# Which Load Model Do You Use For Rail Track Design?

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# WHICH LOAD MODEL DO YOU USE FOR RAIL TRACK DESIGN?

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## ABSTRACT

This paper introduces a novel load model for the design of track systems on earth works, and a comparison to currently available codified procedures. In engineering practice, it is very common to design rail tracks based on loading regimes that have been developed for approximation of the dynamic loading of bridges. For instance, ballastless tracks shall be designed with load model 71 as well as a dynamic amplification factor of 1.50. If, however, a bridge is abstracted as a simple supported beam and a track including the subgrade as elastically bedded beam, design loads for the dimensioning of the two structures must be obviously different.

The present article presents a new load model for railway engineering to address the above discrepancy. Therefore, numerical models were prepared for illustration of the dynamic vehicle-track-soil interaction. The elastic half space was approximated with a macro-model developed within a research project to consider soil dynamic characteristics such as damping and wave propagation. Based on that comprehensive parameter studies with different train types, operational speed, rail track systems, track irregularities as well as soil properties were performed.

The data obtained were statistically evaluated an illustrated by user-friendly spectra. In order to substantiate the quality of the calculation, numerical results were compared to data obtained by measurements. This showed that the presented new method leads to more realistic track responses in contrast to the traditional loading regime particularly in the high-speed sector. The load model presented in this article consists of a modified version of load model 71 as well as speed dependent dynamic amplification factors. Thus, a closed and physically reasonable method for the dimensioning of track systems in vertical direction is available to the designer.

## PROBLEM STATEMENT

In engineering practice equivalent static procedures are used for design and assessment of track systems. Attention is on the wording “static” since track designers prefer “equivalent static” procedures to approximate loadings due to the “dynamic problem” statement of an operating train along a track on the elastic half space. The variability of trains (e.g. freight trains up to high-speed trains), track irregularities (e.g. differences in elevation, position errors) and imperfect geometries (e.g. flat wheels) can be determined in a complete dynamic calculation. Dynamic analyses, however, cannot be expected from practical engineers and they are not functional either for a variety of reasons (for example requirements of software and hardware). Therefore, statically equivalent design loads, which can be separated into two parts, the load pattern and the dynamic amplification (or briefly amplification factor), have prevailed in engineering practice. Hence, the load pattern defines the spatial distribution of static loads and the amplification factor converts the static magnitudes of the loads to dynamic ones.

The current standardization for ballastless tracks (FprEN 16432-1, 2017) recommends load model 71 (LM71) from bridge construction (EN 1991-2, 2012) as well as a dynamic amplification factor of 1.50 for the design of track supporting layers on earthworks. Regardless of classical ballasted track or ballastless track – the different load transfer of a bridge structure in comparison to an earth structure is apparent. It is also obvious that a dynamic amplification factor independent of speed is either not justifiable from an economic point of view or can even lead to uncertain solutions. Hence, the British “Rail Safety and Standards Board” (RSSB) initiated a project which included research work of VCE Vienna Consulting Engineers ZT GmbH in the past two years (VCE Vienna Consulting Engineers ZT GmbH, 2019) in order to clarify this discrepancy. The methodology for a more realistic assessment of dynamic design of a straight track as a result of vertical loads as well as parts of the findings obtained are explained in the following sections in greater detail. The results of a more comprehensive parameter study are shown in (VCE Vienna Consulting Engineers ZT GmbH, 2019). The research project also analysed track curves – they are not subject of this publication.

## METHODOLOGY

### Principles for Modelling and Calculation

The dynamic train-track-soil interaction is numerically represented by a coupled multi-body simulation with the finite element method (Katz, 2006; Shabana, Sugiyama, & Zaazaa, 2008). In the course of a parameter study the magnitude of the dynamic track response is determined. The results from the static and dynamic calculations are opposed to moving loads in order to highlight the relevance of multi-body simulation.

The methodology is explained by means of the following parameter configuration:

- train type: Austrian ÖBB RailJet
- track irregularity (Arbeitsgemeinschaft Rheine-Freren, 1980; Claus & Schiehlen, 1998): “moderate”
- track structure: ballastless track
- stiffness of the subgrade (Lesgidis, Sextos, Moschen, & Gutierrez Gomez, 2019): “moderate” (deformation modulus $E_{\mathrm{V2}} = 80$ MPa).

Based on that a mechanical model is created, which is schematically shown in Figure 1 for a single bogie. The subgrade is represented in Figure 1 by means of a multi-layer composition by Kelvin-Voigt bodies arranged in series (in literature also referred to as “Winkler model”). The elastic half space is approximated with a macro-model for realistic representation of the dynamic properties of the subgrade (dynamic stiffness, radiation damping and wave propagation), see Figure 2. The dynamic properties of the macro-model are obtained by solving an optimization problem, the theoretical principles are discussed in detail in (Lesgidis et al., 2019; VCE Vienna Consulting Engineers ZT GmbH, 2019).

