



ASSESSMENT OF PERMISSIBLE SPEEDS (EN 15528) FOR RAIL VEHICLES ON THE EUROPEAN RAILWAY NETWORK REGARDING DYNAMIC VEHICLE-BRIDGE COMPATIBILITY

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Abstract

The technical network access of rail vehicles (trains) also requires the assessment of the dynamic excitation of bridges during train passage. Due to the regular sequence of axle loads, large structural reactions (oscillation amplitudes of the bridge superstructure) can occur in the event of resonance. EN 15528:2021, table C.1 provides an overview of the so-called limit speed of various types of rail vehicles, above which the dynamic structural response can no longer be captured by a quasi-static approach (dynamic coefficient in quasi-static design) and, hence, a dynamic calculation (train-bridge interaction) is required. In the present study as part of the European research project InBridge4EU, the limit speeds according to EN 15528:2021 were numerically examined for their current validity in relation to evolving train populations and the existing bridge stock in Europe. To this end, a) a vehicle database of European trains was set up, b) a set of bridges was recorded in a bridge database by European railway infrastructure managers and compared with the current assumptions according to EN 1991-2:2003 + AC:2010, c) a methodological approach for performing parameter studies on a generic set of bridges with conservative properties (mass distribution, eigenfrequency, damping, track irregularities) was developed, and d) the results of the parameter studies were assessed in a post-processing analysis (limit speeds of individual train groups) with regard to the ultimate limit state (ULS) of load-bearing capacity, the serviceability limit state (SLS) in terms of bridge acceleration, and fatigue. The values specified in EN 15528:2021 could only be numerically confirmed for the ULS and higher underlying infrastructure capacities (e.g. D4xL, LM71). Lower limit speeds were numerically obtained for the SLS and fatigue. These key findings are intended to serve as a basis for recommendations regarding the revision of future standards (e.g. EN 15528).

Keywords: dynamics, train-bridge interaction, train-bridge compatibility, parameter study, limit velocity

1 Introduction

Trains can dynamically excite railway bridges when passing over them due to the regular sequence of wheelset loads (axle loads), see e.g. [1-3]. The dynamic structural response of the bridge superstructure is usually greater than the structural response under static loading. The dynamic structural response can be considered in a first step by using a dynamic factor (vibration coefficient) during the design or recalculation phase of bridge structures. For this purpose, the dynamic factor Φ according to EN 1991-2:2023 is used in combination with design load models (see, for example, the load model LM71, etc.) in new construction projects.

When performing recalculations with real operating trains, standardized and train-specific dynamic factors ϕ can be applied together with the load pattern of the train configuration, see EN 1991-2:2023. For the implementation, criteria are necessary to determine the level of dynamic action (significantly influenced by the train speed) at which the dynamic structural response (bridge) is no longer covered by a quasi-static approach (static structural response multiplied by the dynamic factor) and a dynamic calculation (numerical time-step analysis) becomes necessary. As a basis, the European standard EN 15528:2021 from the field of railway applications provides a classification system for dealing with the interface between the load limits (line categories) of rail vehicles (freight trains, passenger trains and mixed traffic, special rail vehicles in transport mode) and the infrastructure. It provides approaches for static classification (negligible inertia effects, no significant vibration excitation) and classification of existing and new rail vehicles to ensure static compatibility between rail vehicles and infrastructure. This mainly considers vertical loads (wheelset loads) of rail vehicles. Therefore, rail vehicles are categorized with a focus on the input variables of wheelset load, axle spacing and train mass per unit length, which results in the line category of the rail vehicle. Annex C of EN 15528:2021 also provides an informative tabular overview of so-called permissible limit speeds for estimating whether a quasi-static vehicle-infrastructure compatibility check is sufficient and no additional dynamic compatibility checks are required in this lower velocity range [4]. These speed values were determined in the past based on the experience (empirically confirmed values) of various experts from infrastructure managers, operators and the vehicle stakeholders and are only to be understood as informative (not binding) in EN 15528:2021. Rather, depending on the national implementation concept, national specifications for the respective railway infrastructure must be defined at national level.

