CETRA^{2026} 27-30 May 2026, Bol, Island Brač, Croatia
9th International Conference on Road and Rail Infrastructure

VIBROACOUSTIC CHARACTERISATION OF BALLASTLESS TRAM TRACKS: COMPARING VARIOUS ON-SITE MEASUREMENT APPROACHES

Krešimir Burnać, Ivo Haladin, Katarina Vranešić
University of Zagreb, Faculty of Civil Engineering, Zagreb, Croatia

Abstract

Tramway traffic in urban areas represents a significant contributor to elevated noise and vibration levels, and it can be a nuisance for those who use tramway transportation, as well as for residents who live and work near tramway tracks. The focus of this study was to analyze how the design of two ballastless tramway tracks, one with discrete fastenings and the other as an embedded rail system (ERS), influences noise and vibration in urban environments. In-situ experiments were conducted analyzing track decay rate (TDR) and insertion loss (IL) of the track, using two different force excitation methods: impact hammer testing with medium and large modal hammers of varied tip hardness (direct measurements), and corresponding analyses using tramway pass-bys for excitation (indirect measurements). This dual approach enabled the quantification of vibration attenuation and propagation properties under a variety of force excitation and boundary conditions, leading to practical conclusions about vibration propagation through the track superstructure and to the surrounding area. Based on the comparison of the two measurement procedures (hammer opposed to pass-by), pass-by measurements have shown adequate to replace the more time-consuming hammer tests to achieve similar results. Furthermore, the results revealed a considerable differences in values between the two types of track superstructure, leading to recommendations for employing newel ballasteless track types with better performance in terms of noise and vibration mitigation in urban areas.

Keywords: track decay rate, insertion loss, tramway infrastructure, ballastless track, pass-by noise, urban transit

1 Introduction

In urban areas, where public transport is the backbone of everyday life, providing residents with reliable and safe access to their workplaces and households, it is essential to ensure reliable service, punctuality, and comfort [1]. Traffic noise and vibrations have been identified as one of the most significant factors influencing the quality of life and work in urban surroundings, and they can be an annoyance for both residents and public transportation users. Tramway traffic, in particular, contributes significantly to elevated noise and vibration levels in cities; as a result, reducing those levels has become an essential task for both industry and scientific community to enable more comfortable and secure travel [2, 3]. A significant amount of tramway traffic noise and vibration is generated by wheel-rail interaction, which means that not only should vehicles be designed to reduce excessive noise and vibration levels, but novel types of tramway tracks need be built to do the same [4, 5].

DOI: https://doi.org/10.5592/CO/CETRA.2026.1803

In the city of Osijek, Croatia, around 10 km of existing aging infrastructure with inadequate track condition based on extensive study from 2016 [6] were reconstructed and replaced with new tracks superstructure using Embedded rail system (ERS). The new system was chosen due to its ability to reduce noise and vibration levels, increase the longevity of the tracks and provide a safe and comfortable tramway operation. Because the vehicle-track interaction during vehicle passage causes vibrations that generate noise, the track's dynamic response to these vibrations has a direct impact on the resulting noise and vibration levels [7, 8]. Therefore, the goal of this study is to evaluate track quality in terms of noise and vibration mitigation.

2 Vibroacoustic characterization of tramway tracks – Case study in the city of Osijek, Croatia

To evaluate the effectiveness of the ERS system based on its vibroacoustic properties, various measurements including track decay rate, insertion loss and pass-by noise, were taken at both locations: an existing track superstructure without noise and vibration mitigation characteristics – DEPP system and a newer ERS system.

2.1 Ballastless track superstructure

To assess the Insertion loss of the track, a new tram track structure had to be compared to an existing (referent) track structure commonly used on the network. Therefore aside from ERS section, a section of the superstructure with DEPP (Double elastic fastening system) has been used for direct comparison. Referent DEPP track structure was constructed with inverted DEPP fastenings, which provide support for the track on provisional supports (HEA profiles) used to define the track in height and gauge. The HEA profiles are embedded in a reinforced concrete slab of strength class C25/30, placed on a sub-base of crushed stone material. The track is ballasted with crushed stone on sections located in a separate track corridor. The DEPP fastening system consists of an SKL 1 tension clamp, anchor bolts, two under-rail elastomer pads, and a steel base plate. The newly constructed ERS system (Embedded Rail System) is designed as a continuously supported rail encapsulated in elastomer, aligned to the required height and gauge and embedded in a reinforced concrete slab of strength class C30/37. Between the reinforced concrete slab and the crushed stone sub-base, a blinding layer of concrete of class C16/20 is provided, and the track is closed with an artificial grass surface or asphalt. Embedded rail system – ERS represents a novel type of track superstructure, where rail is continuously embedded into the visco-elastic material.

