World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Research Article)

Wheel-rail impact load due to the loss of sleeper-ballast interface

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World Journal of Advanced Engineering Technology and Sciences, 2024, 11(02), 167–174

Publication history: Received on 01 February 2024; revised on 11 March 2024; accepted on 13 March 2024

Article DOI: https://doi.org/10.30574/wjaets.2024.11.2.0095

Abstract

This paper presents a comprehensive study on the simulation and analysis of the loss of sleeper-ballast interfaces in railway systems. Through a combination of Multibody Dynamics (MBD) and Finite Element Analysis (FEA) techniques, accurate modeling and validation processes were employed to investigate the impact of interface loss on wheel-rail impact load. Various scenarios were explored, revealing significant findings: for fewer than 4 sleeper-ballast interface losses, a notable 30% increase in wheel-rail impact load was observed, while the rate of increase in wheel-rail impact load diminished for more than 4 sleepers. Furthermore, gap size emerged as a critical factor, with sizes between 0.2 mm and 1.6 mm leading to a load increase exceeding 65%. The study also highlighted the substantial influence of train speed on load dynamics, particularly evident at speeds up to 200 km/h, where loads escalated significantly, resulting in a 180% increase under adverse conditions. These findings emphasize the importance of considering various factors in maintaining railway infrastructure integrity and safety.

Keywords: Sleeper-Ballast Interface; Wheel-Rail Interaction; Train-Track Dynamics; Track Vibration

1. Introduction

1.1. The importance of the topic

Railway infrastructure serves as a critical pathway for transportation, facilitating the movement of goods and people with efficiency and reliability. At the heart of this system lies the complex interaction between wheels and rails, a dynamic process crucial for operational safety and efficiency. This interaction is facilitated by sleepers, which provide essential support to rail infrastructure. The integrity of the sleeper-ballast interface is of utmost importance, as any disruptions or deficiencies in this connection can lead to significant consequences for railway operations. Understanding the implications of the loss of the sleeper-ballast interface on wheel-rail interaction is imperative for maintaining the reliability and sustainability of railway networks.

1.2. Literature review

A comprehensive review of existing literature reveals a growing body of research focusing on the impact of sleeper-ballast interfaces on railway dynamics. Sadeghi et al. [1] demonstrated that considering sleeper pressure forces, detailed sleeper geometry, and more realistic assumptions regarding sleeper-ballast contact significantly enhances the accuracy of theoretical models. However, the presence of unsupported or deteriorating sleepers presents significant challenges to this interaction, affecting various aspects of railway operations [2]. Evazzadeh [3] investigated the influence of unsupported sleepers on wheel-rail interaction in railway systems, showing that the dynamic load increases by 2.5% when only one sleeper is unsupported. Augustin et al. [4] observed that up to 50% of the sleepers they investigated on

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multiple railway tracks are unsupported to some extent. Naseri and Mohammadzadeh [5] highlighted the effects of the loss of the sleeper-ballast interface on bridge acceleration and loading, emphasizing that suspended sleeper groups located at specific positions on the bridge span can lead to significant bridge responses. Lammering and Plenge [6] considered suspended sleepers as a long-term cause of track fatigue. Navaratnarajah et al. [7] examined shear behavior at the sleeper-ballast interface, studying the influence of under-sleeper pads (USPs) made of recycled tires on ballast shear behavior. USPs create a softer surface, increasing sleeper-ballast contact area and reducing ballast pressure [8, 9]. Naseri et al. [10] compared wheel-rail interaction with bridge vibration due to local track defects, showing that local defects, particularly at the first quarter of the bridge, can significantly affect both wheel-rail and bridge vibration. Johansson et al. [11] found that integrating USPs decreased stress on the ballast, although its impact on dynamic wheel-rail contact force magnitude was minimal. Grassie and Cox [12] examined the consequences of losing the sleeper-ballast interface on track deflection and sleeper strains, emphasizing the crucial role of ballast in mitigating these effects. Additionally, Kaewunruen and Remennikov [13] investigated track settlement due to the loss of the sleeper-ballast interface through finite element simulation and field experiments. These studies collectively highlight the complex challenges posed by the loss of the sleeper-ballast interface and the need for further investigation to address them comprehensively.

