doi.org/10.62683/SINARG2025.020

Research paper

REQUIREMENTS FOR TRAIN-TRACK-BRIDGE DYNAMIC INTERACTION ANALYSIS

Nikola Mirković[1], Uroš Mirković[2], Dušan Stevanović[3]

Abstract

The analysis of the dynamic interaction between the train, track, and bridge is crucial for ensuring the performance of railway infrastructure and the safety of railway traffic, especially on high-speed rail systems. This paper examines the key requirements for analyzing the dynamic interaction between the train, track, and bridge, with particular emphasis on the guidelines outlined in UIC Code 776-2. The analysis includes the structural strength of the bridge, passenger comfort, and the overall safety of railway traffic, ensuring a comprehensive evaluation of the entire railway system. Specifically, the paper examines the impact of continuously welded rails, which are widely used in modern railways due to their improved performance and reduced maintenance needs. The dynamic behavior of the train, track, and bridge is analyzed to confirm the structural integrity of the system, mitigate vibrations, and enhance passenger comfort. UIC Code 776-2 serves as a key reference for understanding the design and performance requirements for analyzing train-track-bridge dynamic interaction, guaranteeing that safety standards are met while optimizing efficiency. By evaluating the dynamic performance of the train, track, and bridge components, potential risks can be assessed, and strategies can be developed to mitigate them. This research contributes to the development of more resilient railway systems, ensuring the safety of both passengers and infrastructure.

Key words: *Railway Infrastructure, Continuously Welded Rail, Railway Traffic Safety, Bridge Structural Strength, Passenger Comfort, Engineering Application*

[1] PhD, Research Associate, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, nikola.mirkovic@jcerni.rs, ORCID 0000-0002-5980-3049
[2] PhD, Research Assistant, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, uros.mirkovic@jcerni.rs, ORCID 0000-0001-6781-5798
[3] MSc Civ. Eng., PhD student, Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Belgrade, Serbia, dusan.stevanovic@jcerni.rs, ORCID N/A

1. INTRODUCTION

The rapid expansion of high-speed railways has heightened the focus on the train-track-bridge dynamic interaction, attracting significant attention from researchers and engineers around the world. This growing interest highlights the importance of understanding the complex behavior of these interconnected systems to ensure the safety, performance, and durability of modern railway infrastructure.

When a train crosses a bridge, it induces vibrations that affect the bridge structure, resulting in dynamic impacts. These vibrations can, in turn, influence the safety of the train's operation and the comfort of passengers aboard, especially when the train is traveling at high speeds. This interaction between the train, track and, bridge is not only a physical phenomenon but a coupled dynamic system, where the behavior of one directly affects the performance of the other. Such interdependence highlights the need for thorough analysis to ensure both the structural integrity of the bridge and the safety and comfort of the train. Understanding this dynamic coupling is crucial for optimizing the design and operation of railway systems.

Numerous studies have focused on the development of numerical models to simulate train-track-bridge interactions. These models incorporate various factors such as train speed, bridge flexibility, track irregularities, and environmental conditions. Zhai et al. [1] presented research that investigated the evolution of dynamic interaction models, ranging from basic constant force models to advanced train-track-bridge dynamic interaction models. The paper examined key modeling elements, including the train, track, bridge, wheel-rail contact, system excitation and solution algorithm. Additionally, it discussed safety assessment and real-world applications, emphasizing the importance of detailed track modeling and outlining future research challenges in the field. Ribeiro et al. [2] conducted a comprehensive validation of a three-dimensional dynamic model for train-track-bridge interaction on a bowstring-arch railway bridge, demonstrating the effectiveness of numerical simulations in replicating experimental observations. Similarly, a study by Fedorova and Sivaselvan [3] proposed an algorithm for dynamic train-track-bridge interaction analysis. The method modeled the bridge and train separately, coupling them through kinematic constraints, with contact forces treated as Lagrange multipliers. The algorithm was validated using a differential-algebraic equation solver and accounted for wheel-rail contact separation caused by track irregularities. Zhu et al. [4] proposed a hybrid method combining the direct stiffness method and the mode superposition method for the efficient analysis of the train-track-bridge system. The train and track were modeled using multi-body dynamics and the direct stiffness method, respectively, while the bridge was modeled using the mode superposition method. Coupling between the train, track and bridge subsystems was achieved through interaction forces, significantly reducing computational complexity.