Previous regulations (UIC, ERRI) covered dynamic loads on a smeared basis (by factors), tending to be on the conservative side and often independent of the train speed. Between 1990 and 2010, numerical train-bridge interaction models were increasingly used to derive mathematical relationships. In addition, measurement campaigns were carried out on real bridges and compared with the findings of infrastructure managers. As a result, it was found that problems with resonance excitation of railway bridges caused by passing trains do not continuously occur in the railway network, but only selectively on bridges that are prone to resonance. Standard design rules usually result in a bridge design that avoids resonance, but the vehicle population is constantly evolving. As a result, EN 1991-2:2023 provides descriptions of project-specific analyses of bridge dynamics, whereas EN 15528:2021 Appendix C contains informative guidance on distinguishing between the quasi-static approach and the additional dynamic verification [1, 4]. The normative requirements are subject to constant further development, which is reflected, among other things, in new load models for static and dynamic testing adapted to the current vehicle population or the renewal of infrastructure. Since 2023, the EU research project InBridge4EU (<https://inbridge4eu.eu>) has been investigating various topics relating to dynamic train-bridge interaction. As part of the InBridge4EU project, the present study aims to clarify the extent to which the permissible speeds specified in EN 15528:2021 are still applicable to the current train population in Europe and can be reconciled with the respective national railway bridge stock.

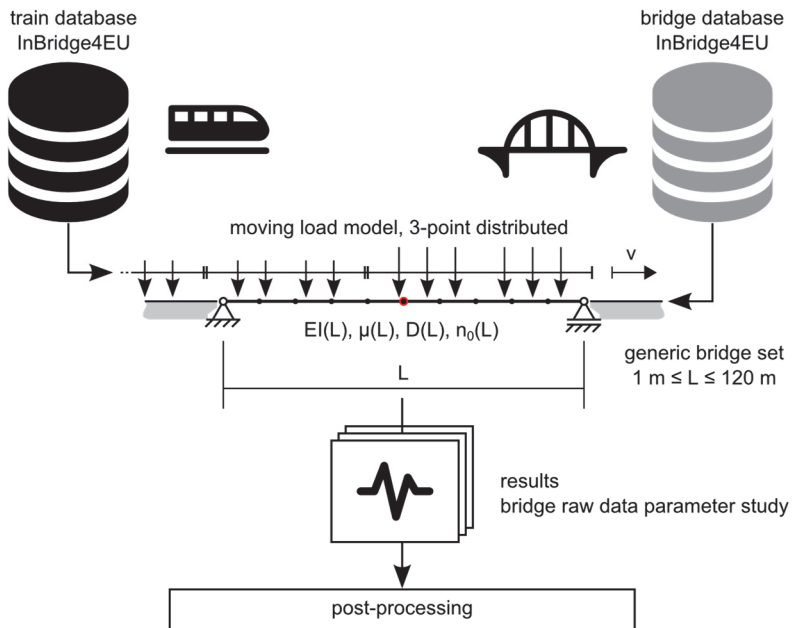


Figure 1 Implemented workflow: moving load model (train configuration with velocity v) for time-step analysis of a finite element discretised bridge superstructure (2D single-span girder with span L) with structural properties bending stiffness EI , distributed mass μ , damping ratio D , first bending eigenfrequency n_0 .

