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Dynamic Behaviour Analysis of Different Railway Sleeper Types with a Modular and Computationally Efficient Simulation Framework

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Abstract

The growing traffic demands in railway systems require innovative sleeper designs. This creates the need for efficient simulation methods to support early-stage design and optimization tasks. In this paper, a modular and computationally efficient simulation framework for analysing the dynamic behaviour of railway sleepers is developed. The framework provides calculation modules with Euler-Bernoulli beams as well as multibody dynamics approaches. The calculation times and result qualities are compared. Furthermore, the framework is applied to compare conventional sleepers with innovative ones, focusing on load distribution, dynamic response, and local pressure behaviour. It is shown that the desired quantities can be calculated within seconds while maintaining sufficient accuracy for a wide range of applications.

Keywords: railway sleepers, vehicle/track interaction, simulation framework, reduced-order modelling, railway dynamics, multibody dynamics

1 Introduction

Railway sleepers are key structural components of ballasted track systems. Due to increasing axle loads, higher train speeds, and growing traffic volumes, the mechanical and dynamic demands on sleepers have increased considerably. Therefore, the design of sleepers is subject to multiple and often conflicting requirements, including sufficient bending stiffness and strength, optimized mass distribution, and resistance to fatigue and environmental degradation. In addition, the dynamic interaction between vehicle and track system leads to high dynamic forces and consequently to high local pressure between the sleepers and the ballast bed. The design goals include the reduction of these forces by distributing loads across a larger number of sleepers and increasing the contact area between the sleeper and the ballast. Furthermore, long-term effects such as settlement behaviour must also be considered. These aspects make sleeper design a highly interdisciplinary challenge within railway systems engineering.

Advanced numerical methods such as finite element modelling (FEM), multibody dynamics (MBD) simulations, and the discrete element method (DEM) are widely used to capture structural dynamics, contact mechanics, and system-level responses with high accuracy. These methods enable detailed investigations of stress distributions, modal characteristics, and the influence of geometric and material variations on the dynamic behaviour. Consequently, performing simulations facilitates the systematic exploration of design alternatives, reduces the need for costly experimental campaigns, and accelerates the development process.

However, high-fidelity models involve high computational cost, which is not suitable for early design stages requiring fast iteration. Long computation times, extensive pre-processing, and demanding parameter identification procedures are consequently limiting factors. Therefore, computationally efficient simulation frameworks are needed for rapid parametric studies and sensitivity analyses. Such frameworks allow the identification of promising design directions before applying more detailed models. A systematic evaluation of such frameworks for sleeper design is still lacking in the current published literature.

At the same time, purely simplified models may fail to capture relevant physical effects, particularly when innovative sleeper concepts with modified structural behaviour are considered. Therefore, modularity is essential, allowing different subsystems (e.g., sleeper, rail, ballast, vehicle) to be represented with varying levels of detail. This enables efficient early-stage modelling using reduced-order approaches and targeted refinement with higher-fidelity models without redefining the entire simulation environment.

Against this background, the central scientific question addressed in this contribution is to what extent a modular, computationally efficient simulation framework can support the dynamic analysis and optimization of railway sleeper properties. In particular, the capability of such a framework to differentiate between and evaluate the dynamic performance of a conventional standard sleeper and an innovative sleeper concept is investigated. The study aims to assess whether reduced modelling depth, combined with targeted modular refinement, provides sufficient accuracy and sensitivity to support robust and informed design decisions in the early and intermediate phases of sleeper development.

2 Modular Simulation Framework

In contrast to existing approaches, the developed simulation framework introduces a modular loop structure that enables iterative coupling and exchange between different model fidelities (see Figure 1). It allows the investigation of load distribution along the sleepers, the local pressure distribution between the sleepers and the foundation, and the settlement behaviour of the sleepers under different operating conditions at an early design stage, serving as optimization targets. The preprocessing, the control of the individual modules, the postprocessing analyses, as well as most of the calculations themselves, were implemented in a Python environment.