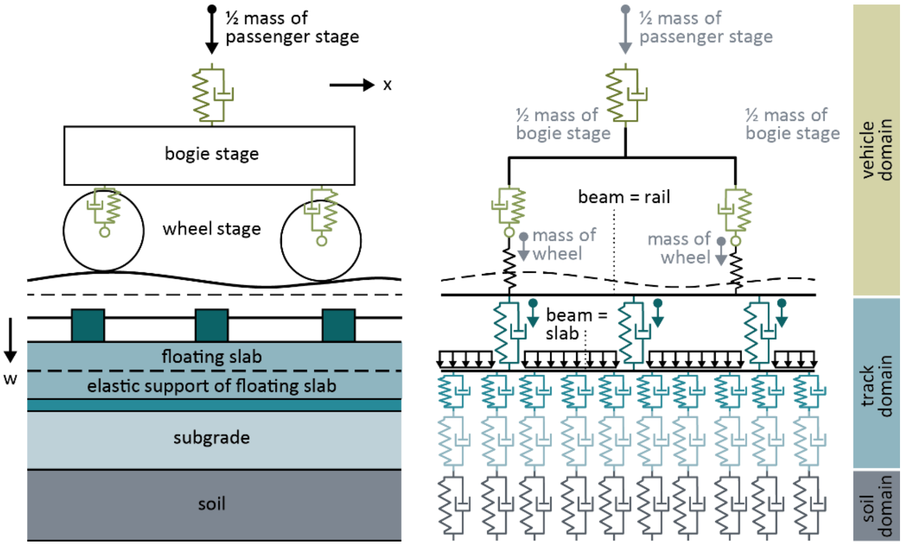

**Figure 1:** Mechanical model of train-track-soil interaction according to (VCE Vienna Consulting Engineers ZT GmbH, 2019).

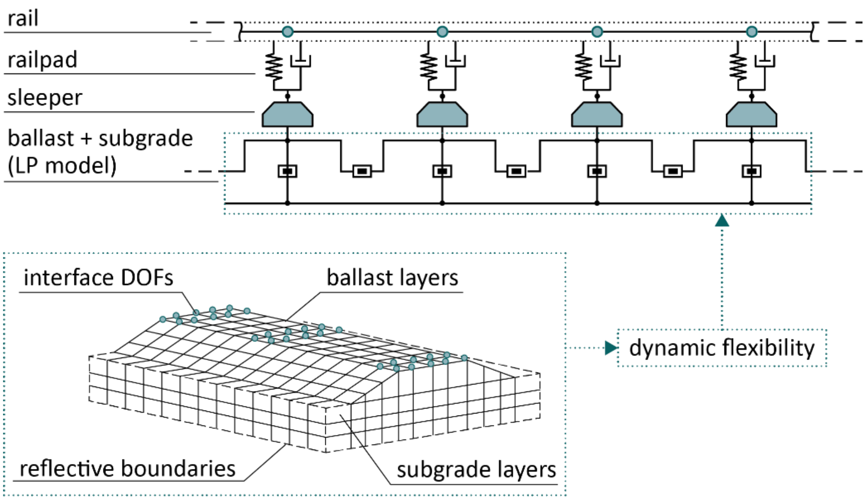

**Figure 2:** Approximation of the elastic half space with an equivalent macro-model (Lesgidis et al., 2019; VCE Vienna Consulting Engineers ZT GmbH, 2019).

Irregularities of the track system, see for example in Figure 3, are considered in the course of multi-body simulation and are obtained by stochastic superposition (Shinozuka & Deodatis, 1991) of trigonometric functions by using amplitudes of power-density spectra according to (Claus & Schiehlen, 1998).