2 Methods

The methodological approach is briefly described in the following (figure 1). Calculating general permissible limit speeds poses several challenges: it requires quantifying vehicle-bridge dynamics for a wide variety of rail vehicles and railway bridge types across the entire European railway network. The dynamic response of the bridge is caused by the vehicle suspension and unsprung masses, track irregularities, the bridge superstructure as a vibration system and the train speed as a parameter due to excitation by repeated wheelset loads during train passage. In general, the effects mentioned are non-linear and are, therefore, specific to the vehicle and bridge structure [5]. For this purpose, the InBridge4EU project worked with partners (infrastructure managers and research institutes) to create a train database by following these steps: i) collection of train configurations from European infrastructure managers and vehicle experts, ii) integration into a train database, iii) calculation of MXD and MND information in accordance with EN 15663:2017 + A2:2024 for passenger trains, special vehicles, freight trains, iv) calculation of the line category of the train configurations as a parameter for further grouping. The maximum vehicle speed (available from technical data sheets) was also stored in the train database. In addition to individual rail vehicles, typical train configurations and multiple-unit trains were also considered (either symmetrical or inverse) as separate train database entries. Load models were excluded, as these already represent envelopes of current rail vehicle types. The evaluated train configurations are summarized in table 1.

Table 1 Number of evaluated train configurations (long-distance and regional passenger trains, locomotives) from the InBridge4EU train database ($L_{\text{train}} \leq 400$ m, $p_{\text{MXD}} \leq 3.5$ t/m)

Vehicle line category	A	B1	C2	D2
Number of configurations	402	259	2,264	2,354

In addition to the train database, the InBridge4EU project selected bridge structures considered dynamically relevant by infrastructure managers in Germany, France, Spain, Sweden and Portugal and included them in a European bridge database with their system properties (geometry, bending eigenfrequency, mass, damping, etc.), see figure 2. Figures 2 and 3 show characteristic values of selected single-span girders contained in the InBridge4EU bridge database in comparison with the standard assumptions (eigenfrequency) according to EN 1991-2:2023 and conservative mass assumptions [5].

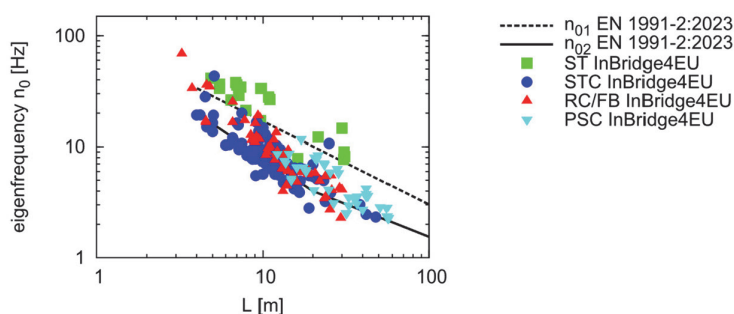


Figure 2 Single-span girders (ST: steel, STC: steel-composite, RC/FB: reinforced concrete / filler beam, PSC: pre-stressed concrete) collected in the InBridge4EU project (bridge database): first bending eigenfrequency n_0 of the bridge superstructure as a function of the span L , normative limit values $n_{01}(L)$ and $n_{02}(L)$ added for comparison

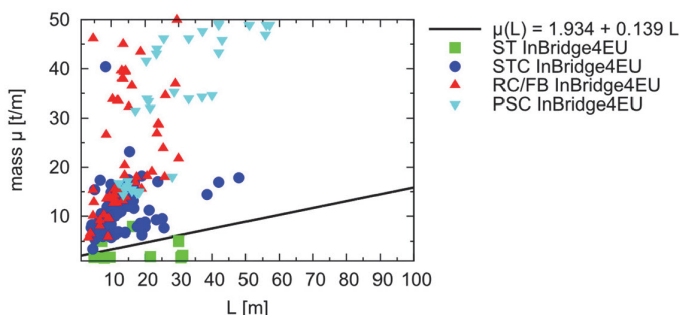


Figure 3 Single-span girders (ST: steel, STC: steel-composite, RC/FB: reinforced concrete / filler beam, PSC: pre-stressed concrete) collected in the InBridge4EU project (bridge database): distributed mass μ of the bridge superstructure as a function of the span L , lower mass function $\mu(L)$, see [5]

For a series of parameter studies, a set of generic bridges with conservative properties was derived and numerically investigated together with the load patterns of the train configurations from the train database. For this purpose, a time-step analysis was performed for each train database entry regarding the objective quantities bending moment (ultimate limit state – ULS), acceleration (serviceability limit state – SLS) and dynamically amplified fatigue [6] at midspan (figure 1). The mathematical evaluation (algorithm) is described in more detail in [5].

