



TRACK INSTRUMENTATION FOR DIGITAL TWIN DEVELOPMENT IN URBAN SLAB TRACK STRUCTURES

Franka Meštrović, Ivo Haladin, Ivan Duvnjak

University of Zagreb, Faculty of Civil Engineering, Zagreb, Croatia

Abstract

The development of public transport in Zagreb has significantly advanced through novel tramway infrastructure solutions, addressing the growing demands of an expanding urban network. With rising passenger numbers and increased loads combined with higher operating speeds, a clear need for track structures offering superior resistance to wear, geometry degradation, and frequent high-traffic usage emerged. A new Zagreb 21-STT slab track structure has been designed, tailored for urban tramways, with improved durability, reduction of noise and vibrations, and enabling efficient maintenance practices while reducing the influence of stray currents. This development reflects broader efforts to modernize public transport for heavier, more frequent services, overall enhancing network resilience and passenger comfort. Ongoing developments include implementing digital twin technology for real-time predictive maintenance as well as numerical modeling to simulate and optimize track behavior under varying conditions. Instrumented vehicles collect vibro-acoustic data from operational trams, while instrumentation of the track structures enables continuous monitoring. By incorporating these two technologies, reduced operational costs, increased safety, and improved transport reliability can be achieved in high-density urban settings.

Keywords: tram, slab track, Zagreb 21-STT, digital twin, predictive maintenance

1 Introduction

Continuous monitoring of track condition represents a key enabler for improving track robustness, ride quality, operational safety, and reliability in dense urban networks, while at the same time supporting travel time reduction by allowing higher operating speeds and tighter headways [1]. Traditional monitoring based on periodic, manual inspections and track possession is no longer sufficient for modern tram networks, as it is time consuming, disruptive to regular traffic, raises operator safety concerns and cannot capture the behavior of the track in loaded conditions [2]. Recent developments in vibro acoustic monitoring using in service vehicles and track side sensors provide the possibility of network wide data acquisition that can be coupled with numerical models and machine-learning based digital twins to diagnose defects at early stages and to support predictive maintenance [3-6]. For the Zagreb tram network, these developments are building on more than a decade of experience in the design and testing of advanced slab track structures [7], as well as the ongoing progress within the URITMIS project, in order to enhance comfort, reduce noise and vibration, and increase the resilience and availability of tramway infrastructure. One of the objectives of this project is the development of a predictive maintenance system through the implementation of digital twin technology [8]. This would provide infrastructure managers with the capability to optimize maintenance schedules, enhance public transport performance, and secure economic benefits by minimizing unplanned track possessions and extending asset lifespans [4].

In this context, monitoring of Zagreb tram network to date [9], combined with the progress in track instrumentation of designated Zagreb 21-STT track sections, presented in this paper, serves as a basis for implementation of a predictive maintenance system. Combined with numerical modeling, this instrumentation offers a valuable opportunity for digital twin development - ultimately supporting long-term asset management and risk-informed decision-making for infrastructure managers.

2 Design and implementation of slab track structures

Advanced slab track structure for urban tramways must reconcile strict geometric constraints, high axle loads, frequent operations, and rigorous environmental requirements regarding noise, vibration, and stray current protection. In Zagreb, the long-term transition from traditional to optimized track structures was triggered by the introduction of new low-floor tram vehicles, which increased wheel loads and altered wheel-rail contact conditions, leading to accelerated rail wear and fastening failures on existing structures [10]. To address these challenges, several track structures were evaluated, ultimately leading to two main track developments - Zagreb 21-CTT and Zagreb 21-STT - both relying on prefabricated elements, standardized elastic fastening components, and improved vibration isolation [10].

2.1 Zagreb 21-STT slab track structure

The Zagreb 21-STT structure (figure 1) is a slab tram track structure consisting of prefabricated double-block concrete sleepers supported on a continuous, reinforced concrete slab. Discretely supported rails are mounted on sleepers with an optimized multi-component fastening system. The rail is placed on a neoprene pad and fixed using elastic clips acting on ribbed plates, that provide defined vertical and lateral stiffness, improved vibration attenuation, and electrical insulation to protect against stray currents [7]. The design allows the track structure to be pre-assembled into modular segments (up to 18 m in length), which can be delivered to the construction site as ready-to-install track segments, significantly increasing installation speed, quality control in the workshop, and efficiency of future maintenance interventions.

