International Conference on Advanced Transport Technology and Infrastructure
25–26 June 2026 • Hanoi, Vietnam

Dynamics of railway bridges; research, methods and engineering codes

José M. Goicolea,
Research team: Khanh Nguyen, Nicola Tarque, Alfredo Cámara, Maha Allasassmeh

School of Civil Engineering, Universidad Politécnica de Madrid – UPM, Dept. of Structural Mechanics
jose.goicolea@upm.es

Type: Keynote Paper (Invited)
Session: Keynote Address **Keynote ID:** ICATTI2026-K0XX

Abstract

The dynamics of railway bridges is a relevant feature for the design and performance of the new railway infrastructure, especially for the new high speed lines. This short paper provides a summary of relevant features for railway bridge dynamics studied and implemented in the past 30+ years, mainly in the European region. These aspects require the application and further development of structural dynamics methods but also additional research. Additionally to a short state of the art a brief description of the salient features of dynamic analysis methods is done, covering from algebraic spectral methods, semi-analytical beam-type models, detailed 3D Finite Element models and coupled models for Vehicle-Bridge Interaction. Some further objectives of research for application in engineering codes are pointed out from the recent experience of the author. Finally, some concluding remarks are summarized.

Keywords: Dynamics of bridges; railway bridges; moving loads; vehicle-bridge interaction; engineering codes.

1. Introduction

The new high speed railway lines have enabled key developments in transport, with important implications in social, economic, political and technological areas. They have changed the patterns for passenger traffic specially for distances between 200 km and 1000 km, taking important shares away from airplane and car. Moreover, these electrified lines are beneficial for sustainability in energy and climate issues. High speed railway has been one of the main public investment expenditures for infrastructure in recent years for some countries, such as Spain and China. Finally, they bring to focus interesting areas for technological development and innovation in several fields, such as infrastructure, signaling, rolling stock.

Following early developments in Japan, France and Germany, Spain opened its first high speed line in 1992 from Madrid to Sevilla with 450 km. Currently the high speed network in Spain has 4000 km, second only to China. From a social point of view it has been a success, with cross-party support. Nevertheless, there are still issues to be developed in economic, safety and technical terms.

One of the key issues for the new infrastructure was the dynamic effects due to the high speed railway traffic. Figure 1 shows one of the viaducts from the Madrid-Sevilla line which experimented problematic resonant response and served as motivation for including dynamic requirements in the regulations. Historically it was already known that the large loads due to rail traffic which enter suddenly needed special consideration, this was the motivation for introducing *Impact Factors* in the design codes. However, the higher train speeds introduced additional challenges due to the potentially much larger effects of resonance. This lead to consider dynamic analysis for speeds above 200 km/h in the regulations at European level [3, 4].

