency of freight railway transport in Serbia. "Z" type freight wagons are tank wagons used for the transportation of liquid, powdered, and gaseous substances. To ensure safe transport, proper tank marking and regular maintenance of critical wagon components are essential. The analysis of the collected data showed that the main causes of failure and withdrawal of "Z" type freight wagons from service are technical malfunctions, inadequate documentation and labeling and various types of damage. The most frequently occurring failures are associated with the air brake system, brake distributor and draw-and-buffering devices. Carefully planned maintenance helps prevent failures that could endanger human life and health, cause environmental damage, and disrupt railway operations. The development of predictive maintenance systems is becoming increasingly important because they are based on a proactive approach to maintenance management. These systems are capable of monitoring, recording and predicting the performance of rail vehicles and their individual components. By analyzing the collected data, it is possible to assess the condition of equipment and identify potential failures before they occur. This enables more effective planning of maintenance activities, reduce downtime, and contributes to the safer and more efficient operation of rail vehicles.

Keywords – freight wagons, tank wagons, failure analysis, predictive maintenance, railway safety.

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FAILURE ANALYSIS AND AVAILABILITY ASSESSMENT OF STADLER FLIRT EMU 413/417 TRAINS IN SERBIA

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Abstract – The reliability and availability of modern electric multiple units (EMUs) are essential for ensuring safe, efficient, and sustainable railway transport. This research presents an analysis of the maintenance process, failure characteristics, and operational availability of Stadler FLIRT 413/417 EMUs operating on the Serbian railway network. The research is based on maintenance records and failure data collected during the warranty period between April 2024 and September 2025, comprising 113 recorded failure events provided by Srbija Voz. The study examines the frequency, distribution, and root causes of failures, identifies the most critical vehicle subsystems, and evaluates their impact on train immobilization and overall fleet availability. Maintenance procedures, including scheduled inspections and corrective interventions, are analyzed to assess their effectiveness in maintaining operational performance. Statistical analysis and data visualization were applied to identify recurring failure patterns and maintenance trends. The most frequent failures by subsystem are concentrated in transformer-related components, information systems, and climate/heating systems. These results indicate that these three subsystems represent the dominant contributors to overall system downtime and reliability issues. The findings provide practical recommendations for improving maintenance strategies, reducing unplanned downtime, and increasing fleet reliability and availability. The proposed approach supports the transition toward more efficient, data-driven, and predictive maintenance practices in modern railway systems.

Keywords – critical subsystems, maintenance evaluation, statistical analysis data visualization.

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FAILURE ANALYSIS OF H-SERIES FREIGHT WAGONS ON THE RAILWAY NETWORK OF THE REPUBLIC OF SERBIA

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Abstract – The aim of this thesis is an analysis of failures and the reasons for the withdrawal of H-series freight wagons from service on the territory of the Republic of Serbia, based on maintenance records provided by Serbia Cargo for the period from 2021 to 2023. H-series freight wagons are primarily intended for the transportation of weather-sensitive cargo, such as grain and paper products, which require protection from atmospheric influences. Their sliding doors are made of aluminum, allowing for efficient loading and unloading of goods. Analysis of available data show that the most common reasons leading to the withdrawal of this type of freight wagon from service are related to brake system malfunctions and damage to the wheel tread surface. This indicates that regular brake maintenance is essential for the safe and reliable operation of freight wagons, as it helps prevent derailments, secures vehicles against unintended movement, and ensures effective speed control during operation. However, cargo may occasionally exert pressure on the sliding doors, resulting in damage that prevents proper closing of the doors. Such damage represents another common reason for withdrawing these wagons from service. Due to inadequate maintenance practices and the deteriorated condition of the railway infrastructure in Serbia, freight wagon derailments and service withdrawals occur relatively frequently. This highlights the need for more intensive infrastructure rehabilitation, regular vehicle maintenance, and more comprehensive inspection procedures. Measures such as thorough wagon inspections performed by certified rolling stock inspectors and timely repairs of H-series freight wagons are essential for improving operational safety, reliability, and service availability.

Keywords: failure analysis, freight wagons, railway maintenance, h-series wagons, railway safety.

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ANALYSIS OF FAILURES OF TYPE “E” FREIGHT WAGONS ON SERBIAN RAILWAYS

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Abstract – The aim of this master's thesis is to analyze the failures of type E freight wagons operating on the Serbian railway network, identify the most common causes of wagon withdrawal from service, and propose measures to improve maintenance reliability and operational availability. The study is based on the analysis of maintenance records and technical data collected for wagons excluded from traffic between January 2021 and April 2024. The research examines wagon failures according to inspection location, technical defects, documentation and labeling irregularities, maintenance records, and annual trends. The results indicate that the primary causes of wagon withdrawal are technical malfunctions, inadequate documentation and labeling, and mechanical damage resulting from operation and cargo handling. The most frequently observed technical failures involve the air brake system, brake distributor, draw-and-buffering devices, side slide springs, and wagon doors and flooring. The findings highlight the importance of systematic maintenance, accurate failure recording, and effective information systems in improving the safety, reliability, and availability of freight wagons. The research concludes that implementing preventive and condition-based maintenance strategies, supported by digital maintenance management systems and continuous monitoring of wagon condition, can significantly reduce unexpected failures, shorten downtime, and optimize maintenance planning within the Serbian railway freight sector.

Keywords – type “e” freight wagons, failure analysis, preventive maintenance, reliability, railway transport.

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AI-BASED REAL-TIME TRANSLATION OF RAILWAY ANNOUNCEMENTS: ACCESSIBILITY AND CYBERSECURITY

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Abstract – Railway passenger information systems rely heavily on audio announcements to communicate important information about journeys, delays, and safety instructions. However, these announcements may be inaccessible to passengers with hearing impairments and difficult to understand for international travelers due to language barriers. This paper presents the concept of an AI-based system designed to improve the accessibility of railway announcements through real-time speech recognition and multilingual translation. The proposed system processes audio announcements from existing onboard public address systems, converts speech into text using automatic speech recognition, and translates the content into different languages using machine translation. The information is then delivered to passengers through a web-based application accessible on their smartphones. In addition to accessibility, the project considers cybersecurity challenges associated with integrating AI-based services into railway environments. Building on previous research into cyber-secure railway systems, the proposed architecture considers secure data transmission, access control, and protection against unauthorized modification of passenger information. These measures aim to support the integrity and reliability of the information delivered to passengers. Key technical challenges include transcription accuracy, translation quality, processing latency, cybersecurity, and reliable information delivery. The presentation introduces the proposed system architecture, discusses accessibility and security considerations, and outlines future development and testing activities. The project aims to explore how AI-based technologies can improve multilingual communication in railway transport while maintaining appropriate cybersecurity and reliability requirements.

Keywords – Artificial Intelligence, Railway Passenger Information, Speech Recognition, Machine Translation, Accessibility, Cybersecurity.

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