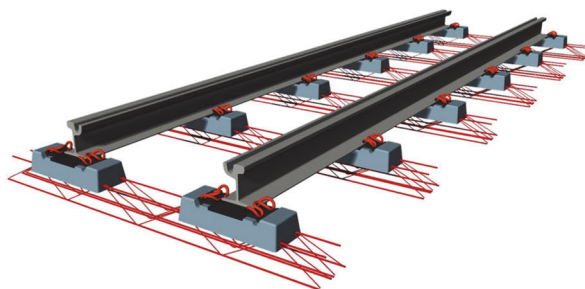


Figure 1 Zagreb 21-STT slab track structure

Track geometry is tailored to the specific requirements of the Zagreb tram network, including a 1000 mm gauge and tight curves and gradients, while the elastic pads and sleeper spacing are selected to accommodate high traffic loads (up to around 15 million gross tons) and short vehicle headways (down to 90 s), without compromising structural durability or ride comfort [10]. After nearly a decade of periodic monitoring, the Zagreb 21-STT structure has demonstrated favorable performance in terms of slowed and reduced track geometry degradation, reduced slab stresses, and lower noise emission compared to traditional structures, confirming its suitability as a reference slab track solution for future network extensions [7].

2.2 Savska road test section

The Savska road test section was developed in a full-scale comparative study to evaluate the long-term behaviour of different tram track structures under identical traffic and environmental conditions, including a conventional Zagreb 3/2 PPE reference track, the upgraded Zagreb 21-CTT classic tram track, and the new Zagreb 21-STT slab tram track. Constructed in 2014, the section comprises three instrumented segments of approximately 55 m, 59 m, and 53 m, respectively, which have been periodically monitored over an 11-year period through visual inspections and detailed measurements of track geometry, weld condition, slab stresses and strains, vibration damping, and noise emission [7].



Figure 2 Zagreb 21-STT slab track structure on Savska road test section

Measurement campaigns were carried out immediately after installation, after about 7 months, after 4 years, and again after approximately 39.3 million gross tons of accumulated traffic, enabling the assessment of degradation trends and the comparison of structural and vibro-acoustic performance among the three structures. Results show that the Zagreb 21-STT track exhibits the smallest increase in track gauge and the lowest maximum longitudinal slab stresses, while also achieving the lowest equivalent noise levels and favourable track decay rates, thereby confirming the benefits of the discretely supported slab track structure with optimized elastic components [7]. These findings have provided the empirical basis for the broader deployment of the 21-STT structure on the Zagreb network and motivated its selection as a reference structure for digital-twin-based monitoring within the URITMIS framework [8].

3 Instrumentation of the test section for monitoring

Systematic monitoring of tramway test sections serves multiple objectives: validating the structural design, quantifying degradation mechanisms, and providing high-quality data for the calibration of numerical and machine-learning models used in predictive maintenance [4, 11]. In the context of the Zagreb 21-STT structure, instrumentation strategies combine traditional measurements of geometry with embedded sensors in the track structure and on in-service vehicles, enabling the joint analysis of track response, vehicle dynamics, and vibro-acoustic behavior under realistic operating conditions [9]. Particular emphasis is placed on capturing both quasi-static parameters (e.g. track geometry, slab stresses, rail wear) and dynamic indicators (e.g. vibration levels, decay rates, noise levels) over extended time periods to identify thresholds for intervention and to support the design of robust predictive models [8].

3.1 Sarajevska road test section

The Sarajevska road project represents the first larger-scale implementation of the Zagreb 21-STT structure within a major tramway network extension in Zagreb, the first such expansion in 20 years. Building on the excellent monitoring results from the Savska road test section [12], the decision was made to comprehensively instrument a designated section of this newly constructed track. This enables a continuous observation of its in-service behavior from the initial, “zero state” condition, which offers a significant advantage for establishing reliable baseline performance and degradation trends. Track structure selected for instrumentation comprises a 10 m long reinforced concrete slab, reinforced with steel and polypropylene microfibres, supporting double-block sleepers at a spacing of 0.8 m, with the standard 21-STT fastening assembly. This configuration was optimized through load-bearing capacity calculations to ensure adequate safety margins under expected tram traffic while maintaining suitable stiffness and vibration performance for the surrounding urban environment.

