

# Track-Bridge Interaction Effects in Ballast Superstructures: Large-Scale Experiments as a Basis for SHM-Driven Bridge Models

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## ABSTRACT

Railway bridges are crucial key components of railway infrastructure. The steady increase in traffic volume (intensification of train traffic along with increasing axle loads) poses a major challenge for infrastructure operators in ensuring the resilience of existing structures and assessing their service life realistically and economically. The application and combination of digital twins and structural health monitoring (SHM) are essential for mastering these challenges. A realistic assessment and prognosis of railway bridge conditions and performance requires detailed information on the actual system parameters. In this context, the computationally implemented interaction between the track and supporting structure significantly influences the generated results and the resulting condition assessments of the railway bridge system. A wide range of mechanical modelling options with different levels of complexity are available for implementing track-bridge interaction (TBI) effects in computational models. However, the considerable range of model-related stiffness and damping parameters makes it particularly more challenging to consider TBI effects realistically in practical applications. Based on this background, the research activities of the Institute of Structural Engineering at TU Wien focus on the experimental investigation of TBI effects in ballast superstructures. This contribution presents the key results of the investigation of vertical and longitudinal TBI effects. Using two large-scale test facilities, the interaction effects occurring in ballast superstructures can be investigated separately in both the vertical and longitudinal directions in an isolated manner. The test setup allows the stiffness and damping properties of the ballast superstructure to be precisely determined, taking into account time-dependent and environmental influences. The overarching goal is to generate a holistic and physically based mechanical model with precisely defined stiffness and damping characteristics for describing TBI effects, which can be implemented as simply as possible in corresponding digital bridge models. This contributes significantly to the reliable condition assessment and condition prognosis of railway bridges.

## INTRODUCTION

High-speed rail networks are currently rapidly expanding worldwide, with the shift of traffic from road to rail being key to mitigating climate change. Railway bridges in the rail network are considered key elements that are subject to increasing strains due to rising traffic volumes. Therefore, regular condition assessments and predictive condition prognoses of railway bridges are required to ensure compatibility between rolling stock and existing structures and the resilience of existing structures against future challenges.

The use of digital bridge twins in combination with on-site structural health monitoring (SHM) is an essential tool to realistically assess the resilience and service life of railway bridges (see [1-3]), which can then be used to establish a cost-effective strategy for predictive bridge maintenance.

However, a realistic condition assessment of railway bridges using digital twins and SHM requires knowledge of the actual system parameters. In this context, the interaction effects between the track and the supporting structures occurring in the superstructure, which are taken into account in computational models, significantly influence the generated results, which serve as a decision-making basis for condition assessments. With regard to the modelling of the superstructure, a large number of different models with varying degrees of complexity are available (see [4-7]). However, the stiffness and damping characteristics associated with these models vary considerably, making it highly challenging to consider track-bridge interaction (TBI) effects realistically in calculations.

Figure 1 shows a model for describing TBI effects based on investigations in [8], which summarizes energy dissipation mechanisms in the vertical and longitudinal directions in an integral manner (see also [9]). In contrast to more detailed models, all interaction effects occurring in the superstructure system are combined in a spring-damper element, which allows for simple and computationally efficient implementation in bridge models.

To illustrate the aforementioned wide range of available dynamic parameters related to different mechanical models, Figure 2 shows the results of a literature study in [10] regarding the dynamic parameters of vertical TBI (red spring-damper elements in Fig. 1). The results demonstrate that both stiffness  $\bar{k}_{ba}$  (Fig. 1(a)) and damping coefficient  $\bar{c}_{ba}$  (Fig. 1(b)) vary by a factor of 25 depending on the source, which makes adequate applicability unfeasible.