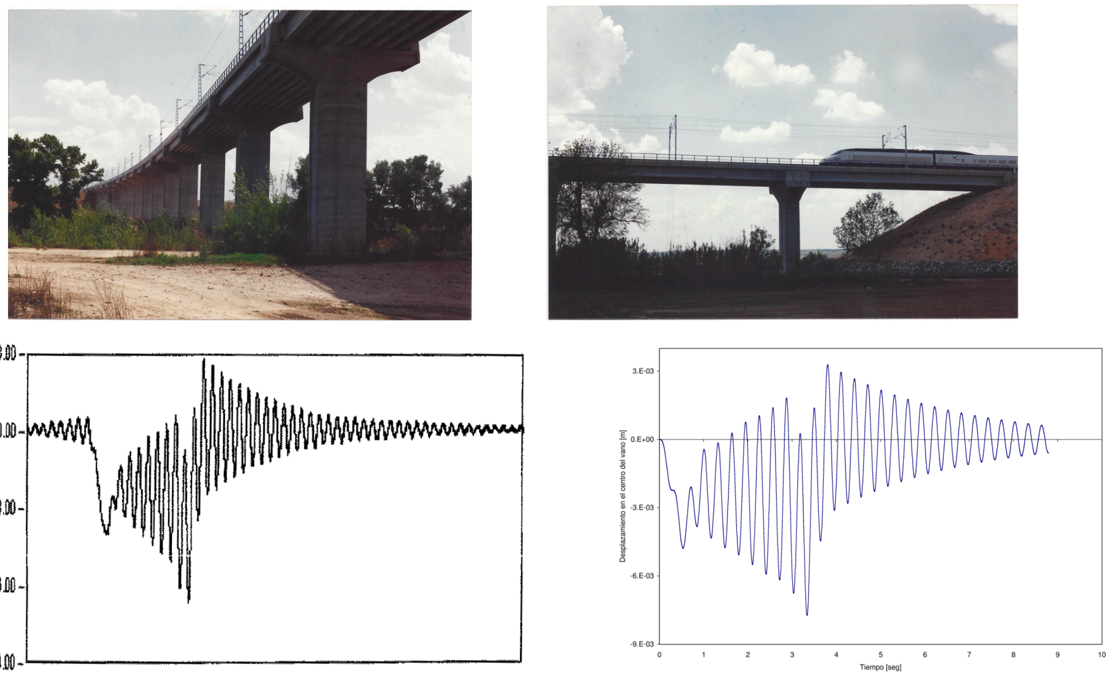

Figure 1. Tajo viaduct in Madrid-Sevilla high speed line 1992 (above), measured resonant response 1996 (below left) and computed response with dynamic analysis 1997 (below right).

The implications of the dynamic response for high speed railway bridges rarely lies on the resistance of the structure (Ultimate Limit State) but rather on serviceability conditions (Service Limit States) [20]. In fact, for the case shown in figure 1 the main problem was the loss of contact between pantograph and catenary. Serviceability requirements include not only comfort criteria, but also criteria for safety of traffic from excessive vibrations. As such, The high relevance of these service limit states is that they are actually ultimate states for the traffic and life of passengers.

In this short paper we first review the state of knowledge related to dynamic analysis for traffic actions on railway bridges, discussing the main advances and available methods. Following, we focus on some key topics related to advanced and also to practical use of dynamic analysis. We will also discuss considerations stemming from both the rolling stock (trains) and the infrastructure (bridges), some of them resulting from a current European Horizon research program InBridge4EU. We then review the open points and research directions for future work. We end summarizing some concluding remarks.

2. State of the Art and Key Challenges

Generally the key requirements for bridge engineers are based on static response, hence the provisions in codes are based on static load models. For railway traffic the main model is LM71 required in Eurocode [3], which actually represents loads 3-4 times larger than those in real passenger trains. These must be multiplied by impact factors (such as $\Phi_2, \varphi', \varphi''$ in [3]). This approach provides a significant margin, but is not sufficient for the large amplifications caused by resonance. As a result, dynamic analysis methods must be applied in certain scenarios with speeds above 200 km/h. The basic vertical dynamic response may be represented by classical linear structural dynamic models with moving loads [1, 6], represented schematically in figure 2.

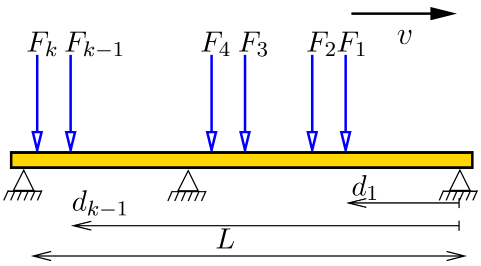

Figure 2. Schematic representation of moving load dynamic model for a bridge beam model.

More realistic and complex dynamic models consider coupled Vehicle-Bridge interaction (VBI). In general, the consideration of interaction with vehicles will allow part of the energy of vibration of the bridge to be transferred to the vehicles, and consequently will predict lower vibrations on the bridge. Vehicle subsystems may be generally considered as rigid bodies, with masses for wheelsets m_w, bogies m_b and vehicle box m_c, and concentrated springs and dampers, as shown in figure 3. Models for vertical dynamics may include only vertical translation degrees of freedom and pitch rotations for vehicle body or bogies. Complete 3D problems include all the rotations and should be handled with general multibody models, either linear or nonlinear, as described e.g. in [2, 6, 8, 11, 12, 13, 14, 15, 19].