The parameter studies are based on the following assumptions:

- carefully maintained track
- damping according to EN 1991-2:2023 and additional damping (from train-bridge interaction) according to EN 1991-2:2003 + AC:2010
- ϕ' and ϕ'' according to EN 1991-2:2023, Annex C
- lower frequency line EN 1991-2:2023, extrapolated for bridges with $L < 4$ m, evaluation of ϕ' and ϕ'' with constant eigenfrequency for $L < 4$ m
- criterion ULS: capacity of the line category (infrastructure), ϕ evaluated with eigenfrequency of lower frequency line $n_{02}(L)$ and constant eigenfrequency for bridges with $L < 4$ m, max. speed assumption 160 km/h quasi-statics
- criterion acceleration: limit value = 3.5 m/s^2 for bridges with $L > 7$ m
- mass function $\mu(L)$ as given in figure 3, see [5]
- criterion fatigue: $\lambda_{\text{fat}} = 1.4$ for bridges $L > 7$ m, see [5]
- criterion fatigue $(1 + \phi'_{\text{dyn}})$ according to DB-Ril 804.3301:2023: limit value $(1 + \phi'_{\text{dyn}}) = 1.5$ for bridges $L > 7$ m
- evaluated trains from InBridge4EU train database (table 1), 3-point distributed moving load model: symmetric and unsymmetric inverse passenger train configurations up to $v_{\text{train}} \times 1.2$ (ULS) and $v_{\text{train}} \times 1.1$ (SLS, fatigue).

The generic bridges cover standard structures (single-span girders, which make up the majority of bridges in the railway networks). Analogies to single-span girders can be formed for special structures. However, this also results in deviating bending eigenfrequencies (e.g. tied arches) with consequently deviating dynamic structural behaviour. In this case, separate considerations are recommended depending on national regulations and the presence of country-specific structures in the railway network [1, 2]. In a post-processing step (figure 1), the load-bearing capacity and respective limit values (criteria) are used to determine the permissible speeds (limit speeds) from the results (raw data) of the time-step analysis. For this purpose, the ULS was investigated by considering the infrastructure line category as underlying capacity for existing bridges [5] in combination with the dynamic coefficient ϕ . For new structures, the capacity of the design level $\Phi_2 \times \alpha \times \text{LM71}$ (undistributed) with various load class coefficients α is also evaluated. The permissible speeds individually determined for each entry from the train database were collected per train group and other grouping characteristics (length of train configuration L_{train} , train mass per unit length of the train configuration p_{MXD} , vehicle line category) and 5%-fractile values for the corresponding limit speed were calculated per train group.

3 Results and discussion

The limit speeds determined for each train group as described above are exemplarily given in tables 2 and 3. For comparison, the limit speeds specified in EN 15528:2021, table C.1, are also given. The obtained results were discussed with a team of experts and checked for plausibility. Regarding the ULS, it appears that the values specified in EN 15528:2021 can only be approximately verified numerically for infrastructure line category D4xL and higher (table 2). For lower infrastructure capacities (e.g. C2 or D2), the normative values cannot be confirmed using the present numerical method (ULS).