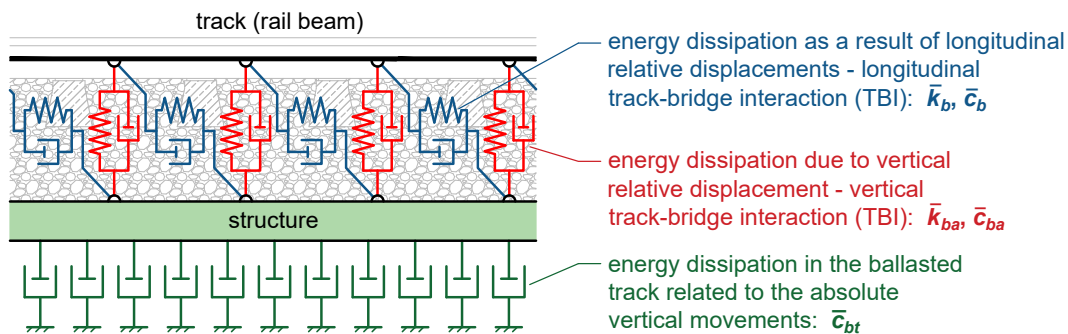


Figure 1. Mechanical model for considering track-bridge interaction (TBI) effects in ballast superstructures.

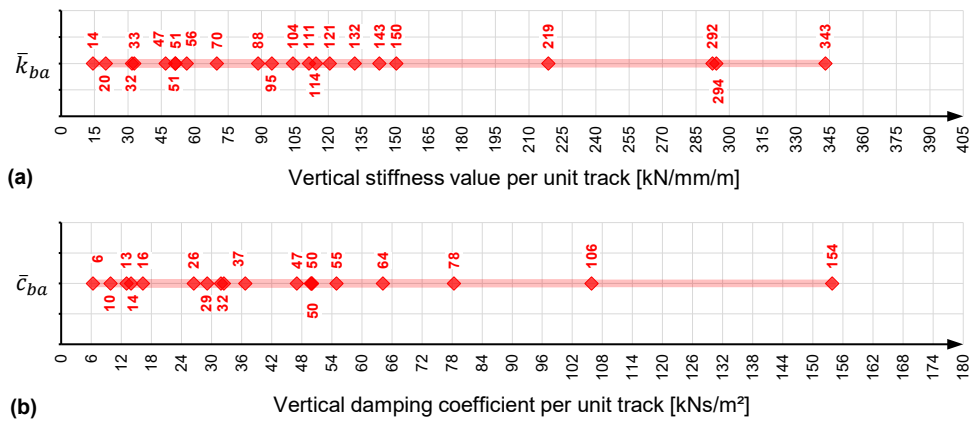


Figure 2. Results of the study in [10] for dynamic parameters describing the vertical track-bridge interaction (TBI) available in the literature: (a) stiffness value and (b) damping coefficient.

Based on the findings in [8] and using the model shown in Figure 1, research activities at the Institute of Structural Engineering at TU Wien focus on the experimental investigation of TBI effects occurring in ballast superstructures using specialized large-scale test facilities.

Given the enormous range of available characteristic values (see e.g. Fig. 2), the overarching goal is to precisely determine model-related stiffness and damping characteristics based on targeted experiments. Some key findings relating to vertical and longitudinal TBI effects are presented in this contribution.

## EXPERIMENTAL ANALYSIS OF VERTICAL TBI EFFECTS

The research into vertical track-bridge interaction (TBI) effects is carried out using a large-scale test facility replicating a dynamically excited section of ballast superstructure located on a bridge on a scale of 1:1.

The test facility (see Fig. 3) consists of a 6.6 m long and 2.7 m wide steel trough (in red), in which a section of ballast superstructure is installed on a scale of 1:1 over a length of 2.40 m. The test facility is designed to replicate a typical steel railway bridge with two main girders as the primary supporting structure, with an intermediate deck plate and transverse girders (cross girders) arranged in the area of the installed ballast superstructure. In terms of width, however, only half the cross-section of a single-track bridge is replicated for testing purposes, with the ballast superstructure consisting of one rail, four half concrete sleepers, a 55 cm ballast bed, and a sub-ballast mat (see Fig. 3 – top right).