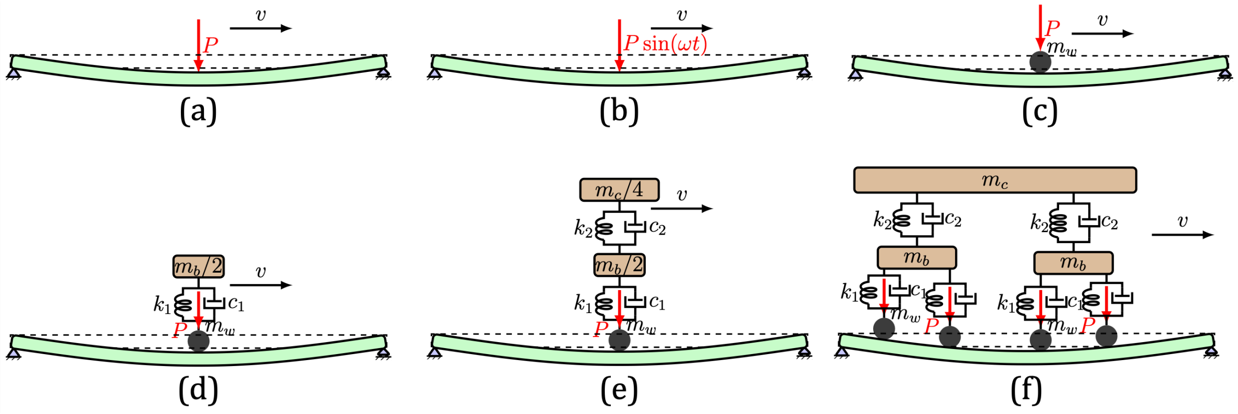

Figure 3. Vehicle-Bridge Interaction (VBI) models for vertical dynamics: (a) moving loads, (b) moving harmonic loads, (c) unsprung moving mass (wheel axles), (d) simplified model of primary suspension (half bogie), (e) simplified model of primary and secondary suspension (quarter vehicle), (f) full vehicle model.

A key requirement is the limit for vertical accelerations of the bridge deck. For design, in a bridge deck with ballasted track this is $a_{max} \leq 3.5$ m/s^2 [4], in order to avoid risk of destabilization of the ballast and unacceptable safety risks to the railway traffic.. For unballasted track bridges the limit is set to 5 m/s^2. For existing bridges higher values are generally accepted, such as 5 m/s^2 service limit for existing ballasted tracks [10]. High levels of acceleration are generally observed in simple short span bridges, due to two reasons: the low overall mass of the bridge, and the fact that the resonant action of the axles (bogies) may be more pronounced for span lengths shorter than the vehicles. However, recent published research has put in doubt the requirement of 5 m/s^2 for safety of traffic on non-ballasted track [16]

A simple and useful alternative for evaluating dynamic response are the so called *spectral methods*. These rely on the fact that for simply supported bridges the analysis may be based only on the first fundamental mode, and as a result the overall response consists in a sum of damped harmonics. Each load will result in a damped harmonic term after leaving the bridge. Accepting some simplifications it is possible to obtain closed form scalar bounds of this series of harmonics. Such is the base of the methods developed in [22, 23] and included in new codes [3]. More details may be found in [21, 25]. The assumptions for these methods are:

- Simply supported bridges under moving loads;
- Only the first (fundamental) mode is considered;
- Some terms are neglected which are small with respect to resonant vibration response.

Following we describe the Residual Influence Line (LIR) model, which considers the residual free vibrations as each axle exits the bridge. The forced terms when the load is on the bridge are neglected, which is a reasonable assumption for resonance in short bridges. For a bridge with mass M, span L and fundamental frequency f_0,the expressions for the maximum acceleration Γ at the center are given by:

$$\Gamma = C_{\text{accel}}\, A(\alpha)\, G(\lambda)\,, \quad \text{with } C_{\text{accel}} = {}^{1}\!/_{M}\,,$$
$$A(\alpha) = \frac{\alpha}{1-\alpha^2}\sqrt{\mathrm{e}^{-2\zeta\pi/\alpha} + 1 + 2\cos\left(\frac{\pi}{\alpha}\right)\mathrm{e}^{-\zeta\pi/\alpha}}\,, \tag{1}$$
$$G(\lambda,\zeta) = \max_{i=1..N}\sqrt{\left[\sum_{x_1}^{x_i} P_i\cos(2\pi\delta_i)\mathrm{e}^{-2\zeta\pi\delta_i}\right]^2 + \left[\sum_{x_1}^{x_i} P_i\sin(2\pi\delta_i)\,\mathrm{e}^{-2\zeta\pi\delta_i}\right]^2}\,,$$

Where the *wavelength* is defined as $\lambda = v/f_0$, being v the train speed, and the non-dimensional speed parameter is $\alpha = \lambda/2L$. Further, ζ is the critical damping ratio, P_i are the axle loads and $\delta_i = (x_i - x_1)/\lambda$ are the non-dimensional coordinates of each axle within the train.