Experimental validation plays a crucial role in verifying the accuracy of numerical models. Mo, Zhuo, and Li [5] introduced an approach based on multi-sensor time-frequency analysis to identify local track irregularities using bridge acceleration data. Their findings highlighted the potential of vibration-based monitoring techniques for track maintenance and infrastructure diagnostics. Zhang, Tian, and Xia [6] analyzed the train-bridge dynamic interaction, emphasizing the need for experimental evaluation methods to ensure the safety and stability of both bridges and trains. The system is modeled using the rigid-body dynamics method for the train, the finite element method for the bridge, and Kalker's linear creep theory for the wheel/rail interaction. This interaction is investigated through theoretical analysis, numerical simulations, and experimental research, considering excitations such as track irregularity, structure deformation, and structural damage, among others. Chang et al. [7] investigated the impact of wheel hollow wear on the dynamic interaction within high-speed train-track-bridge systems. A nonlinear rigid-flexible coupled model was developed for a high-speed train operating on a long-span continuous girder bridge. The model integrated train-track-bridge interaction theory, non-elliptical multi-point wheel-rail contact theory, and a modified Craig-Bampton modal synthesis method. Numerical results indicated that wheel hollow wear altered the wheel-rail contact geometry, exacerbating dynamic interactions and amplifying bridge vibrations at a speed of 350 km/h.

European regulatory frameworks governing train-track-bridge interaction are designed to ensure the safety and performance of railway infrastructure. Key documents include recommendations such as UIC Code 776-1 [8], which focuses on load models for railway bridges; UIC Code 776-2 [9], which provides guidelines for railway bridge design considering train-track-bridge dynamic interaction; and UIC Code 774-3 [10], which addresses rail stresses and bridge deformations caused by track-bridge interaction. Standard EN 1991-2 [11] defines actions on bridges, including dynamic effects from railway traffic. Collectively, these regulations establish design and assessment criteria to mitigate excessive stresses, deformations, and vibrations, thereby ensuring the structural integrity and operational stability of railway bridges.

In the following chapters of this paper, the relevant requirements for conducting the train-track-bridge dynamic interaction analysis, as defined in European technical regulations, will be presented and discussed, along with the criteria that ensure railway traffic safety, bridge structural strength, and passenger comfort. Additionally, distinct situations from engineering practice will be considered to illustrate when dynamic analysis is required.

2. TRAFFIC SAFETY ON RAILWAY BRIDGES

Railway bridges are critical components of transportation infrastructure, enabling the safe passage of trains over rivers, valleys, roads, and other obstacles. However, ensuring traffic safety on railway bridges presents unique challenges due to the fact that these structures are elevated. This height exposes them to various environmental conditions and makes them more susceptible to dynamic forces generated by train operations. Traffic safety on railway bridges is influenced by several key factors, including the quality of the wheel-rail contact, track stability, and the deformations and vibrations the bridge may experience during operation.

When the contact between the wheels of a train and the rail is smooth and consistent, it minimizes the risk of derailment and vibrations that can negatively affect the bridge's structure. Proper wheel-rail interaction helps distribute the load evenly, reducing the forces on the bridge's supports, which is vital for maintaining its integrity over time. Any irregularities, such as wheel wear or rail defects, can lead to uneven forces and excessive rail wear, potentially compromising traffic safety. Therefore, maintaining optimal wheel-rail contact quality is essential for the safe operation of trains, particularly when crossing bridges, as it contributes to both structural stability and overall operational reliability.