A pre-loading device that can be forced down onto the track allows a static axle load of 125 kN to be simulated (corresponding to half the axle load of a train), enabling the superstructure's unloaded and loaded states to be investigated. In addition, Figure 3 (bottom) also contains a longitudinal section of the test facility with all key components. The excitation is applied vertically using hydraulic presses, with the test spectrum covering a frequency range from 1 to 25 Hz and vertical accelerations up to 10 m/s<sup>2</sup>. The test facility, therefore, replicates the superstructure, which is vertically excited by the bridge structure (structure-induced TBI effects).

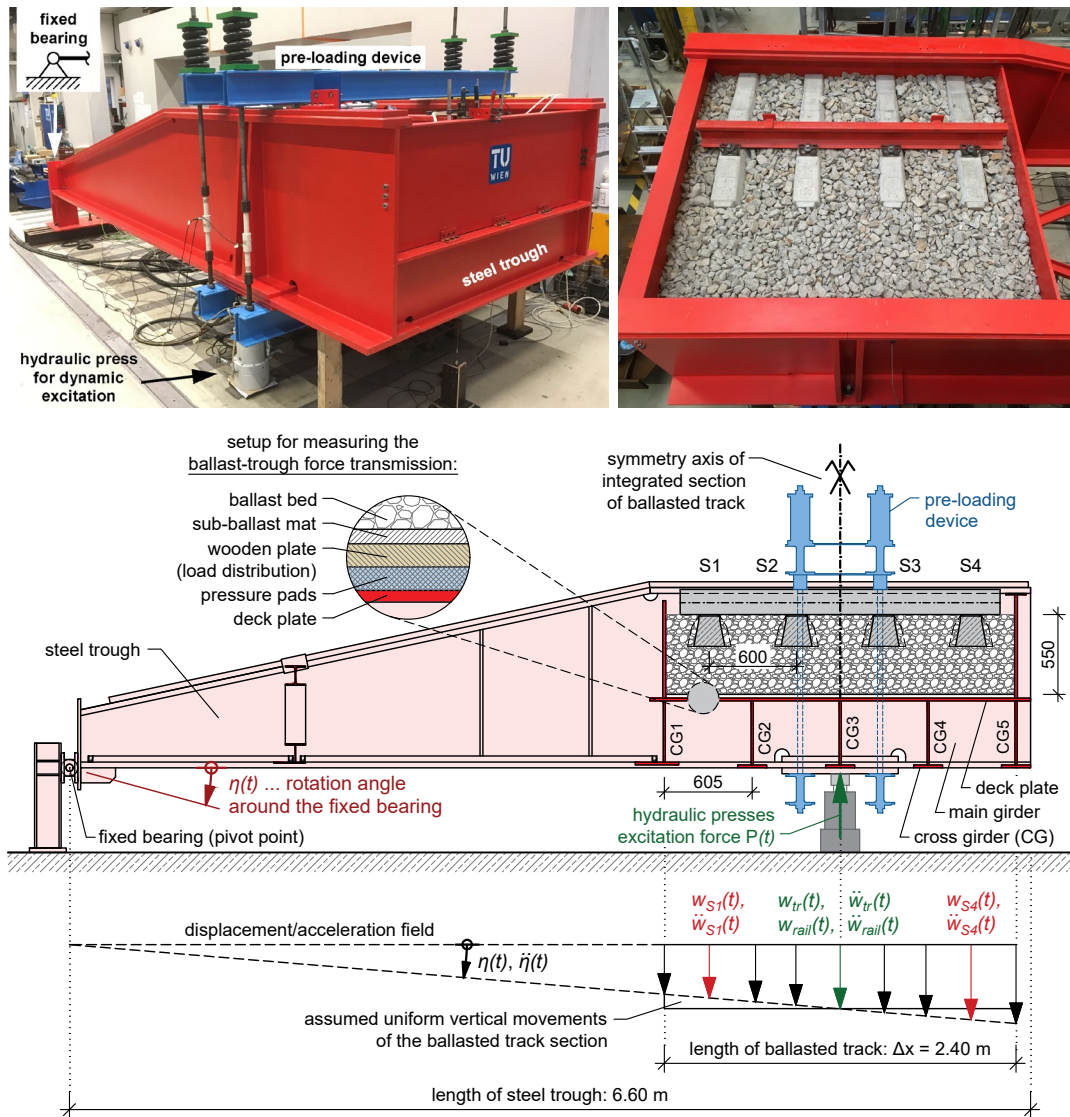


Figure 3. Investigation of vertical track-bridge interaction (TBI) – top left: overview of large-scale test facility – top right: integrated section of ballast superstructure – bottom: longitudinal section.