1.3. Contribution of this study

In line with the existing literature, this study seeks to contribute to a deeper understanding of the impact of the loss of sleeper-ballast interface on wheel-rail interaction dynamics. Through a combination of analytical modeling, numerical simulations, and empirical investigations, this research endeavors to examine the effects of the loss of sleeper-ballast interface on various aspects of track performance, safety, and maintenance requirements. By systematically exploring the impact of the loss of sleeper-ballast interface on the wheel-rail interaction, this study aims to provide valuable insights for railway authorities to develop informed maintenance strategies and optimize track design, thereby enhancing railway integrity and efficiency.

2. Numerical coupled train-track model

Simulation of train-track interaction is a fundamental aspect of railway engineering, offering invaluable insights into the complexities of dynamics and behaviors of trains navigating along track infrastructure. This section provides insight into the importance of simulation techniques in comprehending and optimizing the interaction between trains and tracks, describing the methodologies utilized, critical parameters considered, and the advantages conferred by simulation-based approaches.

2.1. Methodologies Employed

In the realm of numerical simulation for train-track interaction, various methodologies are employed to model the dynamic behavior of both the train and the track. One common approach involves utilizing multibody dynamics (MBD) simulations to represent the complex motion of the train, accounting for factors such as wheel-rail contact, suspension characteristics, and vehicle dynamics. In parallel, finite element analysis (FEA) techniques are employed to simulate the response of the track structure to dynamic loading induced by passing trains. By coupling MBD and FEA simulations, a comprehensive evaluation of the interaction between trains and tracks can be achieved. This allows for the evaluation of critical parameters such as track alignment, track stiffness, and wheel-rail contact forces.

2.1.1. Train dynamics

The characteristics of a train are described through a structured framework composed of three main components: a car-body, two bogies, and four wheelsets per railcar. These parts are interconnected via linear spring-damper systems. The car-body is considered as a rigid beam, with bending mode shapes disregarded. It is linked to both the front and rear bogies through a secondary spring-damper setup. The bogies, reflecting the features of the car-body model, possess two degrees of freedom and are linked to the wheels through the primary spring-damper mechanism. As a result, the total degrees of freedom for a vehicle amount to 10. A detailed explanation of this model is available in reference [9]. A diagram illustrating this simplified vehicle model is provided in Figure 1. The dynamic equations governing the train model's behavior are formulated as follows:

$$[M_v]\{\ddot{u}_v\}+[C_v]\{\dot{u}_v\}+[K_v]\{u_v\}=\{F(t)\} \qquad (1)$$

Where M, C, K, and F are mass, damping, stiffness, and force, respectively.

