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Influence of the locomotive on the dynamic response of single-span bridges under high-speed railway traffic

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Abstract

This short paper evaluates and discusses the dynamic response of single-span bridges under high-speed railway traffic and the influence of the locomotive on resonance-induced speed-dependent acceleration peaks. Prior large-scaled studies investigated different calculation models for the dynamic behavior of railway bridges to determine the influence of vehicle-bridge-interaction. However, the locomotives were not included in these load models. The impact of this neglect was studied by a comparative study conducted at the Institute of Structural Engineering at the TU Wien.

Numerical analyses developed in this study investigate which characteristics of the bridge structures and vehicles are particularly critical for a significant influence on the maximum vertical accelerations and how great the influence of the locomotive becomes. The analyses were based on two train models of an in the ÖBB rail network operating *Railjet*, which either depict the actual train configuration including two locomotives or replace the locomotives with two additional passenger cars.

A parameter study examines the impact of the locomotive on a wide range of bridge structures, defined by a three-dimensional parameter field over their span L, fundamental frequency n_0 and mass per unit length μ. These bridge properties can be used to calculate the bending stiffness EA_{zz}. Furthermore, the train configuration used in the calculations was modeled as a series of moving axle loads as well as a multi-body system that considers the vehicle-bridge-interaction.

This study indicates that the parameter field of bridges can be divided into subsections, which are differentiated by the probability of the occurrence of different resonance scenarios. For each subsection, geometric properties of the locomotives that have a beneficial or unfavorable impact on the relevant acceleration peaks can be found.

In addition, the comparison of the calculation results obtained with load models of different complexity shows that the less sophisticated Moving Load Model can result in uneconomical or even unsafe results regarding the influence of the locomotive.

Keywords: bridge dynamics, high-speed traffic, vehicle-bridge-interaction, locomotive

1 Introduction

As a consequence of the increased use of high-speed trains with operating speeds of over 200 km/h, special attention has to be paid to the traffic-induced resonance vibrations of railway bridges. Recent research [1–5] deals with the computational calculation of the dynamic response of bridges, particularly with the efficient and concurrently realistic consideration of the influence of effects due to vehicle-bridge-interaction.

Large-scaled studies [4, 6] carried out with calculation models with varying complexity often require a focus on particularly critical influencing parameters. However, several aspects like varying characteristics of individual cars were omitted. The influence of the locomotives, which usually feature higher axle loads and differing axle distances than the passenger cars, was often excluded as it was considered non-critical by spot-checks. It was assumed that the available evaluations of the vehicle-bridge-interaction using a load model without considering the locomotives were sufficient to reflect real conditions.

This study investigates the dynamic response of single-span bridges under high-speed railway traffic and the influence of the locomotive on resonance-induced speed-dependent acceleration peaks. Further information and comprehensive analyses are included in [7, 8].

The research questions are the evaluation of characteristics of the bridge structures and vehicles to identify significant influencing parameters on the maximum vertical accelerations related to the locomotives and how pronounced this impact of the locomotive becomes. Several numerical analyses were used to address these questions, including comparative calculations for a parameter field of girder bridges with short spans, which can be idealized as simply supported beams. The results allow a general theoretical understanding of the effects of the locomotives on the speed-dependent acceleration peaks of a parameter field of bridge structures.

All calculations were conducted using two different load models: a series of moving axle loads (Moving Load Model - MLM) and a multi-body system (Detailed Interaction Model - DIM) which takes vehicle-bridge-interaction into account. The results contribute to the understanding of whether omitting the locomotives can negatively impact the comparability of computational investigations with different load models and, if so, under what circumstances.

2 Methods

Comparative calculations on a parameter field of girder bridges were performed to evaluate the impact of the locomotive on bridge vibrations. The parameter field, shown in Figure 1, was obtained by variation of three main bridge characteristics:

- the span L (5 to 40 m)
- the mass per unit length μ (5 to 40 t/m)
- the fundamental frequency n_0 (2 to 40 Hz)

The variation range of those parameters was derived from a catalog of bridges containing reference data [9] and a collection of measured and calculated values for existing Austrian bridges. The upper and lower limits of the frequency range were determined using a regression function dependent on the bridge span. The structural damping ratio ζ of all bridges was set to 1% to simplify the evaluation process. The bending stiffness EA_{zz} required for the analysis was calculated using the bridge properties mentioned above.