2.2 Insertion loss – EN 13481-5:2022 [9] and DIN SPEC 45673-3:2014-04 [10]

The objective of determining the insertion loss of the newly constructed track - ERS - was achieved by measurements conducted in accordance with EN 13481-5:2022 "Railway applications - Track - Performance requirements for fastening systems - Part 5: Fastening systems for ballastless tracks – Annex A" [9] and DIN SPEC 45673-3:2014-04 "Mechanical vibration - Resilient elements used in railway tracks - Part 3 Experimental evaluation of insertion loss of mounted track systems (in a test rig and in situ)" [10], which specify the assessment of insertion loss D_i under in situ track conditions. The technical guideline DIN SPEC 45673-3 [10] specifies that insertion loss testing can be performed using different excitation methods and evaluation procedures to assess the vibration reduction performance of resilient elements in the track structure, i.e. the insertion loss. The two main approaches are the left–right (parallel) method and the before–after method. For the tests of the two track forms on the tram network in Osijek, the left–right method was applied.

Two track types—one with the mitigation measure (new ERS track) and one without it (DEPP)—were installed side by side in the same section, enabling direct, simultaneous comparison under similar environmental and operating conditions, thereby minimizing external influences and increasing the reliability of the results. According to DIN SPEC 45673-3 [10], the following excitation types may be used: impact excitation (by modal hammer blows), harmonic excitation, stochastic excitation, and excitation by the pass-by of a rail vehicle.

2.3 Track decay rate – EN 15461:2008+A1:2010

The parameter used to characterize the track response to vibration and noise is the Track Decay Rate (TDR). The EN 15461:2008+A1:2010 “Railway applications – Noise emission – Characterization of the dynamic properties of track sections for pass-by noise measurements” standard [11] requires that the track structure within the selected test section be uniform with respect to parameters that may influence the TDR. The parameters that must remain constant along the test section include the rail cross-section, rail pad stiffness, rail inclination, and sleeper spacing.

2.4 Pass-by measurements – EN ISO 3095:2025

To evaluate noise levels caused by tram traffic on the reference (DEPP) and newly built tracks (ERS), pass-by measurements were conducted according to the EN ISO 3095:2025 “Railway applications — Acoustics — Measurement of noise emitted by railbound vehicles” standard [12].

3 Measurement campaign

Measurements were conducted at 4 locations in total – 1 location with DEPP system and 3 locations with ERS system. Three type of measurements were used to characterize the vibroacoustic properties of the DEPP and ERS track superstructures:

- track decay rate according to EN 15461 [11]
- insertion loss according to EN 13481-5 [9] and DIN SPEC 45673-3 [10]
- pass-by noise measurements according to ISO 3095 [12]

All four measurement locations were carefully selected to satisfy the requirements related to the type of subgrade and soil through which vibrations propagate from source to receiver. Table 1 contains additional information on the acquisition system and measuring equipment used for each measurement type.

Table 1 Data acquisition and measurement equipment

Measurement	Acquisition system	Impulse	Response
Track decay rate (TDR)	Multichannel data acquisition system with dedicated DAQ software, laptop computer	Large modal impact hammer with hard (metal) tip (varying position)	Accelerometer (vertical direction; fixed position)
		Tramway vehicle pass-by (multiple test runs; varying speed)	
Insertion loss (IL)	Multichannel data acquisition system with dedicated DAQ software, laptop computer	Modal impact hammer with medium-hard and soft tips (fixed position)	Multiple accelerometers (varying positions)
		Tramway vehicle pass-by (multiple test runs; varying speed)	
Pass-by	Class 1 hand-held sound level analyzer	Tramway vehicle pass-by (multiple test runs; varying speed)	Microphone

