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High-Speed Passenger Train Load Model PT60: A Wide-Ranging Dynamic Excitation Source for the Assessment of Railway Bridge Analysis Methods in Moving Load Problems.

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Abstract

This work presents the PT60 model, a reduced and representative passenger-train load model for the dynamic assessment of railway bridges. The model comprises 60 passenger trains selected from a broader database of real and synthetic configurations, including conventional, articulated, regular, loco-hauled, and intermediate-power-car arrangements. The selection was aimed at preserving the main dynamic effects of the complete database while reducing redundancy among dynamically similar vehicles. Therefore, trains with relevant axle-spacing patterns, car-body lengths, axle-load distributions, total train lengths, and strong dynamic signatures were retained. The ten HSLM-A trains were also included to provide a direct link with the European normative framework. The PT60 ensemble is organised from nearly periodic train configurations to increasingly irregular geometries, allowing the progressive representation of resonance-dominated responses as well as transient effects caused by non-perfectly repetitive axle distances. Its dynamic behaviour was evaluated through response and exceedance maps, using a semi-analytical formulation as reference and the Residual Influence Line (LIR) method as a simplified approach. The results, obtained within the framework of the ERJU project InBridge4EU, show that PT60 provides a compact basis for identifying critical resonance conditions and comparing train-induced dynamic effects in railway bridges.

Keywords: railway bridges, moving loads, train subtypes, response and exceedance maps, regular trains, articulated trains, conventional trains.

1 Introduction

The growth of high-speed railway networks has increased the demand for effective and reliable procedures to assess the dynamic behaviour of railway bridges [1-3]. In this context, train-induced vibrations play a central role in bridge design and assessment. In Europe, the dynamic evaluation of railway bridges is commonly carried out in accordance with EN 1991-2, which defines traffic load models and verification criteria, including the High-Speed Load Model A (HSLM-A). Although normative load models provide a practical framework for engineering assessment, they cannot always reproduce the full variability of real or future rolling stock. Real trains may differ from normative models in terms of axle spacing, axle-load distribution, coach length, symmetry, and repetition patterns [4]. These differences may lead to distinct resonance conditions.

In this field, a load model can be understood as an ensemble of several trains intended to represent the dynamic effects of a broader population of vehicles. Museros et al. [5] first assessed the degree of coverage provided by HSLM-A for critical articulated trains, focusing on simply supported (SS) railway bridges. They developed a simplified train-signature formulation incorporating the bogie factor and combined it with time-integration analyses to identify both conservative and non-covered cases. In the same direction, Museros et al. [6] extended this framework to conventional and regular high-speed trains by synthesizing seven realistic load models comprising almost 3800 axle-load sequences.

Recent European research has further highlighted the need to consider a wider diversity of train configurations. In particular, the available database used in this work was inherited from previous projects, including In2Track2 [7], and complemented with the database received from the DZSF project. In addition, the ERA Technical Note considers passenger trains with maximum operating speeds greater than 160 km/h as relevant excitation sources for railway bridges, including articulated, conventional, and regular trains, as well as multiple-unit configurations and different power-car arrangements.

However, when large databases of real or synthetic trains are available, the main challenge is not simply to include a larger number of trains in the dynamic assessment. Many trains may be dynamically similar, with only small variations in axle spacing or axle loads. Consequently, a large database may introduce redundancy and increase computational effort without necessarily improving the representativeness of the assessment. This creates the need for a reduced but well-selected set of trains capable of preserving the critical dynamic effects of the complete database. To address this need, the present contribution proposes the PT60 model, which has been developed in the frame of the InBridge4EU project. The model condenses 280 selected passenger-trains into a representative set of 60 trains. The resulting PT60 model aims to retain key dynamic effects associated with axle-spacing variability, axle-load distribution, train symmetry and asymmetry, and resonance conditions.

2 PT60 model

The PT60 model is proposed as a reduced and representative passenger-train load model for the dynamic assessment of railway bridges. It consists of 60 trains that include three train types: conventional bogie trains (CB), articulated bogie trains (AB), and regular trains with single axles (SA), and this model has been published in the database reported in [8]. Since the initial database was predominantly composed of conventional passenger trains, this characteristic is also reflected in the final composition of PT60. Furthermore, the model covers a wide range of:

- car-body lengths
- axle-spacing patterns
- axle-load distributions
- train lengths, and
- power-car configurations.