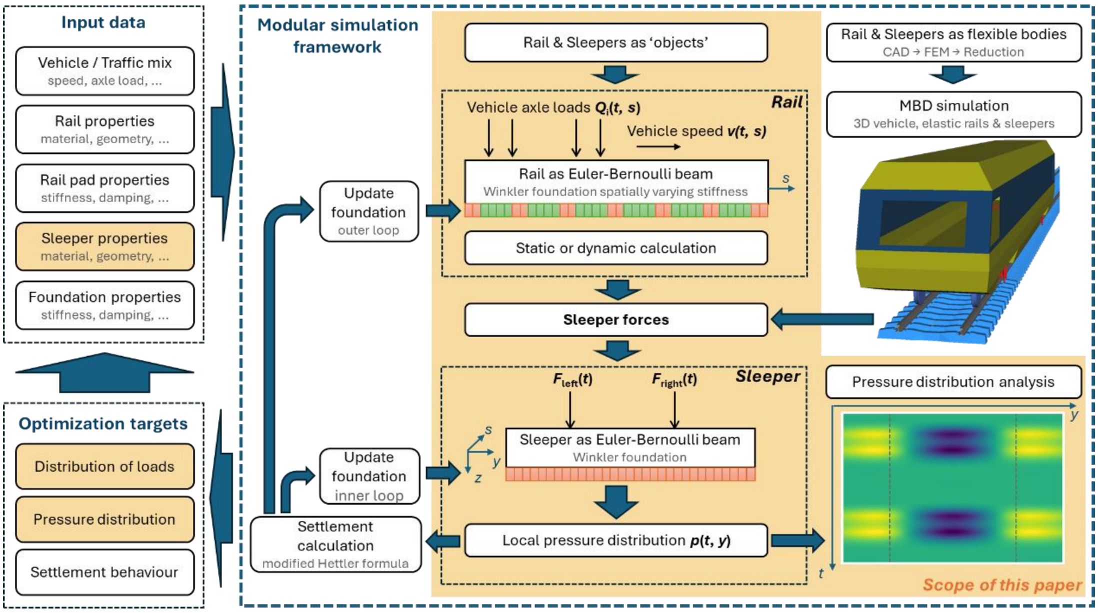

Figure 1: Modular simulation framework with highlighted scope of this paper

The different modules provide two ways of calculating the forces acting on the sleepers caused by a vehicle running over the track. These two approaches complement each other in terms of modelling detail and computational effort. In the first approach, the forces are calculated with MBD simulations (SIMPACK). The modelling process of the MBD module is described in [1]. It contains a full 3D vehicle model, two rails as flexible bodies, rail pads as spring-damper elements, and sleepers as flexible bodies according to their geometry and material properties, which are connected to the ground via spring-damper elements representing simplified foundation properties.

The main scope of this paper is highlighted in orange in Figure 1 and includes the second way to calculate the sleeper forces with the so-called Beam module. In contrast to the MBD approach, this method focuses on a reduced-order representation of the track system. With this module, the rail is modelled as an Euler-Bernoulli beam. The spatially varying stiffness and damping values of the Winkler foundation are calculated by combining rail pad properties and surrogate sleeper foundation stiffness and damping values, which result from the different sleeper bearing area properties.

The dynamic calculation of the beam deflection and the resulting sleeper forces is based on the Euler-Lagrange equation:

$$\rho A(y)\frac{\partial^2 w(y,t)}{\partial t^2} + E(y)I(y)\frac{\partial^4 w(y,t)}{\partial y^4} + k\big(w(y,\, t) - \delta(y)\big) + c\frac{\partial w(y,t)}{\partial t} = \sum F_i(y,t) \qquad (1)$$

where ρ denotes the density, A the cross-sectional area, E the Young's modulus, I the second moment of area, k the foundation stiffness, c the foundation damping and $\sum F_i$ represents all external forces acting on the beam. Additionally, an offset δ from the foundation can be considered in the equation. Each parameter can vary along the beam axis y and the external forces can also vary over time. The dynamic equation is solved for $w(y,\, t)$ with a 1D partial differential equation solver [2] for Octave/Matlab controlled from Python via the Octave/Matlab engine. To decrease the calculation time, the static form of this equation can be used and evaluated directly in Python with the SciPy solver for boundary value problems.

Based on the calculated sleeper forces, the subsequent analysis focuses on the interaction between sleepers and foundation. The investigation target is the local pressure distribution of each sleeper acting on the foundation. Therefore, each sleeper is modelled as an Euler-Bernoulli beam in the same way as the rails. Each of the material, geometric, and foundation properties can vary along the sleeper length (y-direction). The previously calculated sleeper forces act as external forces over time on the sleeper. The calculation method (static or dynamic) can be chosen to get the best compromise between calculation time and result quality.