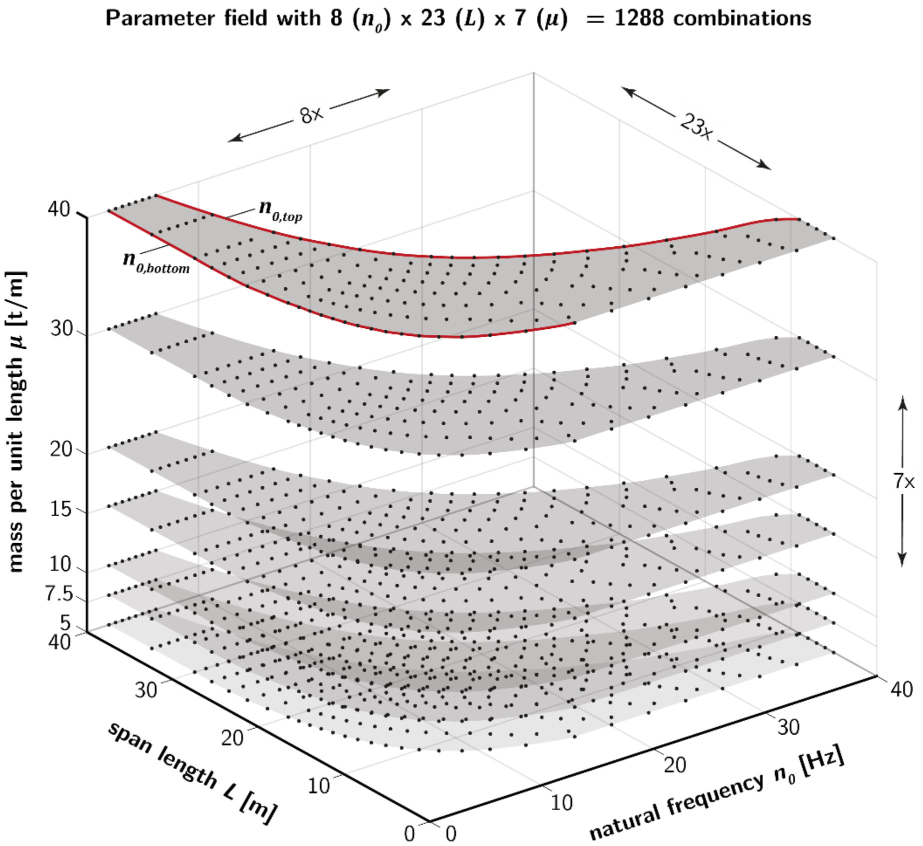

Figure 1: Representation of the calculation points in a three-dimensional parameter field of bridges.

All dynamic calculations were performed by applying both the MLM and the DIM. The load models were created using the properties of a specific configuration of the *Railjet*, a conventional high-speed train with vertically decoupled cars operating in the ÖBB rail network. The examined train configuration consists of 14 passenger cars and two locomotives, both located in the middle of the trainset.

In order to evaluate the influence of the locomotive, two different train models were applied: one model including the actual train configuration with the two locomotives (index *loc*) and a simplified model, for which both locomotives were replaced by passenger cars (index *pc*). This concept of neglecting the locomotive corresponds with the approach in [4].

Hence, a total of four comparative calculations were carried out per bridge. Figure 2 provides an overview of the applied load models.