The LIR result in equations (1) is expressed as the product of three terms: 1) a constant C_{accel}; 2) a function $A(\alpha)$ which does not depend on the train and may be interpreted as a *dynamic influence line of the bridge*; and 3) the *train spectrum* function $G(\lambda,\zeta)$, which only depends on the characteristics of the axle load sequence and the bridge damping ratio ζ. This spectral model allows to obtain the amplitude of vibration without an explicit dynamic analysis, requiring only an algebraic evaluation of equations (1). The results are approximate may not be strictly an upper bound for non-resonant cases, but they generally provide a reasonably tight upper bound for resonant cases, which are in fact the critical design scenarios. Furthermore, from the *train spectrum,* the *dynamic signature* of the train may be derived assuming zero damping, i.e. $S_0(\lambda) = G(\lambda, 0)$. This train signature function depends solely on the train axle loads and distances and is very useful for preliminary evaluations and comparison of the dynamic effects of trains on bridges.

A useful application of spectral / signature methods is shown from recent work in the InBridge4EU project, where a large database of existing trains in Europe has been compiled [24, 25]. The signatures for the different types of trains are represented in figure 4 [24, 25]. Here they are compared to the current High Speed Load Model (HSLM) envelope which is currently considered in European regulations, having been defined some 30 years ago. Following common practice [3] the passenger trains are classified as conventional bogies (CB) with two bogies under each coach; Articulated bogies (AB) with just one bogie between each 2 coaches; and single axle (SA) without bogies and one special axle between coaches. As shown in figure 4 a number of trains exceed the HSLM envelope in different segments of the wavelength spectrum, which justifies discussion on a potential update for the current HSLM.

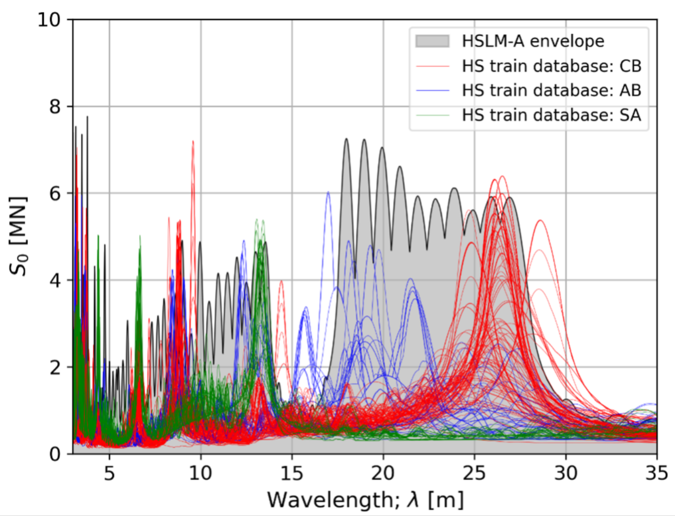

Figure 4. Compilation of train signatures from InBridge4EU rolling stock database compared to current HSLM envelope [ref: InBridge4EU D1.2].

As was reported in a study of the European Railway Research Institute [5] resonant lateral dynamic effects which compromised the traffic safety were noticed in several European bridges. Generally, these bridges had open steel decks and very low lateral bending stiffness and were simply supported. Lateral dynamics are of high relevance as large amplitudes have important safety implications for derailment. From the conclusions obtained in this study limitations of the lateral deformability and frequency were adopted in the Eurocodes [4]. These include a requirement for minimum lateral frequency of viaducts $f_{0,\text{lateral}} \geq 1{,}2$ Hz. Due to the orography of the Iberian Peninsula, often the railway lines have to cross deep valleys and need long viaducts. Usually these viaducts are supported on very tall piers or arches, sometimes taller than 100 m, and have continuous decks which can be longer than 1000 m. Due to that, these structures are very flexible and their first lateral vibrations frequencies are very low, below the required limit, due to which specific dynamic analyses have been carried out [14, 15]. However, it must be said that this limitation of $f_{0,\text{lateral}}$ has been recently put in doubt in a recent publication [17].

3. Core Themes and Insights

As vertical dynamics may be assumed with linear response, modal analysis techniques are perfectly adequate. The more basic and efficient models may be achieved by obtaining first analytical expressions of the modes of vibration, which is feasible for beam models of simply supported and also redundant structures of different types, and then solving the modal equations in time. This may be done with time-stepping calculations or other methods such as Duhamel's integral. They can also be extended for interaction with train vehicle dynamics. In figure 5 the schematic functions of one such program is shown [18].