Track stability is another crucial factor in ensuring traffic safety on railway bridges. A well-aligned track minimizes the risk of derailment, particularly when trains are crossing bridges. Any irregularity, such as track misalignment or insufficient ballast support, can cause uneven forces and vibrations that may weaken the structural integrity of the track. When the track is unstable, it can lead to excessive wear on the rail, irregular wheel-rail contact, and potentially dangerous oscillations, all of which increase the likelihood of accidents. Therefore, ensuring the track's stability is essential for the safe operation of trains, as it directly impacts both the safety of passengers and the long-term durability of railway bridge structures.

According to UIC Code 776-2 [9], the deformation of the bridge deck, in terms of distortion criteria, is calculated using the characteristic load model (LM71) [8] and appropriate load diagrams (such as SW/0 or SW/2) [8], multiplied by dynamic increment coefficient (Φ) [8] and the classification coefficient (α) [8], or the high-speed load diagram, considering the effects of centrifugal force. When the bridge deck carries multiple tracks, with one of them being loaded, it experiences torsion due to the applied operational loads. The distortion of the bridge deck (t), under operational loads, is measured on a 1435 mm wide track over a distance of 3 m, as shown in Figure 1. Total distortion due to total deformation of the bridge deck, must not exceed 7.5 mm per 3 m. As speeds increase, the allowed distortion decreases.

The limit values for distortion of bridge deck are set based on different speed domains [9]:

- for speeds up to 120 km/h, the maximum allowed distortion is 4.5 mm per 3 m of track,
- for speeds between 120 km/h and 200 km/h, the maximum allowed distortion is 3.0 mm per 3 m of track,
- for speeds over 200 km/h, the maximum allowed distortion is 1.5 mm per 3 m of track.

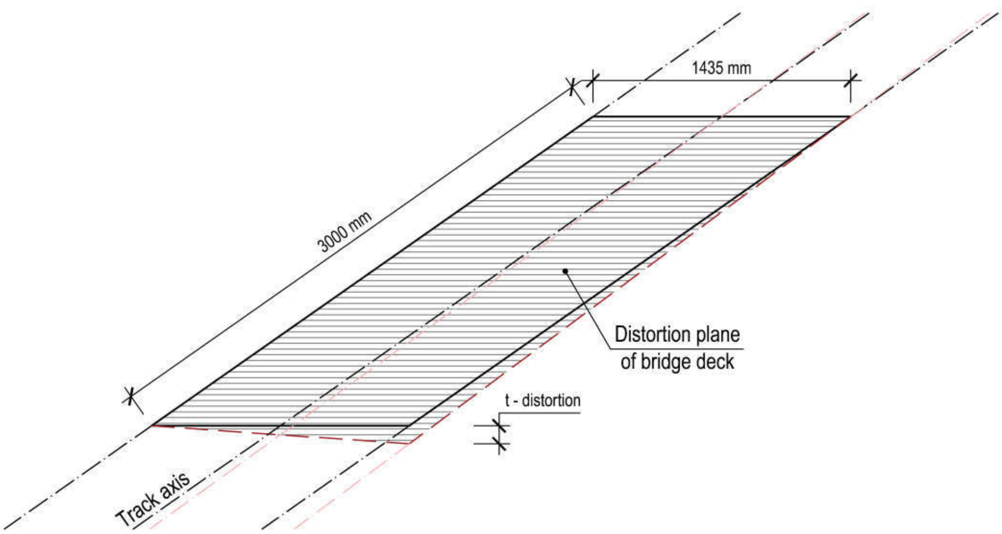

Figure 1. Distortion of bridge deck according to [9]

Horizontal and vertical displacements of the bridge deck are also important for railway traffic safety. If continuously welded rails (CWR) are used, longitudinal horizontal displacements due to vertical operating loads, including the dynamic increment coefficient, must remain below 10 mm, without considering interaction. On the other hand, when considering interaction, according to UIC Code 774-3 [10], longitudinal horizontal displacements due to vertical operating loads, including the dynamic increment coefficient, must remain below 8 mm. For displacements caused by acceleration/braking, the limit must be below 5 mm. In cases where the track has CWR and expansion joints at the end of the bridge, the limit can rise to 30 mm. Vertical displacements at end of bridge deck should be kept below 3 mm for ballasted tracks and 1.5 mm for ballastless tracks [9].