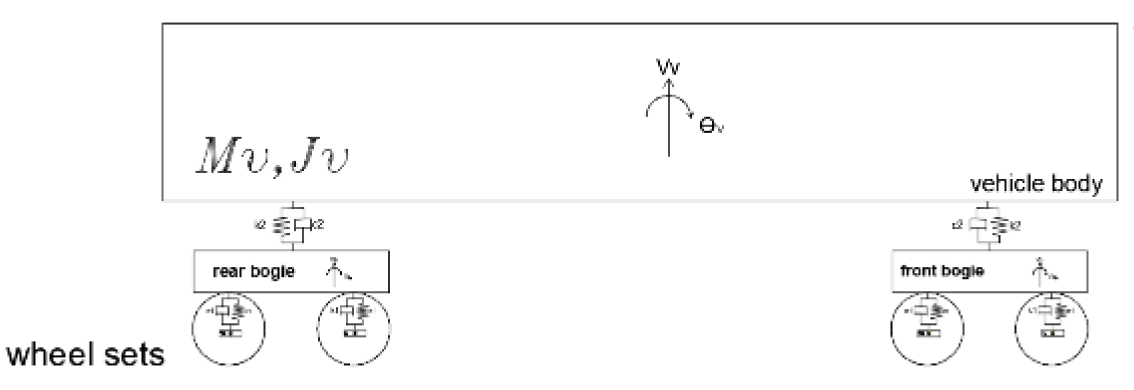

Figure 1 Train model schematic

2.1.2. Track dynamics

Modeling track dynamics is essential for determining how rail infrastructure reacts to dynamic loads induced by passing trains. The methodology employed for simulating track dynamics encompasses several crucial components, including rails, sleepers, ballast, and subgrade. These elements are interconnected to simulate the dynamic interaction between them, capturing the complex behavior of the track system under varying conditions. Various structural characteristics of the rail infrastructure are considered in the modeling process to ensure an accurate representation of its behavior. This includes the stiffness and damping properties of the rails, sleepers, and ballast, as well as the resilience of the subgrade. The shear and vertical interlocking stiffnesses are modeled using the mathematical expressions presented in [14, 15]. Additionally, the condition of the track, including the presence of defects or irregularities, is factored into the model to simulate real-world operating conditions. The behavior of the track system is governed by a set of equations, Equation (2), that describe the dynamic response of each component to applied loads. These equations encompass formulations for the forces and displacements experienced by the rails, sleepers, and ballast, as well as the interactions between them. The schematic representation of the track model is depicted in Figure 2.

$$\begin{bmatrix} M_r & 0 & 0 \\ & M_s & 0 \\ sym. & & M_b \end{bmatrix} \begin{Bmatrix} \ddot{u}_r \\ \ddot{u}_s \\ \ddot{u}_b \end{Bmatrix} + \begin{bmatrix} C_r & C_{r/s} & 0 \\ & C_s & C_{s/b} \\ sym. & & C_b \end{bmatrix} \begin{Bmatrix} \dot{u}_r \\ \dot{u}_s \\ \dot{u}_b \end{Bmatrix} + \begin{bmatrix} K_r & K_{r/s} & 0 \\ & K_s & K_{s/b} \\ sym. & & K_b \end{bmatrix} \begin{Bmatrix} u_r \\ u_s \\ u_b \end{Bmatrix} = \begin{Bmatrix} F_r(t) \\ F_s \\ F_b \end{Bmatrix} \qquad (2)$$

Where *M*, *C*, *K*, and F are mass, damping, stiffness, and force, respectively. The subscripts of *r*, *s*, and b present rail, sleeper, and ballast, respectively. Additionally, *u* is the response, and its derivatives are denoted by dots.

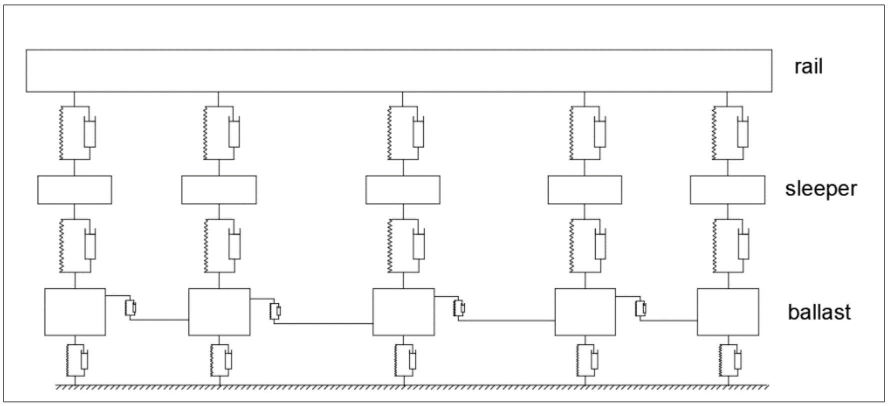

Figure 2 Schematic of track model

2.1.3. Train-Track coupling

The interaction between wheel and rail in railway systems follows Hertzian contact theory principles, which govern forces transmitted between contacting bodies. According to this theory, the interaction force between the wheel and rail at a given location can be described by the equation:

$$F = \begin{cases} cy\sqrt{y} & y \leq 0 \\ 0 & y > 0 \end{cases} \tag{3}$$

Here, F denotes the interaction force, while y represents the relative displacement between the wheelset and the rail. The parameter c signifies the nonlinear Hertzian contact coefficient, which characterizes the stiffness of the contact interface.

2.1.4. Loss of interface model

In this study, the representation of the sleeper-ballast interface incorporates the consideration of a gap beneath the sleeper, as illustrated in Figure 3.

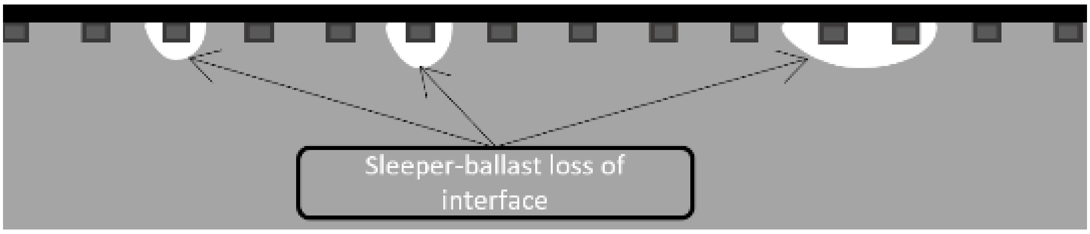

Figure 3 Schematic of sleeper-ballast loss of interface

Utilizing this model, the interaction between the sleeper and the ballast is described by the equation:

$$f = \begin{cases} k(Y - \delta) & Y \leq \delta \\ 0 & Y > \delta \end{cases} \tag{4}$$

Here, k represents the ballast stiffness, Y denotes the sleeper deflection, and δ signifies the gap between interfaces. The behavior of simulated stiffness between the sleeper and ballast is depicted in Figure 4.

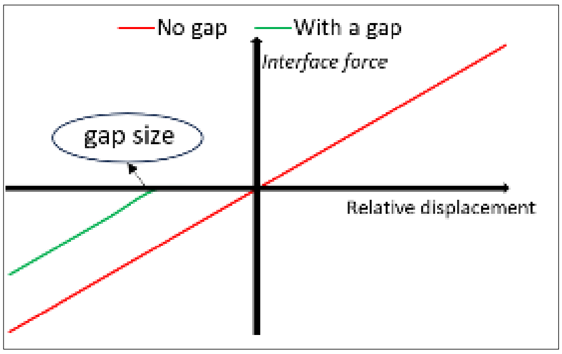

Figure 4 Interface force-relative displacement behavior of the sleeper-ballast interaction model

2.2. Train-track coupling

Modeling the interaction between the train and track components as a coupled system involves considering the dynamic response of both entities to the forces generated during motion. By numerically solving these coupled equations of motion using appropriate integration algorithms, the proposed method can simulate the dynamic behavior of the entire train-track system over time and analyze its response to various operational conditions and environmental factors. In this study, the dynamic equations of both subsystems are solved using Newmark's finite difference scheme, a widely adopted method in engineering practices [16, 17]. Initially, the initial condition of the entire system is defined, and then the responses for subsequent time steps are calculated using the Newmark method.

2.3. Model verification

This section focuses on verifying the robustness and accuracy of the proposed model by comparing its results with those outlined in [18]. This serves as a benchmark for evaluating the model's performance, particularly in simulating wheel-rail interaction dynamics. Figure 5 depicts the outcomes of this validation process, providing a detailed comparison between the two models. A notable level of agreement between the simulated and actual results is apparent from the graphical representation, indicating a high degree of consistency. This corroborative evidence strengthens confidence in the proposed method's ability to precisely capture and analyze the intricate complexities of wheel-rail contact force dynamics.