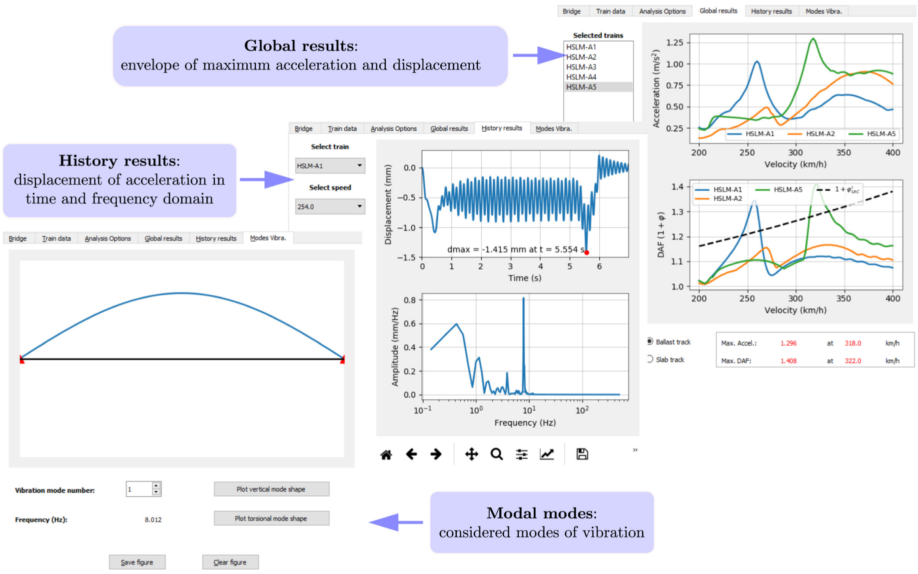

Figure 5..Semi-analytical fast calculations based on modal analysis with beam models (CALDINTAV) [18].

However, beam-type models even including torsion may fail to include some modes of vibration which appear in structures and may be obtained in more detailed 3D Finite Element (FE) models. A relevant example is shown in figure 6, for a simple bridge with a common structural typology of reinforced concrete slab on prestressed I-type beams. Bending and torsional modes correspond approximately with some differences, but a bulging mode with significant response is obtained in the FE 3D model and cannot be represented in beam models. However, many other structural types are represented well without such flaws by beam-type models.

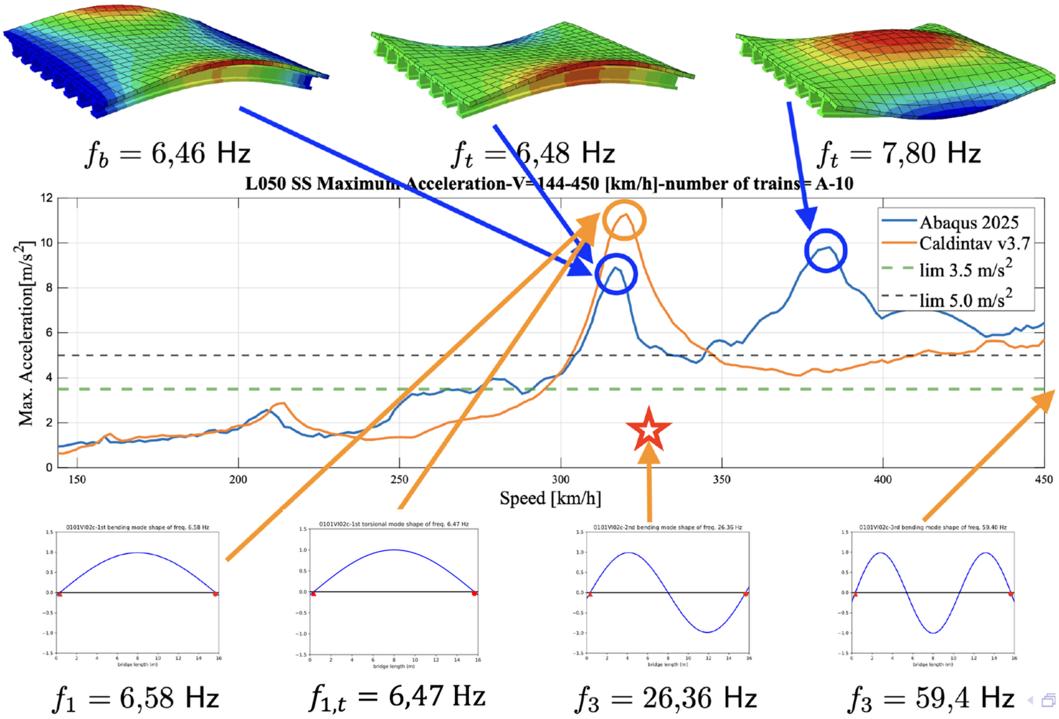

Figure 6..Comparison of results between fast beam-type models and Finite element full 3D models

For considering coupled VBI, Multibody Systems (MBS) models provide an accurate description of railway vehicle response, including both vertical and lateral dynamics, and may be coupled with structural Finite Element models for obtaining vertical and/or lateral dynamic response. In the case of lateral dynamics, when subject to actions originating from wind, earthquake or even the track itself such advanced coupled models are needed. MBS methods establish the dynamic equations for rigid bodies which are connected between them with discrete spring and dampers and joints and/or constraints. A key point in the dynamic interaction between railway vehicles and structures is to establish the geometric, kinematic and dynamic relationships between both subsystems, through adequate wheel-rail contact theories (figure 7). [2, 8, 14, 15, 19].