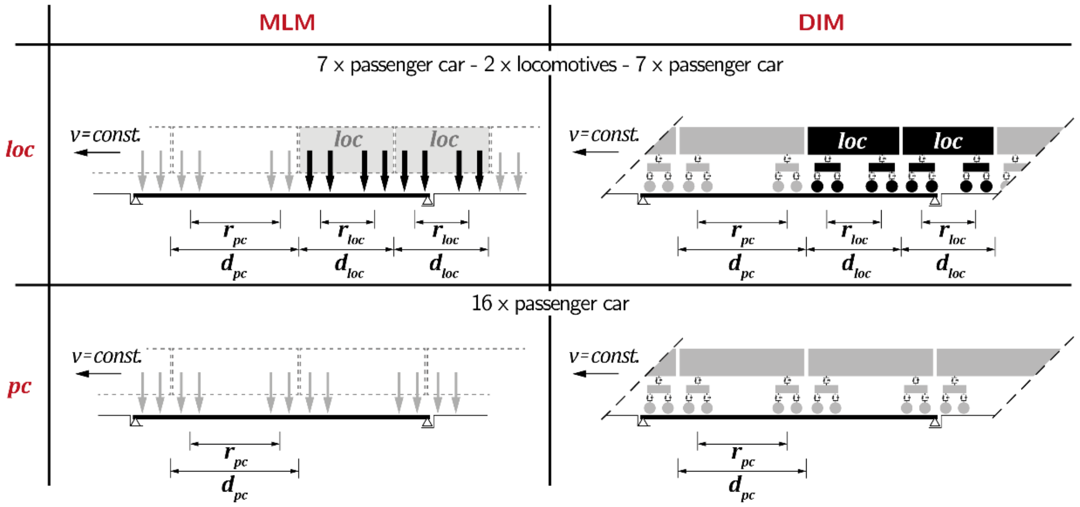

Figure 2: Load models with (loc) and without (pc) locomotives, as MLM or DIM.

The maximum accelerations can be calculated by numerically integrating the differential equations of motion for the parameter field of bridges implementing the MLM and DIM and a speed range of 50 to 350 km/h. The maximum speed-dependent accelerations computed with the individual load models can subsequently be compared to each other.

$$\eta\,[\%] = 100 \cdot \frac{a_{\max,loc}}{a_{\max,pc}} \tag{1}$$

The ratio of the maximum accelerations η (expressed as a percentage) serves as a comparative indicator. Values greater than 100% indicate an unfavorable impact of the locomotives, i.e., neglecting the locomotive underestimates the maximum peak accelerations.

3 Results

The calculations with both the MLM and DIM results in a wide range of η between 60% and 260%. An example is displayed in Figure 3 (a) for the MLM and bridge mass of 15t/m. Structures within the colored areas experience significantly higher accelerations induced by the locomotives ($\eta > 100\%$), whereas grey areas are characterized by lower maximum accelerations ($\eta < 100\%$).

Evaluating the critical resonance speed at which the maximum accelerations of each bridge occur leads to Figure 3 (b). This evaluation considers resonance speeds according to Eq. (2) of the locomotive and passenger car due to their carriage length (index d) or bogie distance (index r). The resonance speeds are represented on a nominal color scale, meaning that each color corresponds to a different resonance scenario.

Especially bridges with fundamental frequencies above 15Hz display their maximum acceleration mainly at speeds close to resonance speeds of the passenger cars and locomotives, i.e., in the range of $v_{r,pc,6} \cong v_{d,loc,6}$. Excepted from this are structures, for which cancellation effects defined by Eq.(3) [10] occur at similar speeds, i.e. $v_{canc,i} \cong v_{r,pc,i}$.

$$v_{x,loc/pc,i}\left[\frac{m}{s}\right]=\frac{n_0 \cdot x_{loc/pc}}{i}; \qquad i=1,2,3,... \tag{2}$$

with $x\,[m]=$ recurring load distance d or r

$$v_{canc,i}\left[\frac{m}{s}\right]=\frac{2 \cdot n_0 \cdot L}{2 \cdot i-1}; \qquad i=1,2,3,... \tag{3}$$