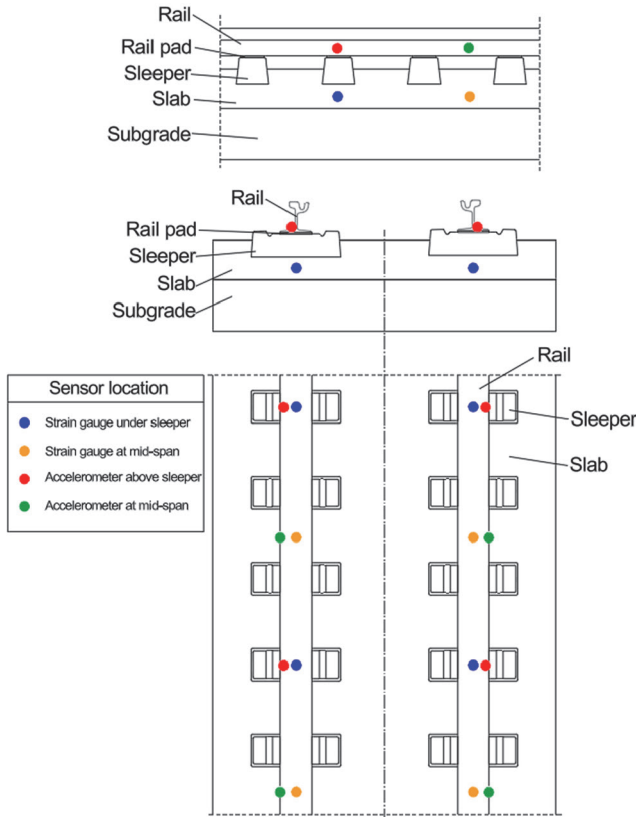


Figure 3 Sensor positions in longitudinal, transversal and birdseye view

The test section on the newly constructed Sarajevska road is envisioned as a strategic location for the implementation of a comprehensive monitoring system, integrating accelerometers, strain gauges, microphones, a weather station, and cameras, in order to provide high-resolution measurements of structural response. These measurements will serve as input data for the development and calibration of a numerical model and the corresponding digital twin of the structure [3, 13, 14].

In addition to the fixed track-side instrumentation, a single in-service tram operating across the entire tram network is equipped with a dedicated onboard monitoring system [9]. This includes accelerometers mounted on the bogie frame, a GPS system for spatial localization, and a microphone for capturing acoustic signatures. Unlike the sensors installed at the Sarajevska test section, which provide detailed insight into local track-structure interaction, the instrumented tram enables continuous, network-wide condition assessment under real operating conditions [8]. Data collected at the Sarajevska test section will primarily be used for the development, calibration, and validation of the numerical model and digital twin. Additionally, data acquired from the instrumented tram will be utilized to assess the overall condition of the tram network and to identify critical locations exhibiting increased degradation or emerging defects. The integration of these two data sources is achieved through spatial and temporal alignment, where GPS-referenced onboard measurements are correlated with track-side data. This combined dataset enables the establishment of transfer functions and signal processing procedures that link indirect vehicle response (e.g. acceleration and acoustic signals) to direct measurements of track condition [15]. Real-time vibration data from in-service vehicles [9], together with embedded sensor measurements, will support the detection of the onset and progression of defects, continuous updating of the digital twin, and the development of predictive maintenance strategies [16].



Figure 4 Sensors installed on the test section in Sarajevska road

4 Numerical modelling

Numerical modelling of the Zagreb 21-STT track structure is an important step, providing the virtual counterpart required to implement a digital twin for predictive maintenance and to explore scenarios that are not practically measurable on an in-service network. Following the development of an initial 30 m long model of the track structure, the need for optimization became evident, prompting the substitution of the fastening system as a critical first step. To this end, a series of benchmark models were created, in which the fastening system is substituted by an equivalent spring system designed to replicate its real-world behavior, including vertical, lateral, and torsional stiffness characteristics.