3.1 Track decay rate – TDR

The measurement of the TDR was conducted in accordance with the EN 15461 standard [11], while the reference limit curve was defined according to the EN ISO 3095 standard [12]. According to EN 15461 [11], track dynamic behavior is characterized by measuring rail frequency response functions (FRF) for vertical excitation using a vertically mounted accelerometer and modal hammer impacts. FRFs were evaluated in one-third-octave bands over 100–5000 Hz, and at each rail test point at least eight hammer excitations were performed so that an average FRF could be computed. Coherence functions were used to assess the quality of the measured FRFs, ensuring reliable data. Measurement points were distributed along the rail above sleepers, in mid-spans, and more densely near the accelerometer, with excitation starting at the accelerometer location and progressing along the rail to determine vibration attenuation, as prescribed in the EN 15461 standard [11].

3.2 Insertion loss – IL

The insertion loss measurements were performed at all four selected locations, with surrounding structures at the following distances:

- L1 – d > 12.0 m (DEPP, existing reference track)
- L2 – d > 12.0 m (ERS, newly constructed track)
- L3 – 7.0 m < d < 12.0 m (ERS, newly constructed track)
- L4 – d < 7.0 m (ERS, newly constructed track).

Accelerometers were installed at various measuring points on the track, on the ground, and on the surrounding buildings to measure the impulse responses. A detailed measurement setup with graphical scheme of measuring points with their locations and distances from the axis is presented in figure 1.

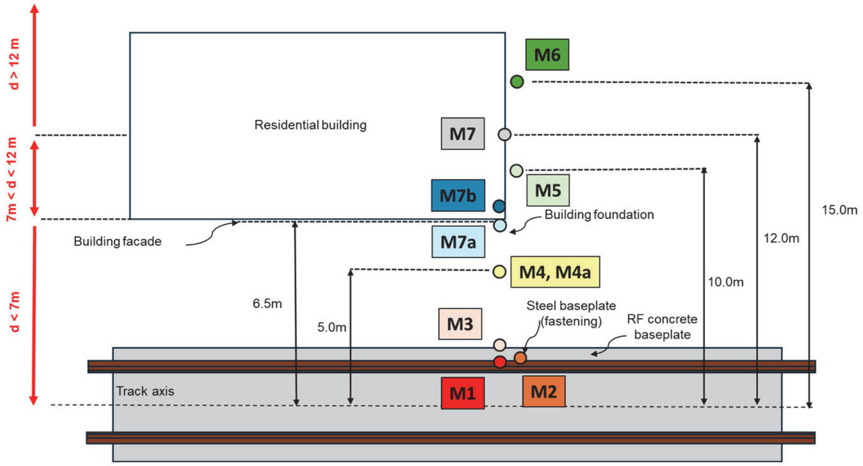

Figure 1 Measurement setup with all the measuring points on location 1 and 2

Measurements were carried out in accordance with the technical specification DIN SPEC 45673-3 [10] for two of the four excitation types: controlled excitation with a modal hammer and tram vehicle pass-by, described in more detail below. For each excitation setup, the key requirement was to obtain representative and directly comparable vibration data for both track types. This was necessary to accurately determine the real impact of the vibration mitigation approach on vibration propagation into the surrounding ground and nearby buildings (insertion loss).

3.2.1 Measuring response to excitation by controlled impact force applied with a modal hammer

An average FRF value was calculated for each test point using at least ten individual frequency response functions (10 modal hammer impulses), with Brüel & Kjær modal hammer type 8210, with a soft (green) and a moderately hard (red) tip used for the excitation. The quality of the obtained frequency response functions was expressed by the coherence function. Coherence was evaluated to verify the quality of the measurements, and after analyzing coherences for one measurement location using various tips, soft (green) tip was chosen as more suitable for this measurement campaign as it had better coherence in most of the wanted frequency range (5 – 250 Hz). Furthermore, for each measurement position, a transfer function was calculated describing the amount of vibration transmitted from the excitation point – the vibration source, to the receiver location (accelerometer).