Finally, the acceleration of the bridge deck plays a crucial role in the railway traffic safety. To ensure safe operation, the maximum acceleration of bridge deck with ballasted track must remain below 0.35g for frequencies up to 30 Hz. For bridges with ballastless tracks, the limit is set at 0.5g for frequencies below 30 Hz [9].

3. STRUCTURAL STRENGTH OF RAILWAY BRIDGES

The structural strength of railway bridges is a critical factor in ensuring the safe and efficient functioning of railway networks. The ability of a bridge to withstand dynamic loads, including the weight of trains, environmental conditions, and the repetitive stresses imposed during operation, is paramount. The guidelines for the design and assessment of the structural strength of railway bridges focus on three key aspects: strength, fatigue, and durability.

The strength of a railway bridge refers to its ability to resist applied forces without failure or excessive deformation. The design must account for the maximum load that can be exerted by trains, including both static and dynamic loads, as well as acceleration and braking forces. Requirements for calculating the structural strength of railway bridges ensure that the structure can safely support the weight of the heaviest trains operating on the line. The strength of materials used in the bridge's construction, such as steel or concrete, is also a crucial consideration, as these materials must be able to withstand the stresses they will be subjected to over the bridge’s service life.

Fatigue is the weakening of a material caused by repeated loading and unloading cycles over time. Railway bridges are particularly susceptible to fatigue due to the continuous passage of trains, which introduce dynamic loads that vary in magnitude and frequency. Fatigue analysis is essential for assessing the long-term performance of a bridge, especially in high-speed or heavily trafficked railway lines. Special attention must be given to the effects of high-frequency train passages, which can significantly reduce the lifespan of the bridge if not properly accounted for in the design. The fatigue life of railway bridges should normally be a minimum of 100 years according to technical regulations and engineering practice.

Durability refers to the ability of a railway bridge to maintain its structural integrity over time, despite exposure to environmental conditions such as moisture, temperature variations, and chemical corrosion. Also, durability is closely related to the concept of fatigue, as prolonged exposure to environmental stressors can exacerbate the fatigue process and lead to premature deterioration of the bridge.

By adhering to these guidelines, it is possible to ensure the safety, reliability, and longevity of railway bridges, which are essential components of modern transport infrastructure. Regular assessment and maintenance are necessary to preserve the structural integrity of railway bridges and to mitigate the effects of fatigue and environmental conditions over time.

In cases where it is necessary to perform a dynamic analysis of the bridge structure with appropriate load models or real trains, it is essential to determine the dynamic increment coefficient, as shown in equation (1) [9]:

$$\varphi'_{dyn} = \max[\gamma_{dyn}/\gamma_{stat}] - 1 \quad (1)$$

where:

φ'_{dyn} - dynamic increment coefficient for the real train and a track without irregularities,

γ_{dyn} - dynamic deflection of bridge deck due to load models or real trains,

γ_{stat} - static deflection of bridge deck.

The decision of whether the structural strength of the railway bridge will be analyzed using load models or real trains is based on the following flowchart in Figure 2.

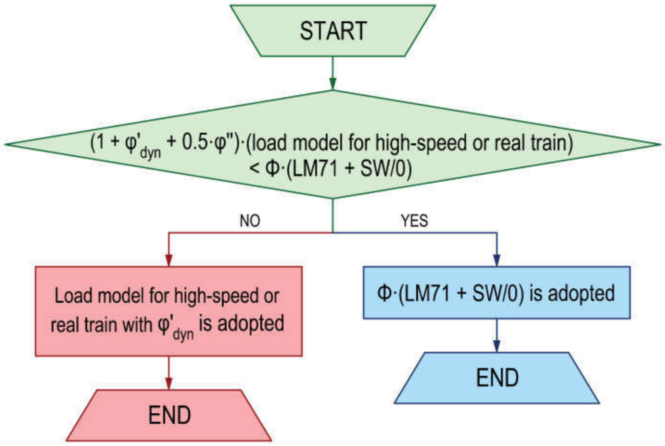

Figure 2. Flowchart for determining the loads to be considered in bridge strength calculations according to [9]

where:

φ'' - dynamic increment coefficient for the real train and a track with irregularities,

Φ - dynamic increment coefficient.