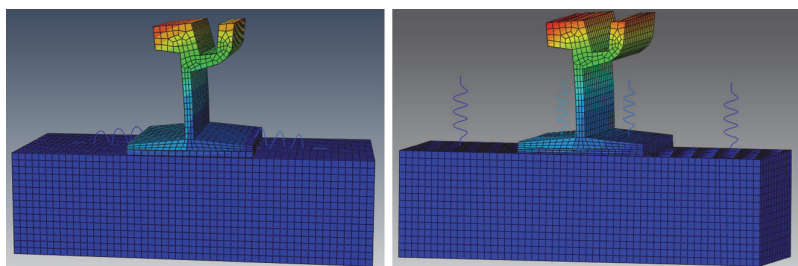


Figure 5 Strain diagrams of benchmark fastening system models

The planned model integrates detailed representation of the Zagreb 21-STT structure, featuring an adjusted fastening system to achieve model cost-effectiveness through reduced analysis time while maintaining adequate result accuracy. Appropriate material properties and dynamic (stiffness-damping) characteristics, derived from laboratory tests and in-situ measurements, are being implemented in the model. In an initial phase, a baseline 3D finite element model will be developed and verified against measured track responses from the Savska test section, focusing on parameters such as slab stresses and strains, rail accelerations, and vibration levels under representative vehicle loading. Furthermore, the potential influence of rolling stock variability is currently being investigated through numerical modelling by simulating the effects of different tram types on the track structure. In this context, differences in axle loads, vehicle geometry, and the configuration of bogies are considered in order to assess their impact on the measured responses.

5 Conclusion

When developing a comprehensive monitoring strategy for a slab track structure, particular attention must be given to the duration and continuity of measurements to capture both short-term transient effects and long-term degradation under realistic traffic and environmental conditions. Long-term monitoring, such as that conducted on the Savska test section, is crucial for connecting changes in track geometry, vibro-acoustic behavior, and structural response to cumulative loading and for distinguishing reversible from irreversible degradation. An integrated instrumentation concept is equally important, combining track-side and embedded sensors with vehicle-based measurements to ensure complementary and redundant data for reliable model calibration and validation. Careful planning of sensor placement, sampling frequency, and synchronization between systems is essential, as these factors directly affect data quality and interpretation.

From a modelling perspective, an appropriate level of complexity must be defined to balance computational efficiency with sufficient accuracy to capture key phenomena, such as element interactions, boundary conditions, and the relevant frequency range for noise and vibration assessment. Parameter identification and updating strategies should clearly link measurable quantities (e.g. acceleration spectra, strain, decay rates) to model parameters (e.g. stiffness, damping, contact conditions), enabling systematic calibration based on monitoring data. Machine learning can support pattern recognition and anomaly detection in large datasets, but its effectiveness depends on high-quality labelled data, robust feature extraction, and continuous validation against measurements and model predictions. The digital twin should therefore be conceived as an evolving system, capable of integrating new sensors, updated vehicle characteristics, and operational changes while maintaining consistency with historical data. Practical aspects such as data management, cybersecurity, and interoperability with existing infrastructure systems are also essential for scalable and sustainable predictive maintenance.

Acknowledgments

This paper was written as a part of the “URITMIS – Urban railway infrastructure predictive maintenance system based on monitoring of vibroacoustic track properties” project NPOO. C3.2.R2-I1.06.0001 that is funded as a part of Development and research grants from National plan of recovery and resilience, financed by EU Commission.