Under dynamic excitation, the steel trough rotates around the fixed bearing (see Fig. 3), where the distance between the superstructure and the pivot point (fixed bearing) allows uniform vertical movements of the superstructure to be assumed. A comprehensive summary of the investigations and results concerning the investigations on vertical TBI effects can be found in [10] and [11].

The dynamic characteristics (stiffness  $\bar{k}_{ba}$  and damping coefficient  $\bar{c}_{ba}$ , see Fig. 1) are determined using hysteresis loops generated from measurement data consisting of the vertical relative displacement between the rail and the steel trough  $w_{rel}$  and the transmission force between the superstructure and the steel trough (measured using pressure pads, see the longitudinal section in Fig. 3). Figure 4 shows the results for vertical stiffness (excerpt from [10]), with non-linear material behavior apparent for both the unloaded state (green markings) and the loaded state (blue markings). Concerning Figure 4 (b), the vertical force  $F_V$  shown on the ordinate describes the product of stiffness  $\bar{k}_{ba}$  and displacement amplitude  $w_{rel}$  ( $F_V = \bar{k}_{ba} w_{rel}$ ).

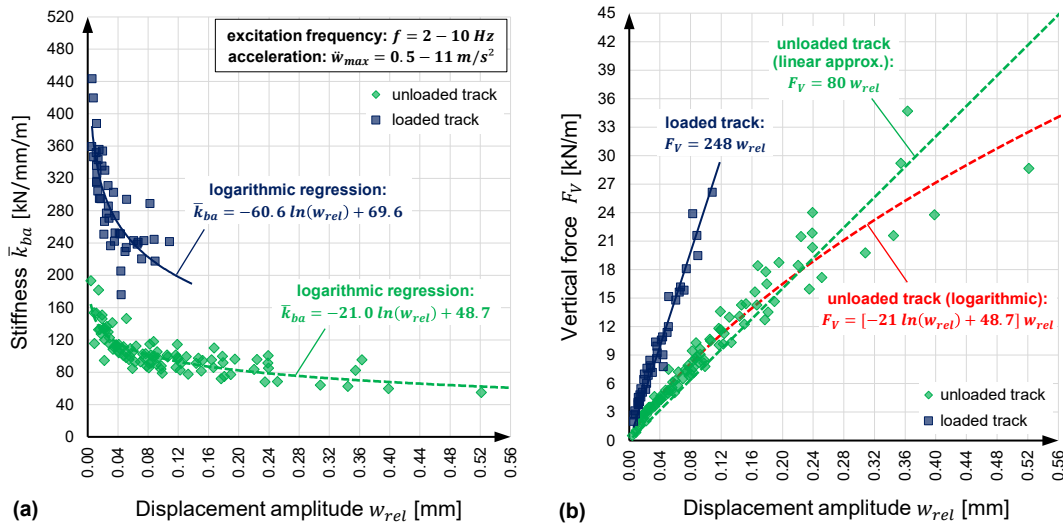


Figure 4. Results for vertical stiffness characteristics: (a) stiffness  $\bar{k}_{ba}$  depending on displacement amplitude, and (b) vertical force in the track depending on the displacement amplitude.

The results in Figure 4 illustrate that the loaded track has significantly higher stiffness. A linear approximation of the results in Figure 4 (b) yields a stiffness of 80 kN/mm per meter of track for the unloaded track (green dashed regression line) and 248 kN/mm for the loaded track (blue regression line). Further results regarding the damping characteristics, settlement behavior, and destabilization processes occurring in the superstructure under vertical excitation are given in [10]. In addition, results and findings regarding lateral track-bridge interaction can be found in [11].