Figure 2 Controlled excitation with a modal hammer (left) and tram vehicle pass-by excitation (right)

3.2.2 Measuring the response to excitation caused by tram vehicle pass-by

This excitation type enabled assessment of the condition of the track and its components under real operating conditions. Measurements were carried out using pass-by excitation, making it possible to determine transfer functions and insertion loss. To determine insertion loss in accordance with DIN 45672-1:2018-02 “Vibration measurement associated with railway traffic systems - Part 1: Measuring method for vibration” [13] for the excitation caused by tram vehicle pass-by, low-floor tram type Končar TMK 2500 was used. For data processing, result presentation, and insertion loss calculation, only pass-bys with comparable speeds were used, with speed differences between DEPP and ERS $\Delta v < 2$ km/h. With the aim of determining the insertion loss, the following formulas were used:
a) excitation by modal hammer

$$D_i = (FRF_{S\text{-}ERS} - FRF_{Di\text{-}ERS}) - (FRF_{S\text{-}REF} - FRF_{Di\text{-}REF}) \qquad (1)$$

Where:

D_i – insertion loss of the ERS system at distance i, expressed in dB

$FRF_{S\text{-}ERS}$ – frequency response function on the newly constructed track (ERS) measured at the excitation source (on the rail)

$FRF_{S\text{-}REF}$ – frequency response function on the existing track (DEPP) measured at the excitation source (on the rail)

$FRF_{Di\text{-}REF}$ – frequency response function on the existing track (DEPP) measured at the observed distance i

$FRF_{Di\text{-}ERS}$ – frequency response function on the newly constructed track (ERS) measured at the observed distance i

b) excitation by tram vehicle pass-by (pass-by)

$$Di = L_{vERS,\ PBi} - L_{vREF,\ PBi} \tag{2}$$

where:

D_i – insertion loss of the ERS system at distance i, expressed in dB
$L_{vERS,\ PBi}$ – vibration level on the newly constructed track (ERS) measured at the observed distance
$L_{vREF,\ PBi}$ – vibration level on the existing track (DEPP) measured at the observed distance i.

The frequency response functions were presented in one-third octave bands over the frequency range from 5 Hz to 250 Hz, and the insertion loss D_i was analyzed individually for the required distances from the track, both for hammer excitation and excitation based on the tram pass-by.

3.3 Pass-by noise measurements

Pass-by noise measurements were conducted according to the EN ISO 3095 standard [12]. For the noise measurements, a B&K hand-held analyzer type 2270 was used, installed 7.5 meters from the track axis on a 1.2 meters height from the rail's upper edge. Measurements were performed on one section for both track types (DEPP and ERS) with 8-10 tramway passages on each location.

4 Results analysis and discussion

This section presents the results of the measurements, as well as a description of how various vibroacoustic properties were analyzed and what value variations were identified between the DEPP and ERS track systems.

4.1 Track decay rate

Track decay rate was assessed using the methods described in earlier chapters, in accordance with the EN 15461 standard [11], at both sites, allowing for a comparison of the different track superstructures' (ERS/DEPP) effectiveness to mitigate track noise and vibration levels. ERS system showed dominant characteristics in comparison with the reference DEPP system in most of the frequency ranges except for the 800 – 1250 Hz range – higher TDR means better performance in damping the noise and vibration levels (figure 3).

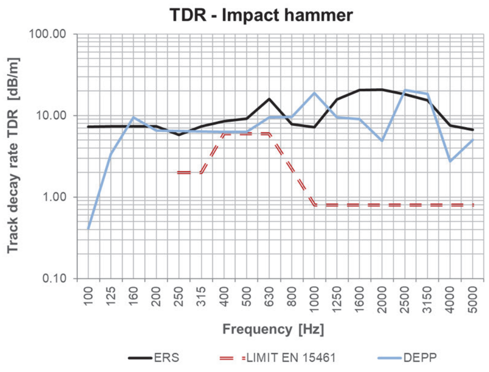

Figure 3 Track decay rate (TDR) comparison for DEPP and ERS system

4.2 Insertion loss

For the measurements of insertion loss in the presented measurement campaign, the following conditions were defined according to the insertion loss levels (D_i), measurement distance from the axis (d) and requested frequency range (f):

- Di < 10 dB @ 63 Hz for d > 12.0m
- 10 dB < Di < 20 dB @ 63 Hz for 7.0m < d < 12.0m
- Di > 20 dB @ 63 Hz for d < 7.0m

Insertion loss (D_i) results are presented in figure 4, combining data for both hammer and pass-by excitation, on various distances.