In particular, the model includes both short and long trains, highly regular and strongly irregular axle-distance patterns, and different loco-hauled arrangements. Moreover, the ten HSLM-A trains are also included in the PT60 model.

A key aspect of the PT60 model is the coverage of car-body length, denoted as D. The selected trains span a broad interval of D values, which is relevant because the characteristic spacing of repeated axle groups controls the main resonance and sub-resonance conditions induced in railway bridges. In this sense, the train set was designed to cover the wavelength (λ) ranges where passenger trains may generate critical dynamic amplification.

The selection process followed a hybrid strategy combining algorithmic pre-classification and manual verification. First, the available trains were grouped according to their geometric and loading characteristics. Then, trains with similar axle-distance patterns and dynamic signatures were compared, retaining those that produced stronger or more representative responses. This manual verification stage was included to ensure that no train with genuinely distinctive geometric or dynamic features was inadvertently excluded from the final set.
The PT60 trains were further organised into subtypes, which are intended to provide information about the type of bridge response that can be expected from each train. One subtype, referred to as repetitive pattern (RP), is common to the three train types. The remaining subtype denominations are specific to CB, AB, or SA trains, and reflect the geometric features of each family:

Regular trains:

- **RP:** Stands for “repetitive pattern”, which refers to a train subtype where the pattern of all axle distances (including power cars, if those are present) shows perfect periodicity.
- **RLH-2fL:** Regular loco-hauled with two front locomotives.
- **RLH-3rL:** Regular loco-hauled with three rear locomotives.

- **RLH-bL:** Regular loco-hauled with both one front and one rear locomotives.
- **RLH-sCbL:** Regular loco-hauled with both one front and one rear locomotive.
- **RLH-2fLrL:** Regular loco-hauled with two front locomotives and one rear locomotive.
- **CRLH-mL:** Double unit with multiple locomotives (two RLH-bL units coupled).

Articulated trains:

- **ART:** articulated trains nearly equal to AB, RP trains.
- **CART:** coupled articulated units, where intermediate distances differ from the RP pattern.
- **CART-2-ART:** Coupled articulated units: two ARTs.
- **ALH:** articulated loco-hauled trains that have conventional CB power cars in both ends, not heavier than 15% of the average of the adjacent loads.
- **CALH-2-ALH:** Coupled articulated loco-hauled: two ALHs.
- **ALH-fLL:** Articulated loco-hauled with one front light locomotive.

Conventional trains:

- **MU:** Multiple units.
- **CMU:** Coupled multiple units.
- **CMU-2-RP:** Coupled multiple units: two RPs.
- **LH-fHL:** Loco-hauled with one front heavy locomotive.
- **LH-rHL:** Loco-hauled with one rear heavy locomotive.
- **LH-bHL:** loco-hauled with both one front and one rear heavy locomotive.
- **LH-fHLrLL:** Loco-hauled with one front heavy locomotive and one rear light locomotive.
- **CLH-bHL:** coupled loco-hauled units, with both one front and one rear heavy locomotive.
- **CLH-mHL:** coupled loco-hauled units, where all units have both one front and one rear heavy locomotive.
- **Irregular:** coupled loco-hauled units, where locomotives are multiple, but the front and/or rear ends of the train do not have any power car.

In the PT60 model, the first trains of the model represent highly repetitive patterns, whereas subsequent trains progressively introduce geometric irregularities, variations in axle spacing, and different power-car configurations. Representative examples of regular, articulated, and conventional trains included in PT60 are shown in Figures 2–4.

3 Methods

The methodology adopted uses exact and simplify methods for the dynamic assessment of SS railway bridges under the PT60 model. The first one is a semi-analytical formulation, and the second one is the LIR method, as described below.

3.1 Semi-analytical method

The dynamic response of SS railway bridges under moving loads was evaluated using a semi-analytic time-domain approach, as detailed in [9]. The bridge was modelled as a Bernoulli–Euler beam, and its dynamic behaviour was represented through modal superposition. Moving axle loads were idealized as concentrated forces travelling at constant speed along the bridge span, as shown in Figure 1. This study was focused on the fundamental shape mode. However, the formulation is prepared to use the equivalent modal load, expressed analytically, for the i-th mode shape. The procedure was implemented through *ad hoc* MATLAB codes over a wide range of train speeds.