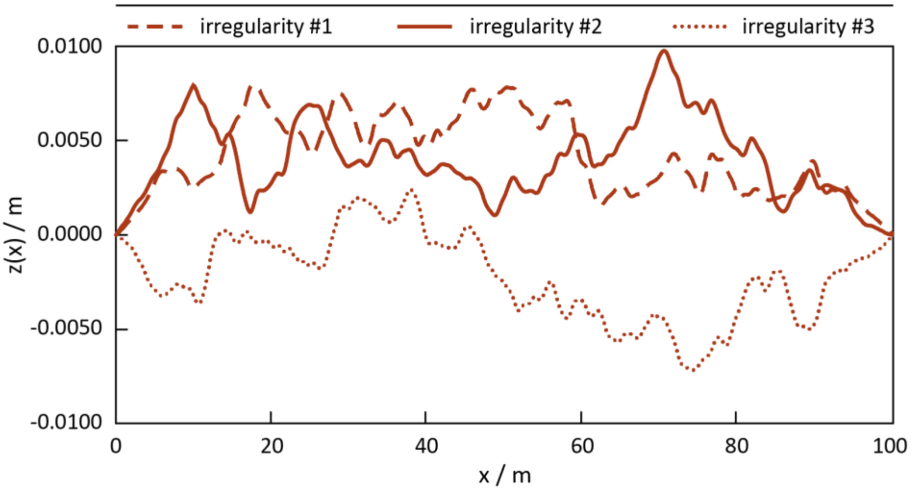

**Figure 3:** Schematic diagram of vertical track irregularities (VCE Vienna Consulting Engineers ZT GmbH, 2019).

Spectrum of the Dynamic Response of the Track System

During analyses the speed of the vehicle is constant for ten different irregularities and the magnitude of the dynamic track response is determined. The maximum envelope force in the rail support is a measure of the dynamic loads acting on the track system. A numerical value of the maximum force can thus be assigned to every parameter configuration consisting of irregularity and speed and can be illustrated in the diagram in Figure 4 by means of a point. This results in a spectral representation, more specifically in a speed-force scatter, where the median is shown as a continuous green line. It is apparent that the dynamic load of the rail support point rises with increasing speed.

Multi-body simulation is relatively time consuming, and therefore, in engineering practice relatively quick dynamic calculations based on moving loads are performed. The spectrum shows the dynamic load of the rail support point by means of a dotted line. Notice, the magnitude and its rise are considerably lower than according to the multi-body simulation. This behaviour can be explained due to the missing interaction of the track system with the train in the model (track irregularities are not incorporated in the calculation) as well as negligence of the inertia of the vehicle.

The horizontal line in Figure 4 results from static analysis. Basically, that means that no dynamic amplification can be considered within the mechanical model, and the force in the rail support is independent of the speed of the train.

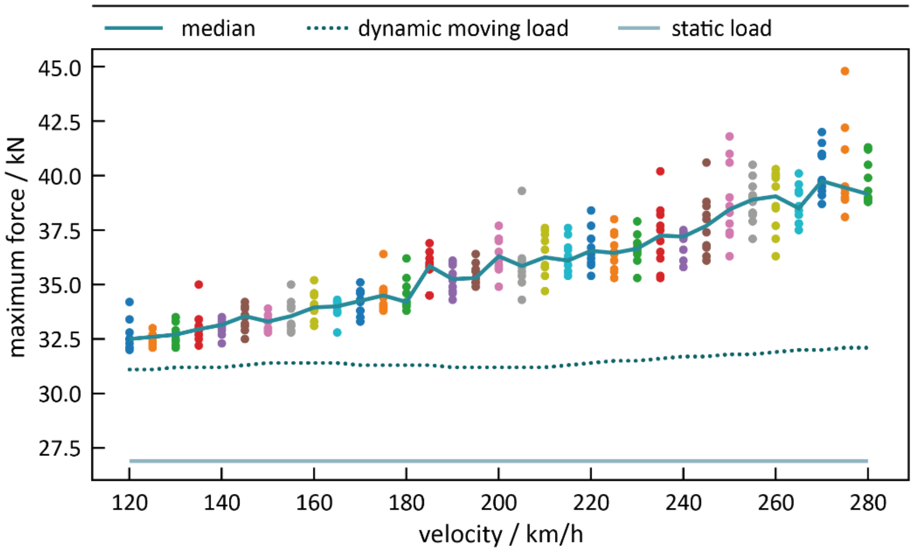

**Figure 4:** Spectral diagram of the maximum force in the rail support point (VCE Vienna Consulting Engineers ZT GmbH, 2019).

A designer-friendly procedure requires the assessment of the median dynamic response with static methods by means of dynamic amplification factors. In this article the "median dynamic amplification factor", $\beta$, is defined as the ratio of the median of the dynamic ($F_{\mathrm{dyn}}$) to the static load ($F_{\mathrm{stat}}$):

$$\beta = \frac{F_{\mathrm{dyn}}}{F_{\mathrm{stat}}} \tag{1}$$

If the dynamic amplification factor is weighted with the ratio of the static axle load of the train ($F_{\mathrm{axle}}$) and the generic axle load of 250 kN of LM71, the "weighted median dynamic amplification factor" reads:

$$\alpha = \frac{F_{\mathrm{dyn}}}{F_{\mathrm{stat}}} \cdot \frac{F_{\mathrm{axle}}}{250\ \mathrm{kN}} \tag{2}$$

In order to emphasize the significance of the weighted median dynamic amplification factors, they are extracted in the following section as a showcase for high-speed trains and for various qualities of the subgrade.