## EXPERIMENTAL ANALYSIS OF LONGITUDINAL TBI EFFECTS

The targeted and isolated investigation of the characteristics of the longitudinal track-bridge interaction (TBI) is likewise carried out on a large-scale test facility (see Fig. 5), which includes a full section of ballast superstructure on a scale of 1:1. The facility consists of an 8 m long and 4.5 m wide steel trough (in green), which corresponds in cross-section to a single-track steel railway bridge (two main girders with deck plate and cross girders in between).

A ballast superstructure is installed in the steel trough over a length of 6 m, consisting of a track with nine soled concrete sleepers, a 55 cm thick ballast bed, and a sub-ballast mat (Fig. 5, top right). The superstructure section installed in the two test facilities (see Fig. 3 and Fig. 5) corresponds in its construction to the typical superstructure in the existing European rail network.

For experimental investigation of longitudinal TBI effects, the track is dynamically excited in the horizontal direction by hydraulic presses positioned at the rail axis level, with the displacement amplitude and excitation frequency being controlled. The test spectrum again covers a frequency range between 1 and 25 Hz with displacement amplitudes of up to 5.5 mm. A pre-loading device located on the track grid (Fig. 5, bottom right in blue) can simulate two axle loads of a train, which also allows the condition of the statically loaded track to be investigated.



Figure 5. Large-scale test facility for isolated research of longitudinal track-bridge interaction (TBI) – top left: overview – top right: integrated section of ballast superstructure – bottom left: front view – bottom right: pre-loading device simulating two static axle loads of a train.

Detailed results of the investigations into the dynamic properties of longitudinal track-bridge interaction (TBI) using the test facility shown in Figure 5 are documented in [12], to which reference is made here.

As a key result concerning longitudinal TBI, Figure 6 shows the longitudinal shear resistance determined from the tests, with the longitudinal force per meter of the track  $F_V$  being shown as a function of the displacement amplitude  $u_0$ . Figure 6 (a) contains the results for tests under normal conditions (summer tests), and Figure 6 (b) shows the longitudinal shear resistances for the frozen ballast bed condition (winter tests), with tests carried out at both  $-2^\circ\text{C}$  and  $-10^\circ\text{C}$ . Both figures contain the results for the loaded and unloaded states. For comparison, the bilinear curves specified in EN 1991-2 [13] are depicted, which are used as the current state of the art to describe longitudinal TBI and provide a bilinear curve as a function of load and temperature.

The results in Figure 6 demonstrate that the actual material behavior is non-linear and displacement-dependent but, at the same time, almost frequency-independent. The individual markings per color in Figure 6 represent tests with frequencies between 1 and 25 Hz. However, the material law can be approximated in relation to the displacement amplitude with different curves depending on the load and temperature. The results from tests with frozen ballast bed reveal that temperature has a significant influence on stiffness and that minor icing (here:  $-2^\circ\text{C}$ ) has almost no impact on stiffness in contrast to  $-10^\circ\text{C}$  (red markings) when comparing the blue and grey markings in Figure 6 (b).