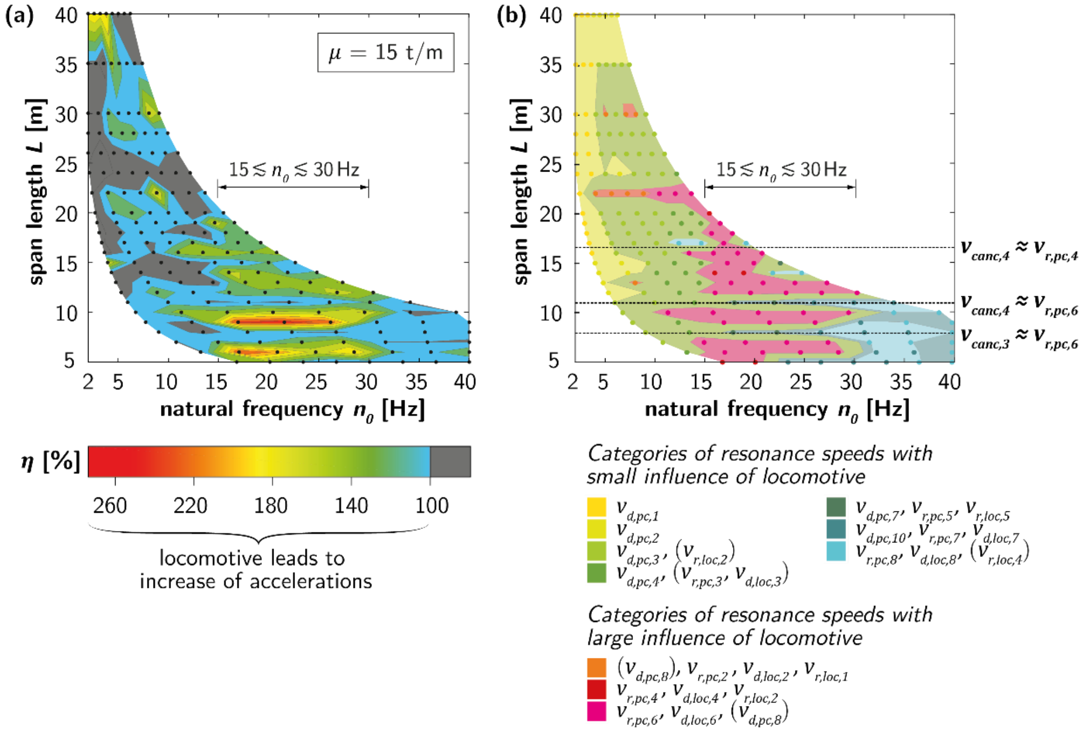

Figure 3: Results for MLM: (a) η for $\mu = 15\ t/m$; (b) resonance speeds at a_{max}

The comparison of both diagrams in Figure 3 shows that an acceleration-increasing influence of the locomotive often occurs in structures for which the maximum accelerations are caused by coinciding resonance incidents due to the locomotives and passenger cars.

Figure 4 displays the speed-dependent accelerations of two exemplary bridges, for which the increasing or decreasing effect of the locomotive is pronounced. The visualization of the lines of action of the axle loads demonstrates how shorter distances d_{loc} and r_{loc} of the locomotive might cause different effects depending on the steady-state vibration wavelength.

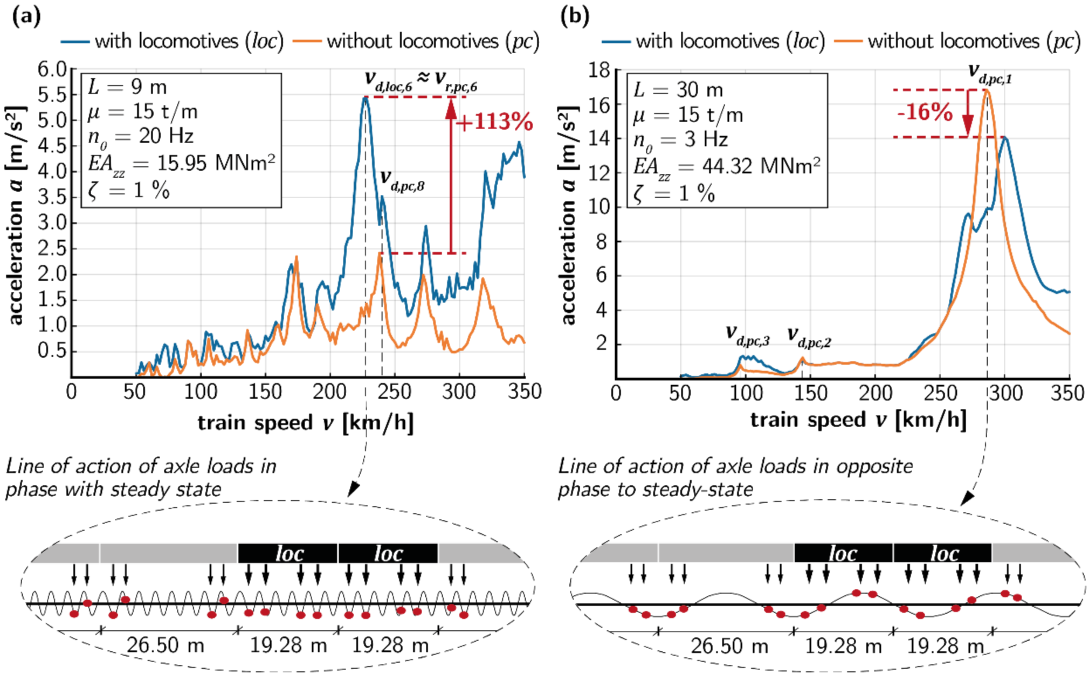

Figure 4: a_{max} at midspan and visualization of lines of action (MLM): (a) acceleration-increasing, (b) acceleration-decreasing effect of locomotives.