3 Results

In the first step, the static calculation can be used to analyse the distribution of the axle load along several sleepers. This step provides the basis for understanding how loads are transferred from the rail to the sleepers. The distribution result depends on the foundation stiffness of the sleepers in combination with the sleeper bearing area, the rail pad stiffness and the bending stiffness of the rail. Figure 2 shows an example of the absolute and relative axle load distribution over multiple sleepers (highlighted in grey) along the track for a given axle load of 22.5 tonnes.

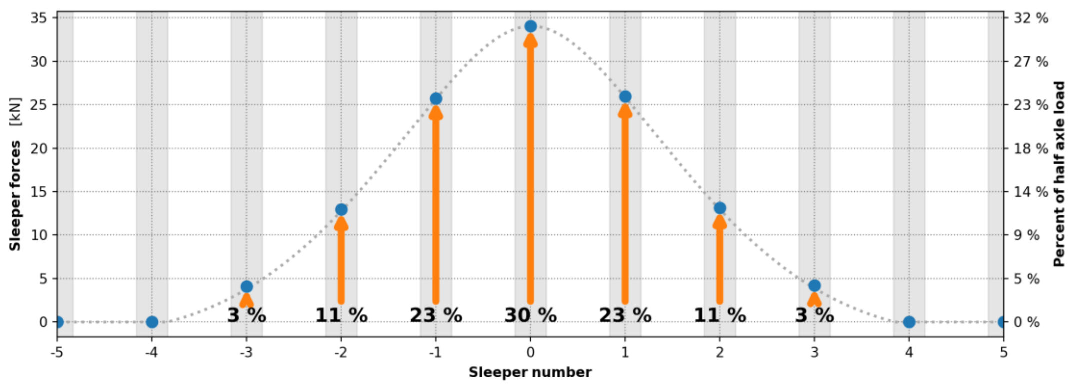

Figure 2: Axle load distribution over multiple sleepers along the track

In the next step, the results of the different calculation methods used to determine the sleeper forces resulting from a simulation of vehicle running over the track are shown in Figure 3. This comparison allows an assessment of the trade-off between model accuracy and computational effort. The MBD result (green) includes the interaction effects between the vehicle and the track and can be seen as the reference shape due to the highest level of modelling detail within the framework. The dynamic beam calculation result (orange) shows the inertia effects of the sleepers and the damping effects of the components, similar to the reference. The static beam calculation result shows a higher peak at the first wheelset and a lower peak at the second wheelset. Nevertheless, the overall shape is similar and appears suitable for use in fast optimization tasks due to the short calculation time. Thus, depending on the application, simplified models may provide sufficient accuracy at significantly reduced computation time.