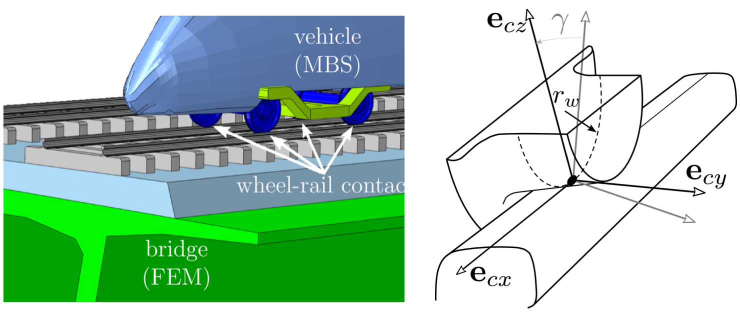

Figure 7. Vehicle-Bridge Interaction for lateral dynamics, with general scheme and contact between the wheel and the rail

Within European project InBridge4EU a large database of bridges has been compiled and subject to a detailed assessment of dynamic performance, including 522 bridges from 11 railway lines of different types in 5 countries [27, 28], see figure 8. For these bridges systematic dynamic calculations have been performed, both using fast beam-type models as discussed above, and more detailed 3D FE models for selected cases more sensitive to dynamics. These systematic assessments yielded 39 bridges which did not comply with vibration limits for European interoperable traffic. These non-compliant bridges were mainly with filler beam decks, also a few solid slab decks, for which suitable reinforcement or even replacement strategies were designed and evaluated. Figure 8 shows some of the structural types considered, in this case limited to double track bridges in Spanish high speed lines which did comply with vibration requirements.

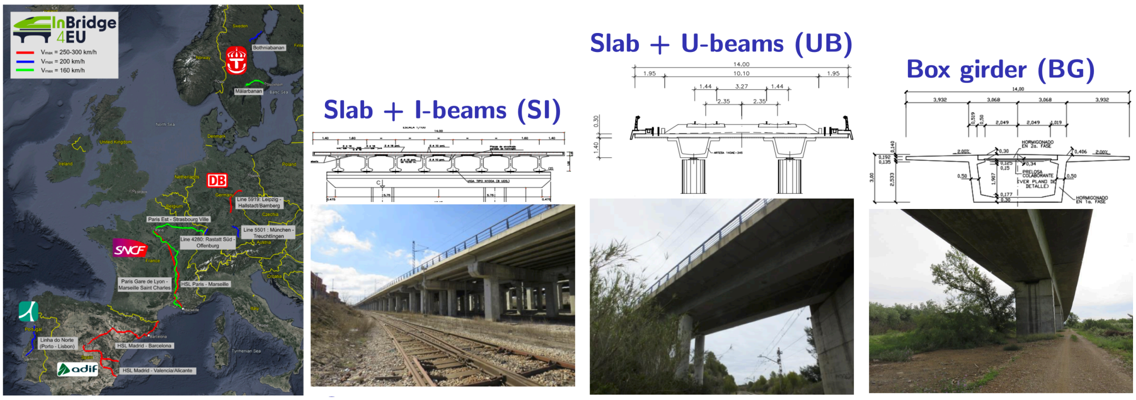

Figure 8. European railway lines studied for InBridge4EU project (left); Some typical structural types for double track bridges subject to detailed studies (right).

4. Implications and Future Directions

Following the above discussion, railway bridge dynamics is a relevant issue, requiring more in depth calculations and considerations as compared to traditional static analysis of civil engineering structures. Its importance lies firstly on the proper design of new bridges but also on adequate assessment of existing bridges. Furthermore, interoperability between different national networks is highly desirable for fostering economic development as well as social and cultural collaboration and exchanges. Finally, the compatibility with all possible rolling stock provides great freedom and economic advantages for citizen service and investments in train purchases. In Europe during the past 30+ years a number of important efforts have been made for research, innovation and common regulations for railway infrastructure, and in particular bridges. However there are still relevant open points and areas where further research in needed.