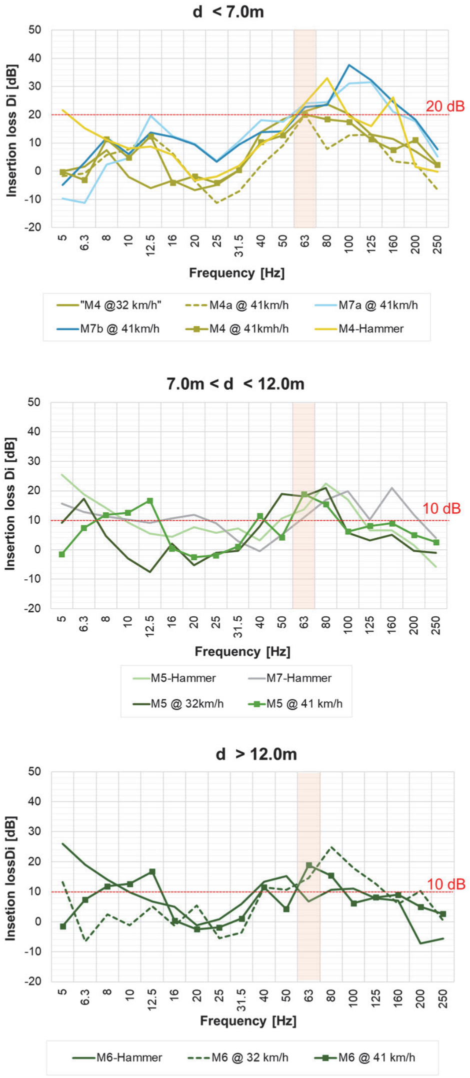

Figure 4 Insertion loss results for ERS track on various distances from the axis presented in third-octave frequency bands

From the insertion-loss results at distances d < 7 m from the track it can be concluded that the ERS system satisfies the requirement of vibration attenuation > 20 dB, both for vibration propagation in natural soil (L2) and based on the nearby building (L4) located 6.5 m from the track axis. Based on the results for distances between 7m and 12m it can be concluded that the ERS system satisfies the requirement of vibration attenuation > 10 dB for vibration propagation in natural soil (L2) and based on the nearby building (L3) located 12 m from the track axis. For distances further than 12 m from the track, it can be concluded that the ERS system satisfies the requirement of vibration attenuation < 10 dB for vibration propagation in natural soil (L2) at a distance of 15 m from the track axis. Measurement with a modal hammer yielded an attenuation of 6.7 dB. It is evident that the results obtained from measurements during tram pass-bys are even more favorable, with measured attenuation of 15–19 dB. It should be noted that vibration insertion loss from tram traffic that exceeds the specified requirement can only have a positive effect on the environment for people and buildings in the vicinity of the tram track.

4.3 Pass-by noise measurements

The vibroacoustic properties variation between the two track types can be also seen through analysis of the pass-by noise measurements. To analyze the results, several passages with the same operating speed and tramway type (Končar TMK 2500) were taking into account, one of them being presented in figure 5.

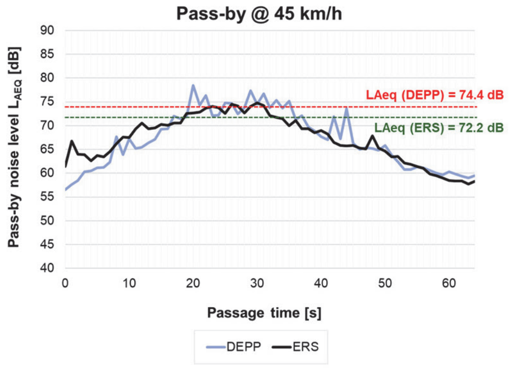

Figure 5 Comparison between equivalent pass-by noise levels at location 1 (DEPP) and location 2 (ERS) with pass-by noise levels for two passages of the tramway type Končar TMK 2500 at 45 km/h

From the pass-by measurements results presented in figure 5, it can be seen that equivalent pass-by noise level L_{Aeq} was more than 2 dB lower for ERS track superstructure in comparison with DEPP system track, which further confirms the significant damping property of ERS system.