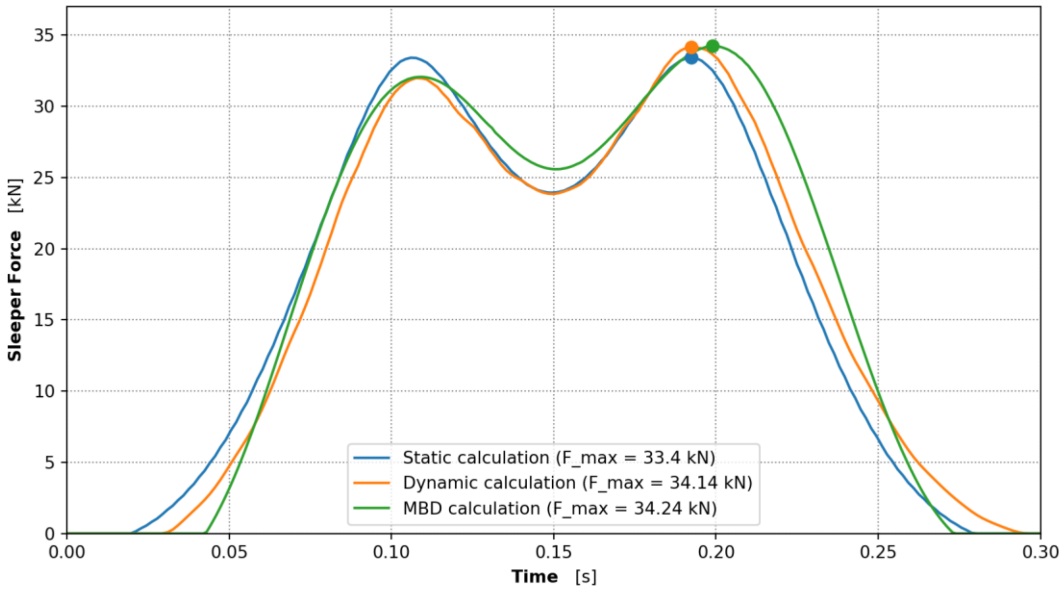

Figure 3: Sleeper forces over time obtained by different calculation methods

The following Table 1 shows the maximum sleeper forces and the calculation time on a conventional laptop with an Intel i7 processor (for a beam discretization of dx = 10 cm):

Quantity	MBD *reference*	Rail as beam *dyn. calc.* dx = 10 cm	Rail as beam *static calc.* dx = 10 cm
F_{max}	34.24 kN	34.14 kN	33.40 kN
ΔF_{max}	-	0.3 %	2.5 %
t_{sim}	840 s	68 s	5 s

Table 1: Result comparison of the different calculation modules

These results further illustrate the significant reduction in computation time while maintaining comparable force shapes and maximum values.

In the final step, these forces are applied as external forces at the desired sleeper. The sleeper is considered as an Euler-Bernoulli beam, in the same way as the rail. The calculation time for a chosen beam discretization of dx = 10 mm is around 26 seconds for the dynamic calculation. Due to the fast static calculation, a reduced discretization of dx = 1 mm still results in a very short calculation time of only 6 seconds.

The dynamic behaviour of the sleeper during a vehicle run can be seen in Figure 4. The applied external forces over time are shown in the first row. The second and third rows show snapshots at different time steps of the deflection and pressure along the sleeper length (y-direction). Additional quantities like bending moments or shear forces can also be investigated. This step provides insight into both global deformation behaviour and local pressure conditions.