3.2 LIR method

The LIR method (Residual Influence Line) is a simplified approach for estimating accelerations in SS beams under the passage of trains. Originating from the ERRI D214 report RP6 (ERRI D214 1999), the method calculates the superposition of phase-shifted free vibrations generated by each axle of the train as it leaves the bridge.

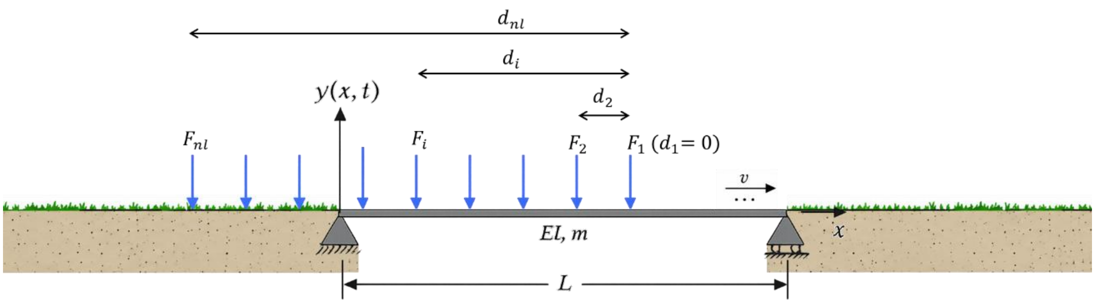


Figure 1: One-span bridge.

This method uses the classical closed-form solution for the temporal response of the SS bridge. Once the point load leaves the bridge, i.e., at the instant $t = L/v$, where L is the bridge length and v is the velocity of a single point load, the bridge enters free vibration. The result of this approach for practical values of damping ratio ζ is given in Equation (2). m represents the linear mass of the beam, and K is the nondimensional speed, which is the ratio between the excitation frequency and the natural frequency of the bridge.

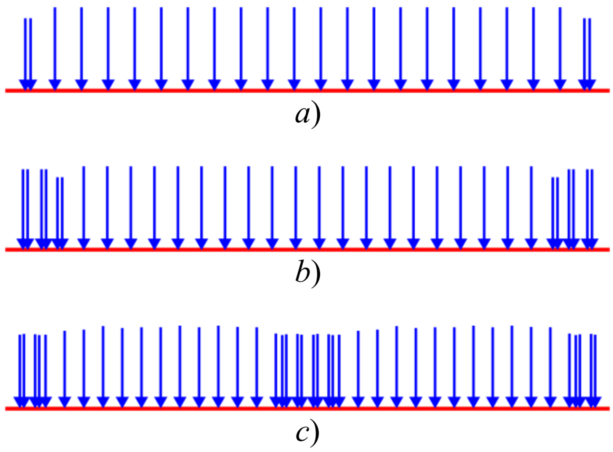


Figure 2: Regular trains: *a*) PT60-01, *b*) PT60-48 and *c*) PT60-57.

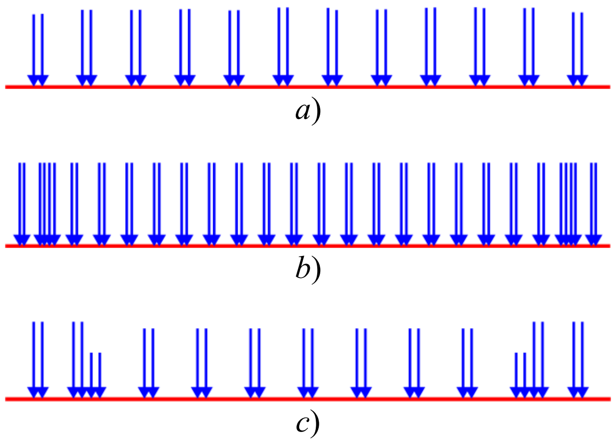


Figure 3: Articulated trains: *a*) PT60-02, *b*) PT60-29 and *c*) PT60-52.