The locomotive's influence described by η in calculations using the more complex DIM is similar to the calculations MLM calculations. By comparing the frequency distribution of η as shown in Figure 5 a dependency on the mass distribution μ can be observed in calculation results using the DIM in contrast to the MLM.

The density functions of η with both load models have their local maximum slightly below 100%. Using the DIM leads more often to acceleration-decreasing effects of the locomotives than the MLM and the number of high values of η is lower.

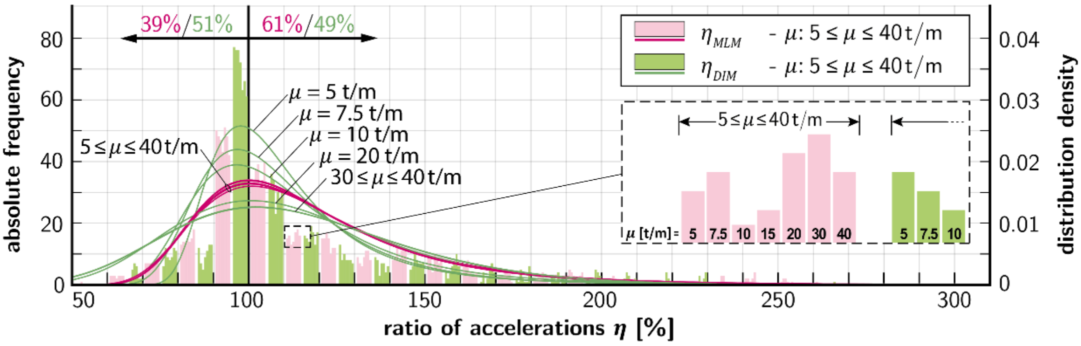

Figure 5: Frequency distribution and density function of η.

4 Conclusions and Contributions

The higher axle loads of the locomotives can result in increased maximum peak accelerations if resonance occurs, as shown for an example bridge in Figure 4(a). A significant increase in the acceleration with η being up to 260% can be observed whenever critical speeds of the passenger cars and locomotives are close to each other, provided that no cancellation effects occur simultaneously. This scenario appears whenever axle distances of the locomotives are close to the primary wavelength of the steady-state vibration or a multiple thereof.

However, the steady-state can also be disturbed by a phase shift in the load distances due to the shortened length of the locomotive or the smaller bogie distance; see example in Figure 4 (b). If the axle loads counteract the steady-state vibration, then the resulting disturbance can be strong enough to reduce the maximum acceleration peaks significantly ($\eta \approx 60\%$). This scenario occurs mainly at the first critical speed due to the total length of the passenger car and, therefore, especially for bridges with low fundamental frequencies.

Based on the analysis results, the parameter field can be divided into subsections in which specific resonance scenarios are probable. Geometric properties of locomotives (in particular the carriage length d and the bogie distance r), which either have a disturbing and therefore beneficial or acceleration-increasing and unfavorable impact on the relevant acceleration peaks, can be found for each subsection.

The calculations with both the MLM and the DIM provide very similar results concerning the influence of the locomotives on average for the parameter field. This confirms the assumption made by various research groups that the influence of the locomotives behaves on average approximately independently of the applied load model.

When considering individual bridges, significant differences between both load models can occur. This can become important whenever general conclusions regarding vehicle-bridge-interaction are drawn from DIM studies omitting the locomotive and implemented in MLM calculations. This approach can lead to uneconomic results of MLM calculations, especially in the case of simultaneously occurring resonance speeds of the locomotives and passenger cars, combined with a low mass of the bridge. It might even lead to unsafe results, as additional calculations performed with the German *ICE 2* and Italian *ETR Y-500* indicate [7].

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