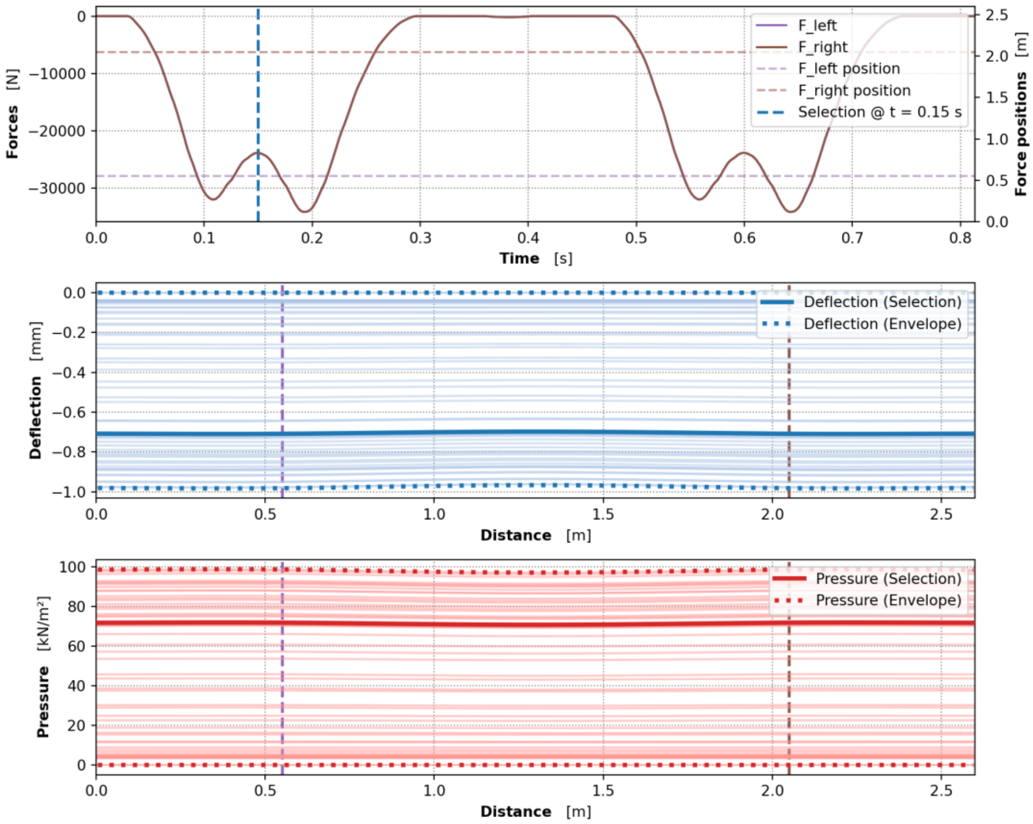

Figure 4: Dynamic behaviour of a sleeper over time during a vehicle run

For a more detailed analysis of the local pressure distribution, a time-distance plot is shown in Figure 5. In each time step, the mean value of the pressure distribution is subtracted, and the resulting delta pressure is visualized with a colour bar. The two rail positions are marked with two dashed lines in grey. It can be observed that the maximum delta pressure (in yellow) occurs outside of the two rail positions.

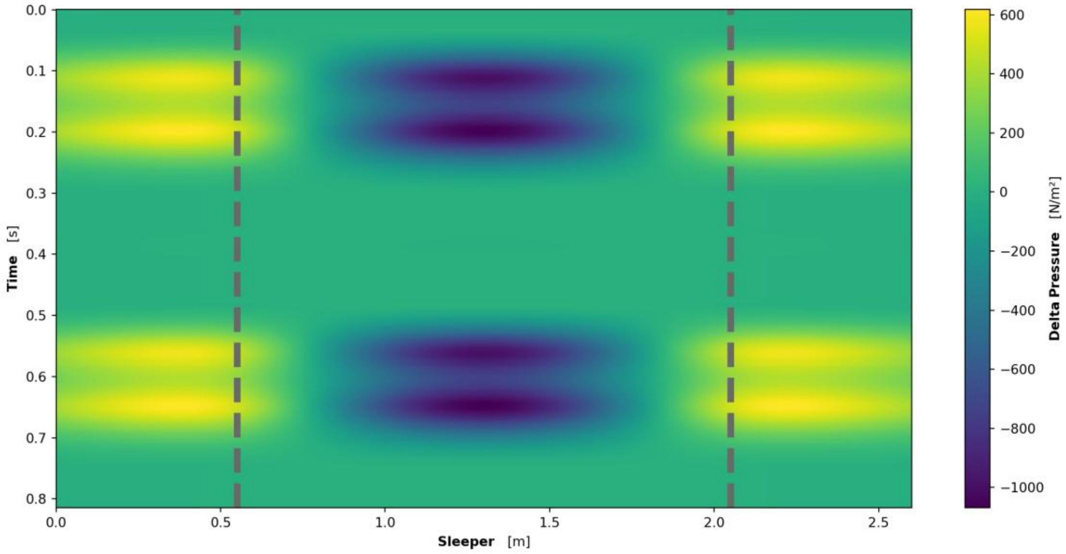

Figure 5: Sleeper foundation local mean-free pressure distribution over time

All previously presented results were calculated for a standard concrete sleeper. To evaluate the potential for design improvement, in the next investigation, the results are compared with the ones for an innovative sleeper. The geometry of this sleeper is modified, which leads to different cross-sectional properties and a larger bearing area. Figure 6 shows the maximum local pressure distribution (envelope) for the standard sleeper (blue) and the innovative sleeper (orange). It can be seen that the larger bearing area leads to a lower mean pressure value, as expected. This indicates a more favourable load distribution in the track substructure.