4. PASSENGER COMFORT ON RAILWAY BRIDGES

This chapter delves into the factors that contribute to passenger comfort on railway bridges, focusing on train-track-bridge interaction, the physiological effects of vertical accelerations, and the resulting passenger fatigue.

The train-track-bridge interaction is a critical aspect of railway design that significantly influences ride quality when trains cross bridges. The interaction forces between train wheels and the track are intensified on bridges as a result of their structural dynamics. Variations in bridge materials and construction conditions can have a significant impact on how vibrations and dynamic loads are transferred between the train and the bridge. These interactions cause oscillations or undulations in the train body, leading to changes in the way passengers perceive comfort. The structural rigidity of a bridge plays a role in how vibrations are propagated. On more flexible bridges, train operation can induce significant oscillations that may lead to passenger discomfort. As trains pass over these flexible structures, their motion may become more irregular, leading to a more noticeable impact on passenger comfort. Track alignment and the quality of track-bed maintenance on bridges are also crucial for minimizing unwanted vertical and lateral forces, which can lead to unpleasant jolts or bumps for passengers. Table 1 provides an overview of the key parameters of passenger comfort on railway bridges.

Table 1. Parameters of passenger comfort on railway bridges

Structural parameters	Operational parameters	Environmental parameters	Human perception parameters
Bridge stiffness and deflection; Natural frequency and resonance; Damping characteristics; Track structure and transitions.	Train speed; Axle load and suspension system; Braking and acceleration; Wheel-rail interaction.	Wind and weather conditions; Noise and vibrations.	Vibration perception; Seating orientation and comfort; Visual stability.

Vertical accelerations are one of the primary factors affecting passenger comfort when trains cross bridges. As a train transitions from solid ground onto a bridge, the change in support structure leads to increased vertical accelerations. If these accelerations are excessive, they can cause discomfort, particularly for passengers seated or standing in the aisles. To mitigate these effects, train manufacturers must focus on developing effective suspension systems and optimizing track design, both of which help absorb or minimize these accelerations, thereby improving overall ride quality. Additionally, train speed plays a significant role in comfort. While higher speeds are often linked to increased efficiency and shorter travel times, they can exacerbate the forces experienced on railway bridges. Striking a balance between speed and comfort is crucial to ensuring a smooth and pleasant journey, especially on bridge sections where dynamic interactions between the train and track are most pronounced.

Prolonged exposure to excessive vertical accelerations and vibrations can lead to physical discomfort, such as muscle strain, and increased stress on the body, especially for passengers who are seated for extended periods. This strain often manifests as fatigue, which, over time, can degrade the overall passenger experience. Understanding the connection between train dynamics and passenger health is essential for improving comfort standards. Research into human response to vertical accelerations has provided insight into the thresholds that lead to fatigue and discomfort. By integrating this knowledge into railway bridge design and train suspension systems, engineers can optimize the experience for passengers, ensuring a reduction in discomfort and fatigue.