Table 2 Permissible limit speeds v (5%-fractile values): line category of underlying infrastructure capacity ILC, passenger train configurations $L_{\text{train}} \leq 400$ m, $\rho_{\text{MXD}} \leq 3.5$ t/m

Vehicle line category	v_{ULS} (ILC = C2) [km/h]	v_{ULS} (ILC = D2) [km/h]	v_{ULS} (ILC = D4xL) [km/h]	v EN 15528 (ILC \geq D2) [km/h]	v_{SLS} [km/h]	v_{fat} (λ_{fat}) [km/h]	v_{fat} ($1 + \Phi'_{\text{dyn}}$) [km/h]
A	152	152	195	160	66	124	71
B1	88	88	195	160	66	96	71
C2	88	88	123	140	66	96	78
D2	-	87	110	120	66	96	80

Table 3 Permissible limit speeds v (5%-fractile values): underlying infrastructure capacity in terms of quasi-static design load model $\Phi_2 \times \alpha \times \text{LM71}$ (undistributed), passenger train configurations $L_{\text{train}} \leq 400$ m, $\rho_{\text{MXD}} \leq 3.5$ t/m

Vehicle line category	v_{ULS} ($\alpha = 1.00$) [km/h]	v_{ULS} ($\alpha = 1.21$) [km/h]	v_{ULS} ($\alpha = 1.33$) [km/h]	v EN 15528 (ILC \geq D2) [km/h]	v_{SLS} [km/h]	v_{fat} (λ_{fat}) [km/h]	v_{fat} ($1 + \Phi'_{\text{dyn}}$) [km/h]
A	202	203	205	160	66	124	71
B1	210	225	228	160	66	96	71
C2	130	190	198	140	66	96	78
D2	113	207	208	120	66	96	80

If a design level of $\Phi_2 \times \alpha \times \text{LM71}$ (undistributed) with $\alpha = 1.21$ or $\alpha = 1.33$ would be available for all railway bridges in the railway network, additional dynamic vehicle-bridge compatibility checks with respect to the ULS up to approximately 200 km/h (train speed) could be omitted (table 3). The computed values in tables 2 and 3 are conservative in nature. In particular, the values determined for the SLS and fatigue are very restrictive due to conservative assumptions regarding infrastructure characteristics (minimum capacity, lower limit) and do not confirm the higher values calculated for the ULS. A refinement can be made by the step-wise analysis of train-bridge interaction presented in [1], but this requires a structure-specific evaluation (specific structure information and model details [7]). More detailed models of train-bridge interaction generally show lower accelerations. Particularly in the case of light-weight (steel) structures, the moving load model does not appear to adequately represent the effect of direct train-bridge interaction, i.e. the influence of varying wheelset loads resulting from the interaction between the train and the bridge or frequency shifts of the coupled system [7]. In addition, the so-called reference method for train comparisons (approved trains versus train to be evaluated) is currently under development and testing, see [2]. Note that the evaluated train configurations may not cover all rail vehicles and may not represent the worst-case scenarios. At the end of the InBridge4EU project, it is planned to review the results for representativeness. The criteria-based presentation of the limit speeds (tables 2 and 3) enables each country to determine, depending on the quality and specific characteristics of its national railway infrastructure, whether the focus should be on the ULS, the SLS and/or fatigue (weighting).

4 Conclusion

In this contribution, limit speeds for current European types of rail vehicles are calculated using the criteria of ULS, SLS and fatigue. The values obtained are compared with the values in the current standard EN 15528:2021, Annex C. The numerical computation of the limit speeds allows different design levels and limit values for existing or new railway bridges to be considered by numerically adjusting the underlying capacities. The values specified in EN 15528:2021 could only be numerically confirmed for the ULS and higher underlying infrastructure capacities. Lower limit speeds were numerically obtained for the SLS and fatigue. Investigations with further variations of the input variables (e.g. damping, bending eigenfrequency of railway bridges, mass functions and approach of φ'') are expected to be completed at the end of the InBridge4EU research project, see publications on the InBridge4EU website (<https://inbridge4eu.eu>), from which recommendations for normative further developments can be derived.

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