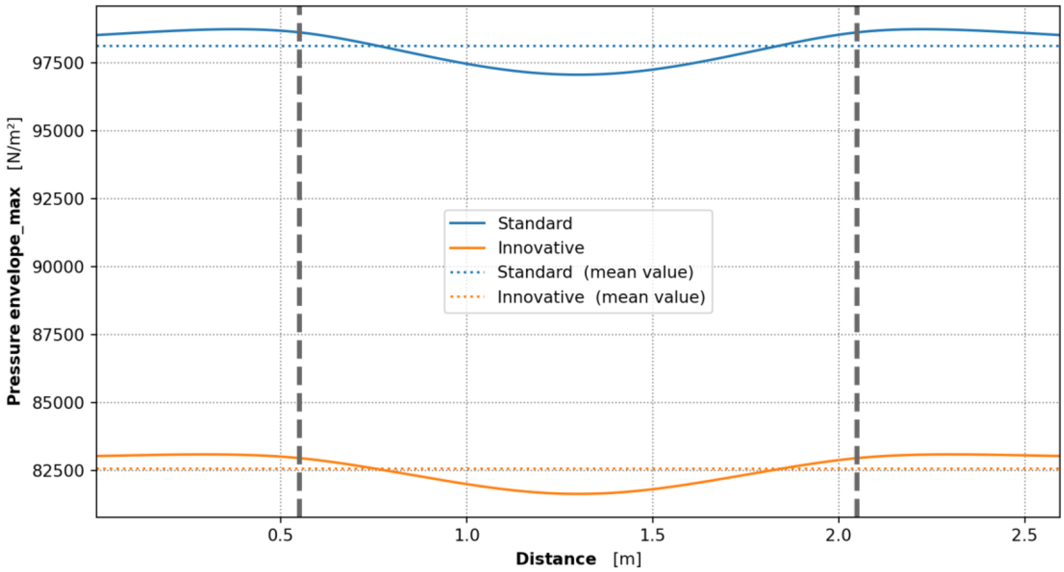

Figure 6: Maximum local pressure distribution comparison for two sleeper types

An additional quantity to analyse the pressure distribution is the difference between the maximum and minimum pressure (Δp_{max}) along the sleeper length. This parameter provides a measure of the uniformity of load transfer. To visualize the comparison result, the mean value of each pressure distribution curve is subtracted and shown in Figure 7. The observed lower Δp_{max} is hence an additional advantage of the innovative sleeper design. Overall, the results demonstrate the improved dynamic performance behaviour of the innovative sleeper concept.

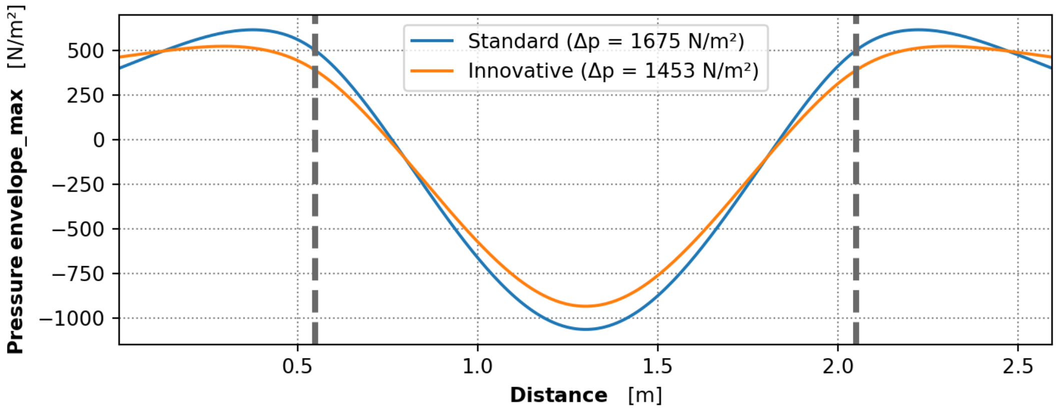

Figure 7: Mean-free local pressure distribution of two sleeper types

4 Conclusions and Contributions

This paper presents a modular and computationally efficient framework to simulate the dynamic behaviour of railway sleepers. A central contribution is the introduction of a modular loop structure that enables the iterative coupling and exchange of models with different levels of fidelity within a unified workflow. The different 'rail' modules used to calculate sleeper forces are compared in terms of modelling depth, result quality, and computational time. In addition, the integration of a dynamically solved beam formulation into this modular architecture provides a novel balance between computational efficiency and physical accuracy. It is shown that the forces can be calculated within seconds while maintaining sufficient accuracy for a wide range of applications. The 'sleeper' module provides detailed and computationally efficient insights into the local pressure distribution within the bearing area. The comparison result of the calculated pressure distributions between the standard sleeper and the innovative sleeper demonstrates the advantages of the new design.

For the early-stage design process, explicit modelling of the vehicle and track using multibody dynamics (MBD) is not required to optimize material and geometric parameters with respect to local pressure distributions. Furthermore, the settlement behaviour and resulting minimized tramping operations can be considered as optimization objects at this stage.

In the future, this work can serve as a foundation for modelling the long-term behaviour of local settlement and, in particular, the evolution of hanging sleepers in both open track and turnout sections. Additionally, the modularity of the framework facilitates its extension with additional modules, such as acoustic analyses or component-specific degradation models.

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