With the aim of improving engineering codes and specifications the following short list of research topics may be drawn.

- Serviceability requirements for railway bridges [3, 4]
    - (safety) vertical acceleration limits for ballasted / non-ballasted track (3,5 m/s^2, 5 m/s^2), especially those for non-ballasted track.
    - (safety) lateral vibration / deflection limits, specifically the $f_{0,\text{lateral}} \geq 1{,}2$ Hz limit
    - (comfort) criteria for passenger comfort, currently specified for achieving maximum passenger vibration $a_{\text{passenger}} \leq 1\ \text{m/s}^2$, which should be better based on EN 12299:2024 from CEN/TC256, with mean comfort indices leading to simple requirements for bridge design/assessment.
- Dynamic response to traffic actions ([3], Technical Specifications for Interoperability – Infrastructure subsystem)
    - Apply adjustable Dynamic Train Categories (DTC's) [26] graduated and adjustable/restricted to specific traffic if desired, in [3] and Technical Specifications for Interoperability – Infrastructure subsystem Annex E. These train models should complement or replace the current High Speed Load Model HSLM. Furthermore, they should include provisions for existing bridges.
    - Further research on dynamic factors $\Phi_2, \varphi', \varphi''$ (Annex C of [3])
    - Improved guidance for dynamic analysis, including train-bridge interaction ([3], new CEN Technical Specification)
    - Improved guidance and criteria for safe damping values in bridges, based on initial results from InBridge4EU [29]
    - Combination of dynamic effects for traffic, wind and earthquake [14, 15].

5. Conclusion

As a result of the above, the following concluding remarks may be stated.

- For the infrastructure of railways, and specially high speed passenger traffic, it is essential to consider dynamic effects from traffic actions, and specially for bridges.
- Dynamic effects are relevant for the design and construction of new bridges. They are also significant for existing bridges, related to their assessment, studying the compatibility with new traffic, or enabling the interoperability of networks.
- A range of methods is available for dynamic analysis with different level of complexity and reliability. These cover spectral / train signature methods, dynamic analysis with moving loads on beam models or on detailed FE models, or coupled VBI analyses. For lateral dynamics additional consideration is needed for wheel-rail contact and possible derailment. Furthermore, experimental measures may be needed for validation, assessment or maintenance of infrastructure.
- It is essential to cover the dynamic effects in the engineering codes and regulations with adequate clauses and requirements. These must be practical, reasonable, and achieve consensus from stakeholders (academy, industry, administration).
- Further research is still of key importance, even if substantial progress in knowledge has been developed in the last years. It is important also to share and discuss at international forums.

Acknowledgements

Some of the work reported has received funding from the Europe’s Rail Joint Undertaking under Horizon Europe research and innovation programme, InBridge4EU grant agreement No. 101121765 (HORIZON-ER-JU-2022-ExplR-02). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Europe’s Rail Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

References

[1] J.M. Goicolea, F. Gabaldon (2011). Dynamics of high-speed railway bridges: methods and design issues. in Bridge Vibration and Controls: New Research, H. , Xia, G. de Roeck, and J. M. Goicolea, Eds. CRC, ISBN: 978-1-62100-868-2

[2] H. Xia, K. Wang and Z. Yu (2011). Dynamic Interaction Analysis Of Coupled Train-Bridge System. in Bridge Vibration and Controls: New Research, H. , Xia, G. de Roeck, and J. M. Goicolea, Eds. CRC, ISBN: 978-1-62100-868-2

[3] CEN/TC250 Structural Eurocodes (2024), “EN_1991-2: Actions on structures - Part 2: Traffic loads on bridges and other civil engineering works,”.

[4] CEN/TC250 Structural Eurocodes (2024), “EN_1990-1 Eurocode - Bases for structural and geotechnical design + Annex A2 Application for bridges,”.

[5] ERRI Specialists Committee D181 (1995), “Lateral Forces on Railway Bridges ERRI D181/RP6,” Utrecht, 1995.

[6] J. M. Goicolea and P. Antolin (2012), “The Dynamics of High-Speed Railway Bridges: A Review of Design Issues and New Research for Lateral Dynamics,” International Journal of Railway Technology, vol. 1, no. 1.

[7] P. A. Montenegro et al. (2021), “Assessment of train running safety on bridges: A literature review,” Engineering Structures, vol. 241.

[8] W. Zhai et al (2019), “Train–track–bridge dynamic interaction: a state-of-the-art review,” Vehicle System Dynamics, vol. 57, no. 7.