According to UIC Code 776-2 [9], passenger comfort in trains operating over railway bridges is classified into three distinct levels based on the vertical acceleration experienced in the vehicles. The highest comfort level is considered "very good", where vertical acceleration does not exceed 1.0 m/s^2. This level ensures a smooth and comfortable ride with minimal vibrations. The "good" level of comfort allows vertical acceleration up to 1.3 m/s^2, providing an adequate level of comfort, although it is slightly less smooth compared to the "very good" level. Finally, the "acceptable" comfort level is defined by vertical acceleration of up to 2 m/s^2. While this level is still within safety standards, it may be perceived as less comfortable, with more noticeable vibrations during travel. These comfort levels are crucial for optimizing the passenger experience while ensuring the safe operation of trains. Also, the criteria for ensuring passenger comfort on railway bridges are based on the vertical deflection of the bridge decks, considering factors such as vertical acceleration in the vehicles, train speed, span length, the number of span sections, and the bridge configuration.

5. VALIDATION PROCEDURES FOR DYNAMIC ANALYSIS IN ENGINEERING PRACTICE

The UIC Code 776-2 [9], as well as standard EN 1991-2 [11] provide a flowchart to assist in determining the need for dynamic analysis (Figure 3). The parameters of this flowchart include:

V [km/h] - maximum traffic speed,
L [m] - bridge span,
n_0 [Hz] - first natural bending frequency of the unloaded bridge,
n_T [Hz] - first natural torsional frequency of the unloaded bridge,
v_{lim}/n_0 and $(v/n_0)_{lim}$ - defined in Tables 8 and 9 of Appendix A in [9].

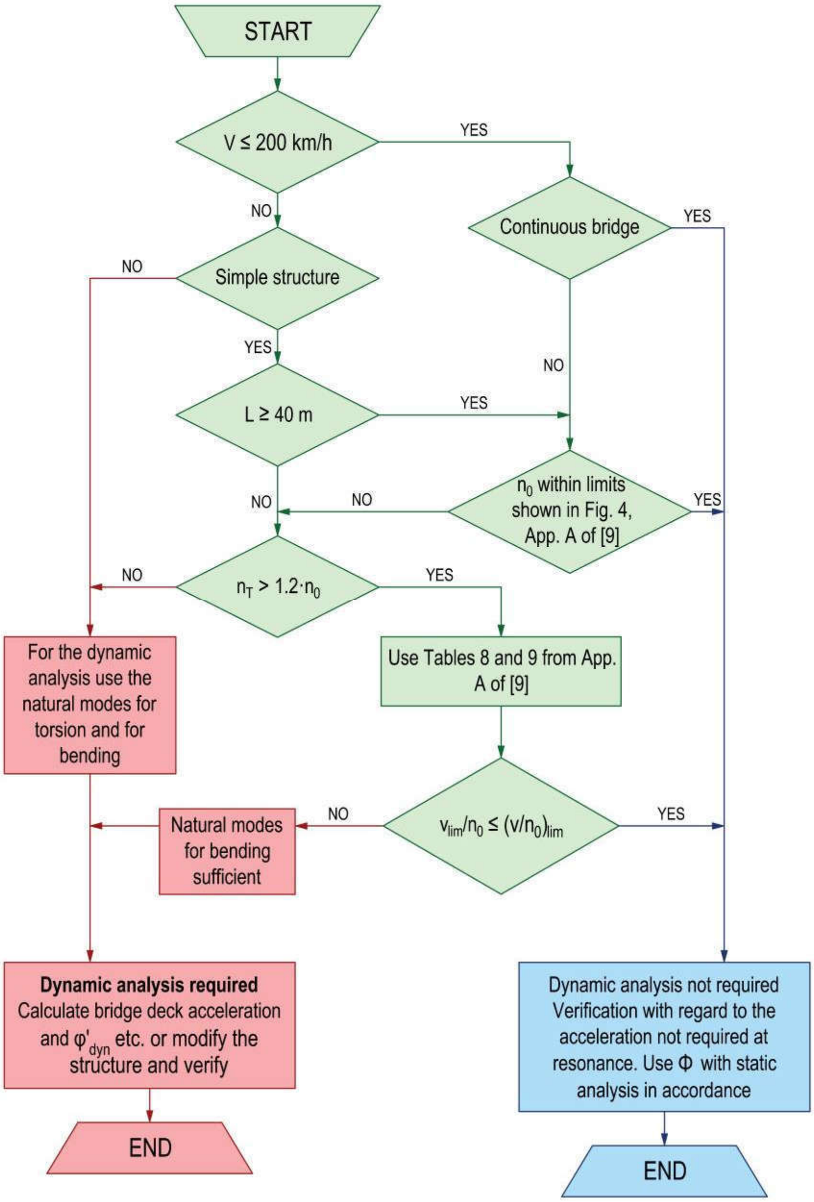

Figure 3. Flowchart for determining the need for dynamic analysis according to [9]