## WEIGHTED DYNAMIC AMPLIFICATION FACTORS

Figure 5 presents spectra of the weighted median dynamic amplification factors according to Equation 2 (coloured spectra), as well as the recommended dynamic amplification factor of EN 16432-1 (FprEN 16432-1, 2017) (black horizontal line). Spectra were represented for the high-speed trains ICE3 and "UK" (= new high-speed train of the project "High Speed 2", for copyright reason it must not be mentioned). The qualities of the subgrade correspond to $E_{\mathrm{V2}} = 40$ MPa (soft), $E_{\mathrm{V2}} = 80$ MPa (medium) and $E_{\mathrm{V2}} = 120$ MPa (stiff). The track irregularity corresponds to a medium quality (Claus & Schiehlen, 1998). The following information is obtained:

- The weighted median dynamic amplification highly depends on the speed and the quality of the subgrade.

- The rise is less sensitive to speed and subgrade properties and is almost independent of the train type.
- The dynamic amplification factor according to EN 16432-1 is applicable for stiff subgrade conditions. In other words, EN 16432-1 leads to conservative solutions and the design according to EN 16432-1 can be uneconomic in some cases. For example, the dynamic amplification factor is approximately 1.10 in case of a speed of 200 km/h.
- For soft and medium subgrade stiffness conditions a design according to EN 16432-1 at speeds of approximately 210 km/h and 360 km/h might be questionable. Due to the applicable semi-probabilistic safety concept with the corresponding partial safety factors on the impact side, however, no safety risk is expected. In fact, reduced durability of such a design is to be expected.

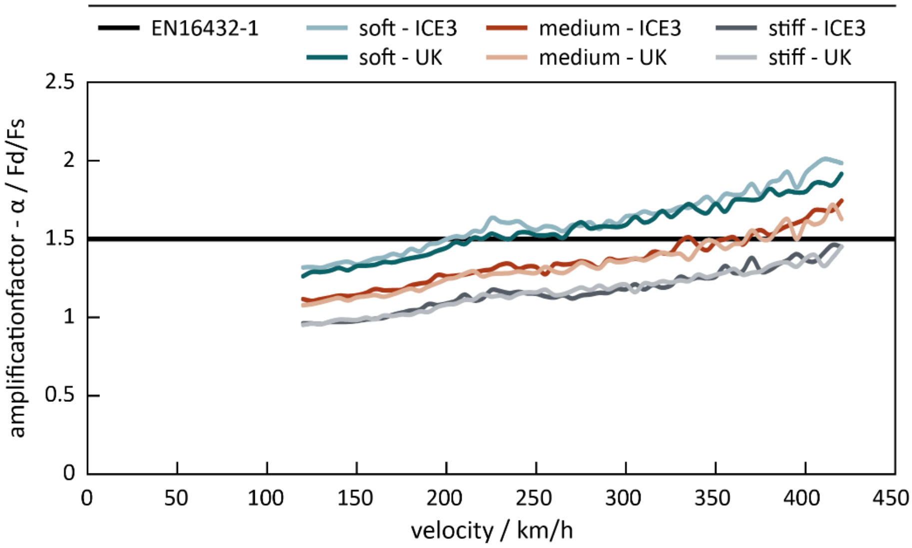

**Figure 5:** Spectra of weighted median dynamic amplification factors for high-speed trains (VCE Vienna Consulting Engineers ZT GmbH, 2019).

For further condensation of results the vehicle speed associated with exceeding 1.50 times the dynamic amplification factor is of interest. This might be helpful for the designing engineer in the early project phase to provide a rough but still code-conform estimate of track design. Table 1 lists the weighted median dynamic amplification factor for high-speed trains on ballastless tracks as well as on conventional ballasted track for different subgrade qualities. The speeds were obtained by means of linear regression and thus slightly differ from Figure 5.

**Table 1.** Speed at the time of exceeding the 1.50-fold dynamic amplification factor.

| Track system | Subgrade conditions $E_{V2}$ in MPa | | |
|---|---|---|---|
| | 40 | 80 | 120 |
| Ballast-less track | 330 | 395 | - |
| Ballasted track | 255 | 320 | 370 |

## SUMMARY AND CONCLUSIONS

A new methodology for the dynamic design of track systems was presented and its derivation for high-speed trains was demonstrated. The currently valid standard situation recommends speed independent dynamic amplification factors. The methodology offers the possibility to consider speed, subgrade properties and track quality during the determination of the dynamic amplification factor. A more economic design with a constant safety level is reached by combining the four single loads of load model 71 and the presented dynamic amplification factor.

## ACKNOWLEDGEMENTS

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