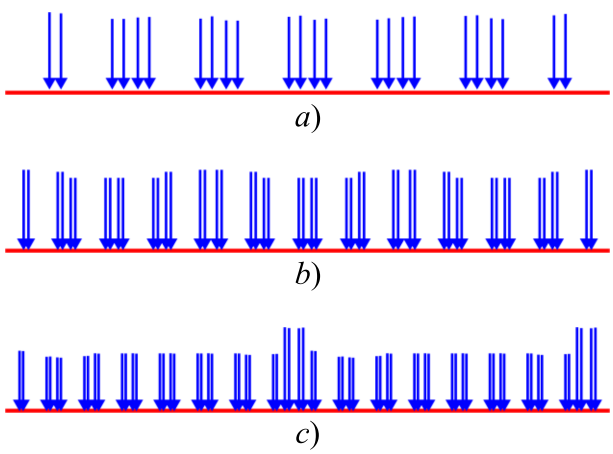


Figure 4: Conventionals trains: *a*) PT60-03, *b*) PT60-20 and *c*) PT60-60.

By amplifying the LIR curve with the superposition effect of the load convoy characteristics, or signature (see Equation 3), the bridge acceleration can be estimated as defined in Equation (1). The (damped) signature is defined based on each load F_i, along with its respective position d_i, relative to the first load entering the bridge, see Figure 1. Furthermore, v and T refer to the velocity of the loads and the natural period, respectively, the product of which determines λ (Equation (4)).

$$a_{\max} = \Gamma_{\max} \cdot G \tag{1}$$

$$\Gamma_{\max} = \frac{1}{mL/2}\frac{K}{1-K^2}\sqrt{1 + e^{-2\zeta\pi/K} + 2\, e^{-\zeta\pi/K} \cos\left(\frac{\pi}{K}\right)} \tag{2}$$

$$G = \sqrt{\left(\sum_{i=1}^{k} F_i\theta_i \cos(2\pi\delta_i)\right)^2 + \left(\sum_{i=1}^{k} F_i\theta_i \sin(2\pi\delta_i)\right)^2} \tag{3}$$

Where:

$$\theta_i = e^{-2\pi\delta_i\zeta}$$
$$\delta_i = \frac{d_k - d_i}{\lambda} \tag{4}$$
$$\lambda = vT$$

4 Results

The results of the SS railway bridges under the PT60 model are presented in terms of response maps and exceedance maps. First, the maximum acceleration response of the complete PT60 set is compared with the individual contributions of regular, articulated, and conventional trains. Then, the influence of load-pattern regularity is analysed. Finally, the maximum response of two trains of the PT60 model is used to compare the LIR-based predictions with the semi-analytical reference solution, allowing the accuracy of the simplified approach to be assessed in terms of acceleration.

The maximum absolute acceleration response obtained for all trains included in the PT60 model is shown in Figure 5. The response map covers bridges with spans ranging from 4 to 40 m, together with a speed range from 50 to 400 km/h. Although high acceleration levels are observed, it should be noted that the figure represents the dynamic response, including resonance conditions, of hundreds of bridge spans subjected to the complete PT60 model over a wide range of train speeds.

Four translucent surfaces are also included in the figure to indicate selected λ values. In particular, λ = 6.5 m, 13.5 m, 18.0 m, and 28.5 m are highlighted because they are relevant for interpreting the main response patterns, as discussed in more detail in the following section. In addition, the solid and dashed red lines represent the first and second cancellation valleys, respectively, which are extended across the figure for *K* values of 0.33 and 0.20 [1].