5 Conclusion

The study demonstrates that the vibroacoustic behavior of ballastless tram tracks depends strongly on track superstructure design, with the embedded rail system (ERS) clearly outperforming the DEPP reference track in most metrics. Track decay rate measurements in accordance with EN 15461 [11] showed higher decay levels for ERS across almost the entire frequency range, indicating more effective vibration and noise damping. Insertion loss tests performed according to EN 13481-5 [9] and DIN SPEC 45673-3 [10], using both controlled modal hammer excitation and tram pass-bys, confirmed that ERS meets or exceeds all prescribed vibration attenuation criteria at distances representative for ground and nearby buildings.

Additional pass-by noise measurements following EN ISO 3095 [12] further reveal more than a 2 dB reduction in equivalent noise level for ERS compared with DEPP, supporting the recommendation to preferentially apply embedded rail systems on urban tram networks where noise and vibration mitigation is required.

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] Haladin, I., Lakušić, S., Bogut, M.: Overview of methods for assessing ride comfort on tram tracks, Građevinar, 71 (2019) 10, pp. 901-921, DOI: https://doi.org/10.14256/JCE.2731.2019

[2] Haladin, I., Burnać, K., Vranešić, K.: Monitoring of vibrations on earthquake-damaged masonry structures induced by tram traffic, 28th International Congress on Sound and Vibration – ICSV28, Singapore, Singapore 25-27 July 2022.

[3] Haladin, I., Bogut, M., Lakušić, S.: Analysis of Tram Traffic-Induced Vibration Influence on Earthquake Damaged Buildings, Buildings, 11 (2021), 12, 590, DOI: 10.3390/buildings11120590

[4] Lakušić, S., Haladin, I., Ahac, M.: The effect of rail fastening system modifications on tram traffic noise and vibration, Shock and Vibration, 2016., DOI: 10.1155/2016/4671302

[5] Meštrović, F., Haladin, I.: Development of a Numerical Model of the Slab Tram Track Structure Zagreb 21-STT, 11th meeting of young researchers in the field of civil engineering and related technical sciences, pp. 79-86, Rijeka, Croatia, 9–12 July 2025., DOI: 10.32762/zt.2025.12

[6] Lakušić, S., Haladin, I., Ahac, M., Grgić, V., Vranešić, K., Košćak, J., and Bogut, M.: Evaluation of Tramway Track Condition on GPP Osijek Network, Zagreb, 2016.

[7] Haladin, I., Burnać, K., Ivančev, M., Košćak, J.: Vibroacoustic track analysis and noise measurements on the R201 Zaprešić – Zabok railway line, 7th International Conference on Road and Rail Infrastructure CETRA 2022, pp. 245-252, Pula, Croatia, 11-13 May 2022., DOI: 10.5592/CO/CETRA.2022.1487

[8] Burnać, K., Haladin, I., Vranešić, K.: Evaluation of Rail Corrugation and Roughness Using In-Service Tramway Bogie Frame Vibrations: Addressing Challenges and Perspectives, Infrastructures, 10 (2025) 8, 208, DOI:10.3390/infrastructures10080209

[9] European committee for standardization (CEN): EN 13481-5:2022 Railway applications - Track - Performance requirements for fastening systems - Part 5: Fastening systems for ballastless tracks, 2022.

[10] DIN - German Institute for Standardization: DIN SPEC 45673-3:2014-04 Mechanical vibration - Resilient elements used in railway tracks - Part 3: Experimental evaluation of insertion loss of mounted track systems (in a test rig and in situ), 2014.

[11] European committee for standardization (CEN): EN 15461:2008+A1:2010 Railway applications – Noise emission – Characterization of the dynamic properties of track sections for pass-by noise measurements, 2010.

[12] European committee for standardization (CEN): EN ISO 3095:2013 Acoustics - Railway applications - Measurement of noise emitted by railbound vehicles, 2013.

[13] DIN - German Institute for Standardization: DIN 45672-1:2018-02 Vibration measurement associated with railway traffic systems - Part 1: Measuring method for vibration, 2018.

8

URBAN MOBILITY AND TRAFFIC SAFETY