References

- [1] Nampalli, R.C.R.: Leveraging AI and Deep Learning for Predictive Rail Infrastructure Maintenance: Enhancing Safety and Reducing Downtime, *International Journal of Engineering and Computer Science*, 12 (2024) 12, pp. 26014-26027, DOI: 10.18535/ijecs/v12i12.4805
- [2] Diana, D., Angga Mukti, A.: AI-Driven Digital Twin for Predictive Maintenance in Urban Infrastructure: Enhancing Structural Resilience and Sustainability, *Civil Engineering Science and Technology (CEST)*, 1 (2025) 1, DOI: 10.51903/3c72e647
- [3] Le-Nguyen, M.H., Turgis, F., Fayemi, P.E., Bifet, A.: Real-time learning for real-time data: online machine learning for predictive maintenance of railway systems, *Transport Research Arena -TRA Lisbon 2022*, pp. 171–178, Lisboa, Portugal, 14-17 November 2022.
- [4] Bianchi, G., Fanelli, C., Freddi, F., Giuliani, F., La Placa, A.: Systematic review railway infrastructure monitoring: From classic techniques to predictive maintenance, *Advances in Mechanical Engineering*, 17 (2025) 1, pp. 1-26, DOI: 10.1177/16878132241285631
- [5] Nwamekwe, C.O., Okpala, C.C., Charles Onyeka, N., Chikwendu, C.: Machine learning-augmented digital twin systems for predictive maintenance in high-speed rail networks, *International Journal of Multidisciplinary Research and Growth Evaluation*, 6 (2025) 1, pp. 1783-1795
- [6] Rocha, L., Gonçalves, G.: Digital Twins as Enablers of Predictive Maintenance in Rail Transport Services, *International Journal on Advances in Software*, 17 (2024) 3, pp. 153–164
- [7] Haladin, I., Lakušić, S., Koščak, J., Bartolac, M.: Monitoring of Dynamic Properties of New Type of Tram Track Fastening Systems Under Traffic Load, 4th International Conference on Road and Rail Infrastructure - CETRA 2016, pp. 791–799, Šibenik, Croatia, 23-25 May 2016.
- [8] Haladin, I., Burnač, K., Baniček, M., Vranešić, K., Trifunović, N.: The possibility of using machine learning for network-wide predictive maintenance on urban railway tracks - URITMIS project overview, 8th International Conference on Road and Rail Infrastructure – CETRA 2024, pp. 1063-1070, Cavtat, Croatia, 15-17 May 2024.
- [9] Burnač, K., Haladin, I.: Evaluation of rail irregularities by processing tramway vehicle bogie acceleration data, 8th International Conference on Road and Rail Infrastructure – CETRA 2024, pp. 1249-1253, Cavtat, Croatia, 15-17 May 2024.
- [10] Lakušić, S., Haladin, I., Ahac, M.: The effect of rail fastening system modifications on tram traffic noise and vibration, *Shock and Vibration*, 2016 (2016) 1, pp. 1-15, DOI: 10.1155/2016/4671302
- [11] Vinkó, Á., Bocz, P.: Experimental investigation on condition monitoring opportunities of tramway tracks, *Periodica Polytechnica Civil Engineering*, 62 (2018) 1, pp. 180–190, DOI: 10.3311/PPci.10541
- [12] Lakušić, S., Haladin, I., Koščak, J.: Izvještaj o monitoringu sustava pričvršćenja tramvajskog kolosijeka “Zagreb 21-CTT” i “Zagreb 21-STT” na Savskoj cesti u Zagrebu, University of Zagreb, Faculty of Civil Engineering, 2015.
- [13] Febrianto, E., Butler, L., Girolami, M., Cirak, F.: Digital twinning of self-sensing structures using the statistical finite element method, *Data-Centric Engineering*, 3 (2022) 3, pp. 1-22, DOI: 10.1017/dce.2022.28
- [14] Kampczyk, A., Dybeł, K.: The fundamental approach of the digital twin application in railway turnouts with innovative monitoring of weather conditions, *Sensors*, 21 (2021) 17, pp. 1-14, DOI: 10.3390/s21175757
- [15] Burnač, K., Haladin, I.: Experimental analysis of wheel and bogie frame transfer functions for on-board measurements of rail roughness, *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, pp. 6968–6976, Nantes, France, 25-29 August 2024.
- [16] Malekjafarian, A., Sarrabezolles, C.A., Khan, M.A., Golpayegani, F.: A Machine-Learning-Based Approach for Railway Track Monitoring Using Acceleration Measured on an In-Service Train, *Sensors*, 23 (2023) 17, pp. 1-17, DOI: 10.3390/s23177568