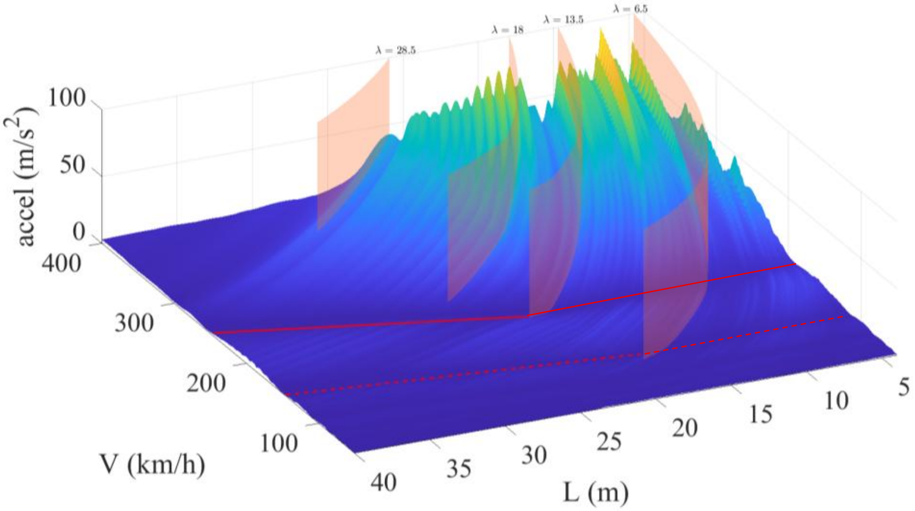
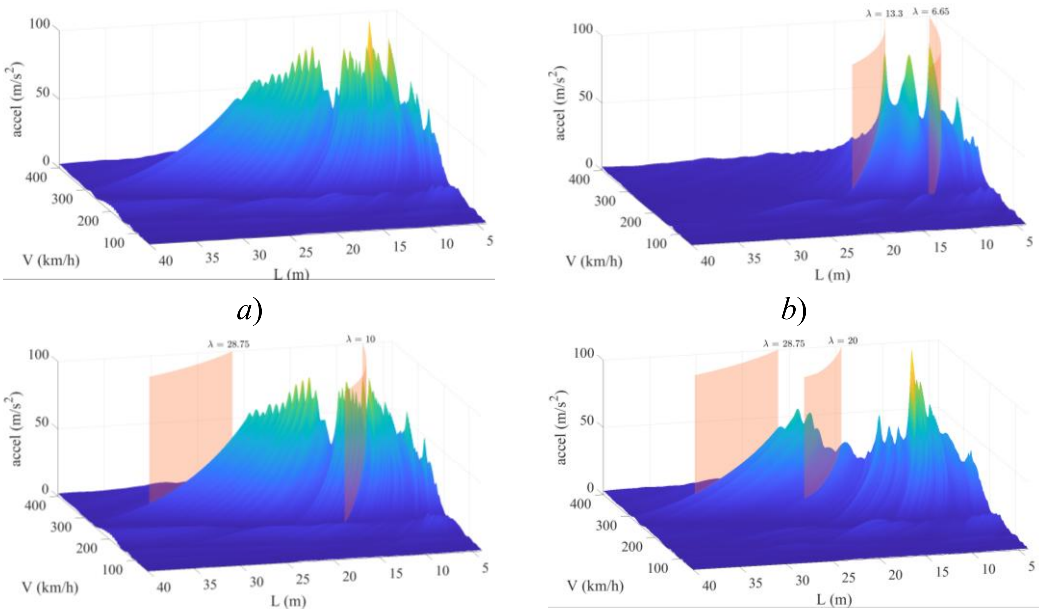


Figure 5: Response maps of the PT60 model.

4.1 Train types

Figure 6 shows the maximum acceleration response of the PT60 model (part a), deliberately repeated from Figure 5, together with the contributions to this response from the PT60 subgroups corresponding to regular trains (part b), articulated trains (part c), and conventional trains (part d). Regular trains have a characteristic length D of approximately 13.3 m, which generates resonances when $\lambda = D$, and second sub-harmonics for $\lambda = D/2$, as shown in Figure 6b. In addition, some higher-order sub-harmonics with lower response amplitudes can also be observed.



a) *b*) *c*) *d*)

Figure 6: Response maps of the PT60 model and internal train types: a) PT60 model, b) Regulars trains, c) Articulated trains and d) Conventionals trains.

The articulated trains included in PT60 have D values ranging from 10.0 m to 28.75 m. Therefore, the peaks located within this range correspond to first resonances, as shown in Figure 6c. Between λ = 13.5 m and λ = 18.0 m, a reduction in the response is observed due to the bogie-factor effect. Nevertheless, the second and higher-order sub-harmonics extend the resonance regions even below λ = 10 m.