However, the use of this flowchart is not straightforward, as there are seven distinct situations in engineering practice where dynamic analysis becomes necessary:

1. When the maximum traffic speed is less than or equal to 200 km/h, the bridge structure is not classified as a "Continuous bridge", n_0 is not within the limits shown in Figure 4 of Appendix A in [9], n_T is not greater than $1.2 \cdot n_0$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of torsion and bending;
2. When the maximum traffic speed is less than or equal to 200 km/h, the bridge structure is not classified as a "Continuous bridge", n_0 is not within the limits shown in Figure 4 of Appendix A in [9], n_T is greater than $1.2 \cdot n_0$, Table 8 and 9 from Appendix A in [9] shall be used. If v_{lim}/n_0 is not less than or equal to $(v/n_0)_{lim}$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of bending;
3. When the maximum traffic speed is not less than or equal to 200 km/h, the bridge structure is not classified as a "Simple bridge", a train-track-bridge dynamic interaction analysis is required, considering the natural modes of torsion and bending;
4. When the maximum traffic speed is not less than or equal to 200 km/h, the bridge structure is classified as a "Simple bridge", the bridge span (L) is greater than or equal to 40 m, n_0 is not within the limits shown in Figure 4 of Appendix A in [9], n_T is not greater than $1.2 \cdot n_0$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of torsion and bending;
5. When the maximum traffic speed is not less than or equal to 200 km/h, the bridge structure is classified as a "Simple bridge", the bridge span (L) is greater than or equal to 40 m, n_0 is not within the limits shown in Figure 4 of Appendix A in [9], n_T is greater than $1.2 \cdot n_0$, Table 8 and 9 from Appendix A in [9] shall be used. If v_{lim}/n_0 is not less than or equal to $(v/n_0)_{lim}$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of bending;
6. When the maximum traffic speed is not less than or equal to 200 km/h, the bridge structure is classified as a "Simple bridge", the bridge span (L) is not greater than or equal to 40 m, n_T is not greater than $1.2 \cdot n_0$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of torsion and bending;
7. When the maximum traffic speed is not less than or equal to 200 km/h, the bridge structure is classified as a "Simple bridge", the bridge span (L) is not greater than or equal to 40 m, n_T is greater than $1.2 \cdot n_0$, Table 8 and 9 from Appendix A in [9] shall be used. If v_{lim}/n_0 is not less than or equal to $(v/n_0)_{lim}$, a train-track-bridge dynamic interaction analysis is required, considering the natural modes of bending.

The application of dynamic analysis, with particular emphasis on bending and torsional modes, is essential for accurately assessing the behavior of bridge structures under realistic operational conditions. This methodology aids in identifying potential critical points of bridge structure that may arise due to resonance, which could lead to failure. By utilizing this methodology, engineers can predict the dynamic response of bridge structures under varying loads and conditions, ensuring more robust and safer designs. Table 2 systematically presents all seven situations in engineering practice that require dynamic analysis.