[9] N. Zhang, H. Xia, and W. Guo (2008), “Vehicle–bridge interaction analysis under high-speed trains,” Journal of Sound and Vibration, vol. 309, no. 3–5.

[10] H. Xia, N. Zhang, and G. de Roeck (2003), “Dynamic analysis of high speed railway bridge under articulated trains,” Computers & Structures, vol. 81, no. 26–27.

[11] M. Tanabe et al (2011), “An efficient numerical model for dynamic interaction of high speed train and railway structure including post-derailment during an earthquake,” in Proceedings of the 8th International Conference on Structural Dynamics, EURODYN 2011.

[12] P. Antolín et al (2013), “Consideration of nonlinear wheel-rail contact forces for dynamic vehicle-bridge interaction in high-speed railways,” Journal of Sound and Vibration, vol. 332, no. 5.

[13] P. Antolín, J. M. Goicolea, and M. A. Astiz (2011). “Strategies for Modeling Train-Bridge Lateral Dynamic Interaction,” in Bridge Vibration and Controls: New Research, H. , Xia, G. de Roeck, and J. M. Goicolea, Eds. CRC, , ISBN: 978-1-62100-868-2.

[14] P. A. Montenegro et al. (2022), “Impact of the train-track-bridge system characteristics in the runnability of high-speed trains against crosswinds - Part I: Running safety,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 224.

[15] P. A. Montenegro et al. (2022), “Impact of the train-track-bridge system characteristics in the runnability of high-speed trains against crosswinds - Part II: Riding comfort,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 224.

[16] G Ferreira et al (2024), Critical analysis of the current Eurocode deck accelerGonçalo Ferreira et al, Eng Struct.

[17] M.A. Peixer et al (2026), Reassessing eurocode’s lateral vibration criteria for railway bridges, Eng Struct

[18] K Nguyen and J.M. Goicolea (2024), CALDINTAV: A simple software for dynamic analysis of high-speed railway bridges using the semi-analytical modal method, Software Impacts

[19] P. Antolin, K. Nguyen and J.M. Goicolea (2026), A General and Robust 3D Finite Element Dynamics Framework for Railway Vehicle–Bridge Interaction with Nonlinear Wheel–Rail Contact Modeling, P. Antolin, K. Nguyen and J.M. Goicolea, accepted for publication in Railway Engineering Science.

[20] J. Nasarre (2009). Serviceability limit states in relation to the track in railway bridges. In R. Calçada et al (eds), Bridges for High-Speed Railways: 211-220. London: Taylor & Francis.

[21] J Domínguez Barbero (2001). “Dinámica de puentes de ferrocarril para alta velocidad: métodos de cálculo y estudio de la resonancia”. PhD thesis (in Spanish), Technical University of Madrid. Available online http://oa.upm.es/1311/

[22] ERRI - European Railway Research Institute (1998). ERRI committee D214 final report: “Design of Railway Bridges for Speed up to 350 km/h; Dynamic loading effects including resonance”. Utrecht, The Netherlands.

[23] JP Tartary and N Jobert (2000). “Recherche du train universel pour calculs dynamics”. Report for ERRI D214 committee, A.V.L.S..

[24] InBridge4EU (2025). Database of rolling stock and definition of critical parameters. Report D1.1. by University Of Huddersfield. Europe’s-Rail Europe’s Rail Joint Undertaking under Horizon Europe research and innovation programme

[25] InBridge4EU (2026). Limitations of DER/LIR and improved Spectral Methods Report D1.2. by Universitat Politecnica de Valencia. Europe’s-Rail Europe’s Rail Joint Undertaking under Horizon Europe research and innovation programme

[26] InBridge4EU (2026). Dynamic Train Categories (DTCs). Report D1.3. by Universidad Politécnica de Madrid. Europe’s-Rail Europe’s Rail Joint Undertaking under Horizon Europe research and innovation programme

[27] InBridge4EU (2025). Bridge database. Report D2.1. by Universidad de Sevilla. Europe’s-Rail Europe’s Rail Joint Undertaking under Horizon Europe research and innovation programme

[28] InBridge4EU (2026). Worst-case combination of critical parameters of existing bridges. Report D2.2. by Universidad de Sevilla. Europe’s-Rail Europe’s Rail Joint Undertaking under Horizon Europe research and innovation programme

[29] InBridge4EU (2025). Revision of damping in railway bridges. Report D4.1. by University Of Porto. Europe’s-Rail Europe’s Rail Joint Undertaking under Horizon Europe research and innovation programme