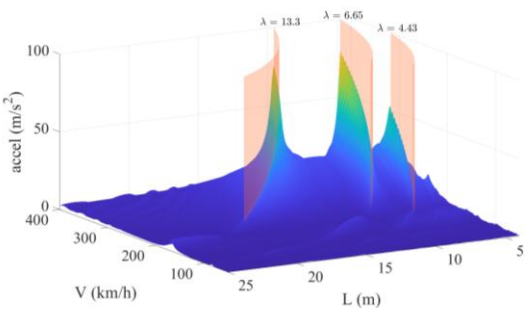
Conventional trains have D values ranging from 20.0 m to 28.75 m. The second subharmonics are generally attenuated by the bogie spacing within the same car, producing a low-response region that often overlaps with the second subharmonic of conventional train configurations.

4.2 Load pattern effects

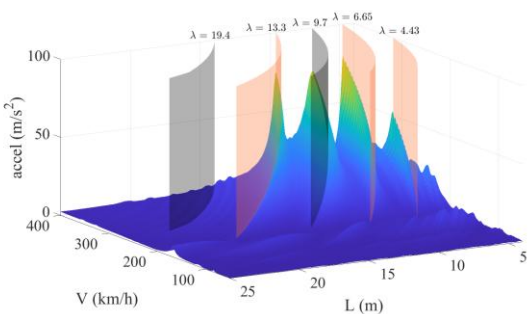
In the PT60 model, the trains are arranged from the most regular to the most irregular configurations. To highlight the differences between possible load patterns, two comparisons are developed below based on the subtypes of the model:

Figure 7a shows the response map of a regular train, specifically the most regular train in the PT60 model, PT60-01. In this case, the first resonance, as well as the second and third subharmonics, are clearly developed, as highlighted by the translucent surfaces.

In contrast, PT60-46, although also classified as a regular train and having a similar characteristic length, D, belongs to the RLH-3rL subtype, i.e., a regular loco-hauled train with three rear locomotives. This train exhibits a resonance at (λ = 9.7 m), which corresponds to the second subharmonic of the resonance induced by the series arrangement of the power-car lengths. However, the first resonance associated with this power-car effect is cancelled by the wheelbase distance. For this reason, this resonance is not observed on the grey surface located on the left-hand side of Figure 7b.



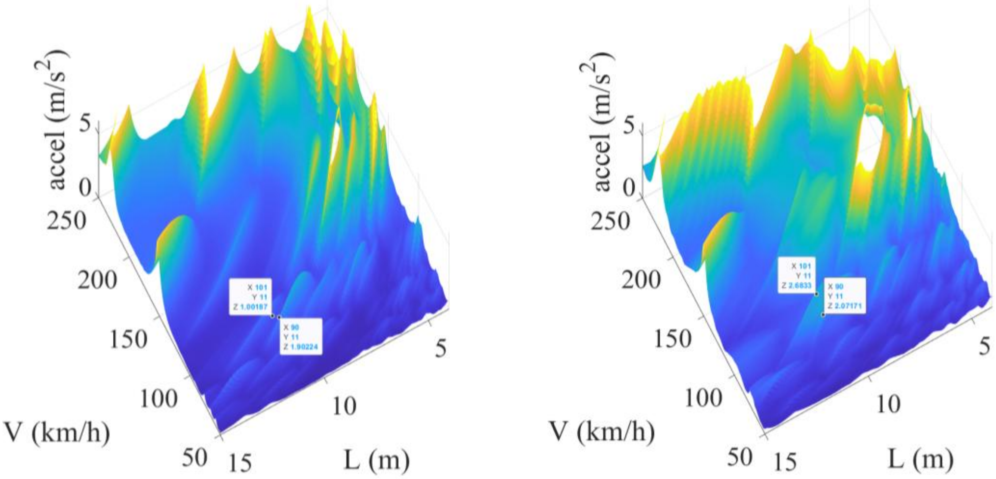
a)



b)

Figure 7: Response maps of the PT60 model for regular trains: a) PT60-01, b) PT60-46.

As shown in Figure 8a, train PT60-05, which belongs to the RP subtype, exhibits well-separated and clearly defined resonance ridges. For this train, a resonance peak can be observed for a bridge length of (L = 11 m) and a travelling speed of approximately (90 km/h). However, when the speed is slightly increased, this resonance rapidly vanishes. In contrast, Figure 8b shows the response map of train PT60-45, classified as LH-rHL, where a plateau is formed by closely spaced resonance ridges. This behaviour is mainly associated with the presence of a very heavy locomotive, which induces relevant transient effects. Therefore, by simply adding a rear locomotive to the train configuration, the dynamic response changes significantly. Although PT60-45 also shows a relevant response for (L = 11 m) and (90 km/h), increasing the speed to (101 km/h) does not suppress the resonance, as occurred for PT60-05. Instead, the response increases due to effects induced by the power car and its interaction with the rest of the train.