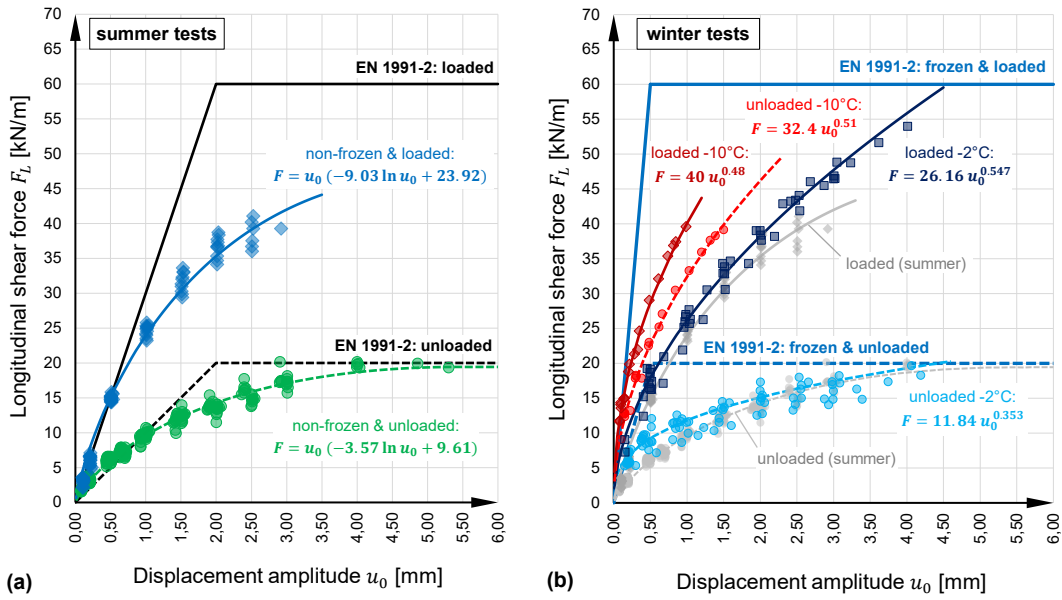


Figure 6. Results for longitudinal stiffness characteristics: (a) longitudinal shear resistance per unit track for non-frozen conditions (summer tests) and (b) longitudinal shear resistance per unit track for the frozen ballast bed for different temperatures (winter tests).

## CONCLUSIONS AND OUTLOOK

The results presented in this contribution provide essential insights into the experimental investigation of track-bridge interaction (TBI) effects occurring in ballast superstructures, which serve as a basis for implementation in SHM-driven bridge models. Concerning TBI effects, the experiments revealed that vertical stiffness is highly dependent on load, increasing by a factor of three (Fig. 4, [10]), while longitudinal resistance is significantly influenced by temperature, especially under frozen conditions (Fig. 6, [12]). Further results from the experiments regarding energy dissipation in the ballast superstructure and the vertical, longitudinal, and lateral TBI effects are described in detail in [8] and [10-12].

Practical applications of the results presented here include assessing and predicting rail stresses for evaluating track conditions, fatigue predictions, and planning rail expansion joints (see [14–16]). Additionally, accounting for vertical coupling between the track and supporting structure significantly influences the dynamic assessment of bridges under high-speed train traffic. Considering vertical TBI improves computational vibration predictions (see [17], [18]). Further large-scale tests are planned at TU Wien to investigate dynamic parameters and experimentally determine the load-distributing effect of the superstructure under vertical dynamic excitation (track-induced vertical TBI effects).

The overarching goal of developing a holistic model with precise characteristic values for TBI—and implementing it in prediction models—supports realistic condition assessment and predictive prognosis of railway bridges, forming the basis for an economical bridge maintenance strategy.