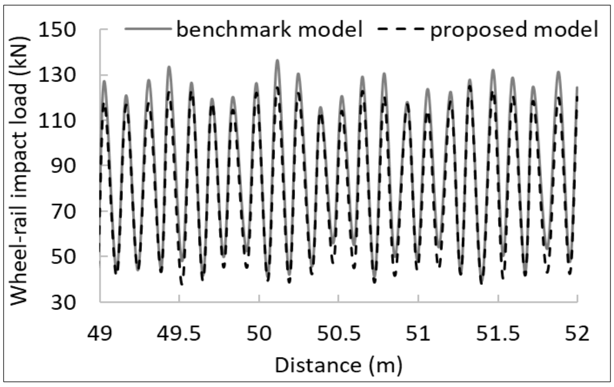

Figure 5 Model verification with the benchmark results

3. Results and discussions

The model presented here is utilized to explore variations in wheel-rail interaction resulting from different factors: the number of sleeper-ballast interface losses, interface gap size, and train speed. In the first two scenarios, the train speed is set at 90 km/h. The specifics of each analysis are elaborated upon as follows:

3.1. Effects of sleeper-ballast interface losses

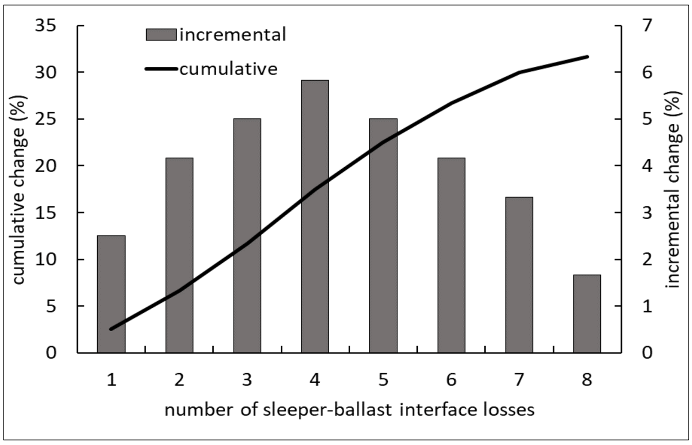

Figure 6 Wheel-rail impact force variation with respect to sleeper-ballast interface losses

Figure 6 demonstrates changes in wheel-rail impact loads attributed to variations in the length of the region where the sleeper-ballast interface is compromised. This region is progressively extended to encompass up to 8 consecutive sleeper-ballast interfaces. The analysis evaluates both the incremental and cumulative rates of wheel-rail impact load. The bar chart illustrates that up to 4 consecutive sleepers, an increase in the number of lost sleeper-ballast interfaces leads to a corresponding enhancement in the impact load compared to the preceding scenario. However, beyond 4 consecutive interfaces, the rate of wheel-rail impact load diminishes, indicating the track's contribution to the system's bending motion. The line graph further illustrates that as the number of lost sleeper-ballast interfaces rises, the load increases by over 30% when compared to the scenario where no such interface loss occurs. This underscores the significant impact of sleeper-ballast interface losses on the overall wheel-rail interaction dynamics.

3.2. Effects of sleeper-ballast interface gap size

Figure 7 depicts the fluctuation in wheel-rail impact load concerning various gap sizes between the sleeper and ballast interfaces. The bar chart reveals that the impact force increases with the enlargement of the gap between the sleeper-ballast interface, reaching its peak at 1.6 mm.However, beyond this threshold, the rate of increase in impact force between the wheel and rail diminishes as the gap size exceeds 1.6 mm. The line graph further elucidates that the impact force between the wheel and rail in scenarios with a gap between the sleeper-ballast interface is approximately 45% greater compared to cases without such a gap. This underscores the substantial influence of gap sizes on wheel-rail interaction dynamics.