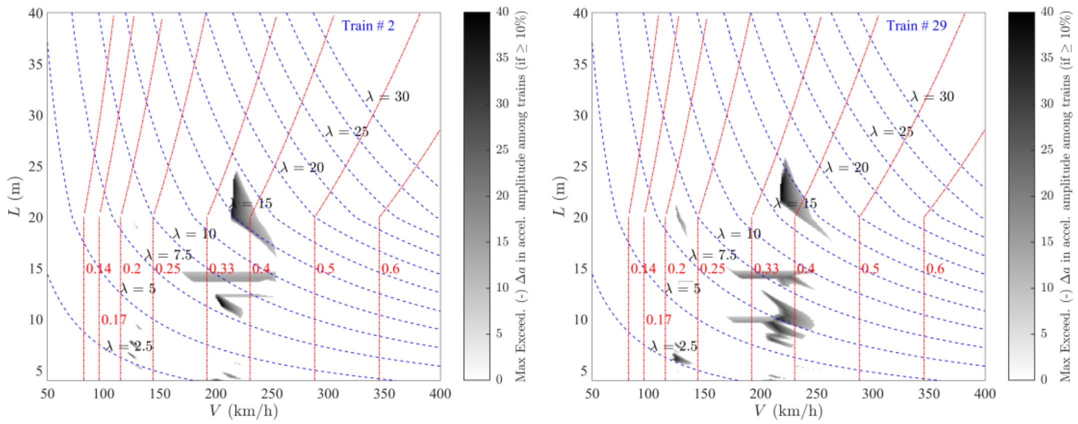


a) *b*)

Figure 8: Response maps of the PT60 model for conventional trains: a) PT60-05, b) PT60-45.

4.3 LIR vs semi analytical exceedance map of PT60 model

The PT60 model is not only useful for identifying the regions of maximum response associated with different train typologies, but its application also extends to different types of comparisons. For instance, this section presents the comparison between the maximum acceleration response of SS bridges obtained using the LIR method and that obtained from semi-analytical solution. The exceedance map shows the percentage error between both methods once it exceeds a threshold of 10% and the acceleration at the corresponding point (L, V) is greater than a prescribed threshold of 2.5 m/s², as shown in Figure 9. This map shows that, for the articulated train with the less regular load pattern, PT60-02, the discrepancy between the LIR method and the semi-analytical solution is smaller (gray areas). In contrast, this discrepancy increases for PT60-29 (articulated train), which exhibits a more irregular load pattern. This highlights the importance of assessing bridge dynamic response using a varied train set capable of generating different dynamic effects. Moreover, the K lines are shown as blue dashed lines, whereas the λ lines are represented by red dash-dot lines.



a) *b*)

Figure 9: Exceedance maps: *a*) PT60-02 train and *b*) PT60-29.

5 Conclusions and Contributions

Based on the analytical and numerical results obtained in the framework of the ERJU project InBridge4EU, the most relevant conclusions of this study are summarized below:

- The proposed PT60 train model provides a compact framework for analysing critical resonance conditions and comparing train-induced dynamic effects in railway bridges, covering regular, articulated, and conventional train typologies.
- The model comprises trains with increasing levels of complexity, ranging from regular train configurations to variants of loco-hauled trains.
- The response maps show that each train type contributes differently to the maximum acceleration response of the PT60 model.
- Regular trains produce clear resonance regions for wavelength close to their characteristic length D and its sub-harmonics. Also, resonance phenomena are induced when several power cars are connected in series.
- Conventional trains generate important responses in the third sub-harmonic region, including the maximum response observed in the PT60 model.
- The comparison between train groups shows that more regular load patterns produce clearer and sharper, better defined resonance ridges.
- When trains with more irregular geometries are analyzed, wider ridges frequently appear, together with additional secondary ridges grouped into dense clusters.
- The trains included in the PT60 model should be used to compare calculation methods, since simplified approaches remain highly relevant and applicable, particularly for the analysis of large railway networks.

Acknowledgements

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