Table 2. Summary of situations requiring dynamic analysis

Situation	V ≤ 200 km/h	Bridge type	L ≥ 40 m	n_0 within limits	$n_T > 1.2 \cdot n_0$	$v_{lim}/n_0 \leq (v/n_0)_{lim}$	Natural modes
1	✓	Not continuous	-	✗	✗	-	Bending + torsion
2	✓	Not continuous	-	✗	✓	✗	Bending
3	✗	Not simple	-	-	-	-	Bending + torsion
4	✗	Simple	✓	✗	✗	-	Bending + torsion
5	✗	Simple	✓	✗	✓	✗	Bending
6	✗	Simple	✗	-	✗	-	Bending + torsion
7	✗	Simple	✗	-	✓	✗	Bending

6. CONCLUSION

In this paper, a comprehensive analysis of the dynamic interaction between train, track, and bridge was conducted, with an emphasis on the requirements for ensuring traffic safety, passenger comfort, and the structural strength of railway bridges. By examining the guidelines outlined in UIC Code 776-2, the research identifies key factors influencing the train-track-bridge dynamic interaction, such as bridge deformations, vertical accelerations, and vibrations, while also highlighting the role of CWR in minimizing rail wear and enhancing the overall performance of railway bridges. Additionally, seven distinct situations in engineering practice that require dynamic analysis have been identified and are presented in Table 2. These findings contribute to the development of more resilient railway infrastructures, supporting the optimization of high-speed rail systems while ensuring compliance with international railway safety regulations.

REFERENCES

[1] Zhai Wanming, Han Zhaoling, Chen Zhaowei, Ling Liang, Zhu Shengyang: **Train–track–bridge dynamic interaction: a state-of-the-art review**. *Vehicle System Dynamics*, 57(7), 984-1027, 2019, https://doi.org/10.1080/00423114.2019.1605085.

[2] Ribeiro Diogo, Calçada Rui, Brehm Maik, Zabel Volkmar: **Train–Track–Bridge Dynamic Interaction on a Bowstring-Arch Railway Bridge: Advanced Modeling and Experimental Validation**. *Sensors*, 23(1), 171, 2022, https://doi.org/10.3390/s23010171.

[3] Fedorova Maria, Sivaselvan Mettupalayam V.: **An algorithm for dynamic vehicle-track-structure interaction analysis for high-speed trains**. *Engineering Structures*, 148, 857-877, 2017, https://doi.org/10.1016/j.engstruct.2017.05.065.

[4] Zhu Zhihui, Zhang Lei, Gong Wei, Wang Lidong, Bai Yu, Harik Issam E.: **An efficient hybrid method for dynamic interaction of train–track–bridge coupled system**. *Canadian Journal of Civil Engineering*, 47(9), 1084-1093, 2020, https://doi.org/10.1139/cjce-2019-0020.

[5] Mo Ye, Zhuo Yi, Li Shunlong: **Local track irregularity identification based on multi-sensor time–frequency features of high-speed railway bridge accelerations**. *Sustainability*, 15(10), 8237, 2023, https://doi.org/10.3390/su15108237.

[6] Zhang Nan, Tian Yuan, Xia He: **A train-bridge dynamic interaction analysis method and its experimental validation**. *Engineering*, 2(4), 528-536, 2016, https://doi.org/10.1016/J.ENG.2016.04.012.

[7] Chang Chao, Ling Liang, Han Zhaoling, Wang Kaiyun, Zhai Wanming: **High-Speed Train-Track-Bridge Dynamic Interaction considering Wheel-Rail Contact Nonlinearity due to Wheel Hollow Wear**. *Shock and Vibration*, 2019(1), 5874678, 2019, https://doi.org/10.1155/2019/5874678.

[8] **UIC Code 776-1R, Loads to be considered in railway bridge design, 5th edition**. *International Union of Railways*, Paris, France, 2006.

[9] **UIC Code 776-2R, Design requirements for rail-bridges based on interaction phenomena between train, track and bridge, 2nd edition**. *International Union of Railways*, Paris, France, 2009.

[10] **UIC Code 774-3R, Track/bridge Interaction, Recommendations for calculations, 2nd edition**. *International Union of Railways*, Paris, France, 2001.

[11] **EN 1991-2:2003/AC:2010, Eurocode 1: Actions on structures - Part 2: Traffic loads on bridges**. *European Committee for Standardization/Technical Committee 250*, Brussels, Belgium, 2010.