## REFERENCES

1. Kaewunruen, S., M. AbdelHadi, M. Kongpuang et al. 2023. "Digital Twins for Managing Railway Bridge Maintenance, Resilience, and Climate Change Adaption," *Sensors*, 23(1):252. <https://doi.org/10.3390/s23010252>
2. Chacón, R., C. Ramonell, H. Posada et al. 2024. "Digital twinning during load tests of railway bridges – case study: the high-speed railway network, Extremadura, Spain," *Struct. Infrastruct. Eng.*, 20(7-8):1105-1119. <https://doi.org/10.1080/15732479.2023.2264840>
3. Armijo, A. and D. Zamora-Sánchez. 2024. "Integration of Railway Bridge Structural Health Monitoring into the Internet of Things with a Digital Twin: A Case Study," *Sensors*, 24(7):2115. <https://doi.org/10.3390/s24072115>
4. Zhai, W., Z. Han, Z. Chen et al. 2019. "Train-track-bridge dynamic interaction: a state-of-the-art review," *Veh. Syst. Dyn.*, 57(7):984-1027. <https://doi.org/10.1080/00423114.2019.1605085>
5. Arvidsson, T. and R. Karoumi. 2014. "Train-bridge interaction – a review and discussion of key model parameters," *Int. J. Rail Transport.*, 2(3):147-186. <https://doi.org/10.1080/23248378.2014.897790>
6. Cantero, D., T. Arvidsson, E. O'Brien and R. Karoumi. 2016. "Train-track-bridge modelling and review of parameters," *Struct. Infrastruct. Eng.*, 12(9):1051-1064. <https://doi.org/10.1080/15732479.2015.1076854>
7. Moliner, E., M.D. Martinez-Rodrigo, P. Galvin et al. 2022. "On the vertical coupling effect of ballasted tracks in multi-span simply-supported railway bridges under operating systems," *Struct. Infrastruct. Eng.* 19(11):1633-1655. <https://doi.org/10.1080/15732479.2022.2049828>
8. Stollwitzer, A., J. Fink and T. Malik. 2020. "Experimental analysis of damping mechanisms in ballasted track on single-track railway bridges," *Eng. Struct.* 220:110982. <https://doi.org/10.1016/j.engstruct.2020.110982>
9. König, P. and C. Adam. 2024. "A model considering the longitudinal track-bridge interaction in ballasted railway bridges subjected to high-speed trains," *Acta Mech.* 235:1395-1418. <https://doi.org/10.1007/s00707-023-03605-3>
10. Stollwitzer, A., L. Bettinelli and J. Fink. 2024. "Vertical Track-Bridge Interaction in Railway Bridges with Ballast Superstructure: Experimental Analysis of Dynamic Stiffness and Damping Behavior," *Int. J. Struct. Stab. Dyn.*, 2540008. <https://doi.org/10.1142/S0219455425400085>
11. Stollwitzer, A., L. Bettinelli, S. Loidl and J. Fink. 2025. "Acceleration-dependent lateral track resistance for the condition assessment of railway bridges with ballasted track," *Roads and Bridges – Drogi i Mosty*, 24(1):37-45. <https://doi.org/10.7409/rabd.025.002>
12. Stollwitzer, A., L. Bettinelli and J. Fink. 2024. "The longitudinal track-bridge interaction of ballasted track in railway bridges: Experimental determination of dynamic stiffness and damping characteristics," *Eng. Struct.* 273, 115115. <https://doi.org/10.1016/j.engstruct.2022.115115>
13. EN 1991-2:2012 03 01 Eurocode 1: Actions on structures – Part 2: Traffic loads on bridges (consolidated version). Austrian Standard International, Vienna.
14. Yan, B., W. Kuang, R. Gan et al. 2022. "Track-Bridge Interaction of CWR on Chinese Large-Span Bridge of High-Speed Railway," *Appl. Sci.* 12(18):9100. <https://doi.org/10.3390/app12189100>
15. Kang, C., M. Wenner and S. Marx. 2021. "Background investigation on the permissible additional rail stresses due to track/bridge interaction," *Eng. Struct.* 228:111505. <https://doi.org/10.1016/j.engstruct.2020.111505>
16. Liu, W., H. Lai, G. Dai et al. 2021. "Numerical Study on Track-Bridge Interaction of Integral Railway Rigid-Frame Bridge," *Appl. Sci.* 11(3):922. <https://doi.org/10.3390/app11030922>
17. Bettinelli, L., A. Stollwitzer and J. Fink. 2023. "Numerical Study on the Influence of Coupling Beam Modeling on Structural Accelerations during High-Speed Train Crossings," *Appl. Sci.* 13(15):8746 <https://doi.org/10.3390/app13158746>
18. Allahvirdizadeh, R., E. Moliner and P. Museros. 2025. "Data-Driven Relationship for Reduction Factor of Ballasted Railway Bridge Deflections Due to Load Distribution Within Track," *Int. J. Struct. Stab. Dyn.*, 2540017. <https://doi.org/10.1142/S0219455425400176>