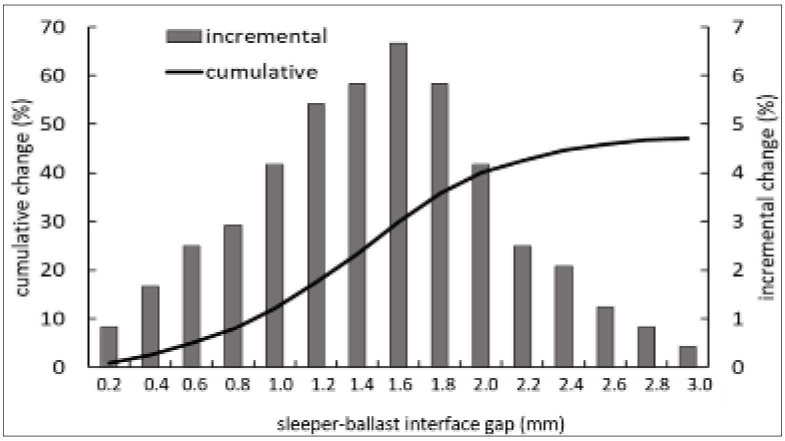

Figure 7 Wheel-rail impact force variation with respect to sleeper-ballast interface gap size

3.3. Effects of train speed

Figure 8 provides a visual representation of the alterations in wheel-rail interaction forces as the train speed increases from 60 to 200 km/h. A notable observation from the figure is the discernible trend of both incremental and cumulative increases in wheel-rail impact force, exhibiting a pattern indicative of exponential growth. At lower speeds, the fluctuations in wheel-rail interaction force are relatively subtle, indicating a relatively stable interaction between the train's wheels and the rail. However, as the train's velocity escalates, the dynamic forces at play become more pronounced and impactful. This escalation in speed leads to a noticeable amplification in the variations of wheel-rail interaction force, suggesting a heightened sensitivity to speed changes. This observation underscores the critical role that velocity plays in shaping the dynamics of wheel-rail interaction, with higher speeds amplifying the forces involved in this intricate interaction.

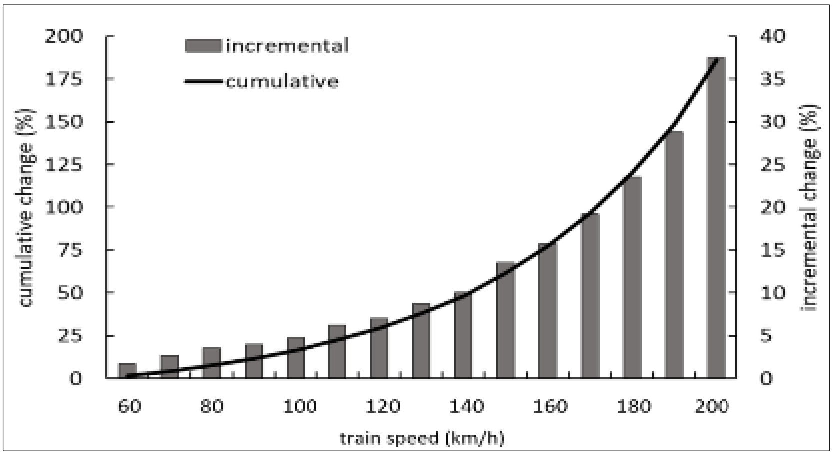

Figure 8 Wheel-rail impact force variation with respect to the train speed

4. Conclusion

This research aimed to simulate the loss of the sleeper-ballast interface, focusing particularly on the gap between the sleeper and ballast layers. We ensured precise modeling and validation through benchmarking procedures by employing a blend of MBD and FEA techniques. The investigation encompassed various scenarios, revealing that the impact of interface loss on wheel-rail impact load varied depending on the number of lost sleeper-ballast interfaces. The key findings are outlined below.

- In instances where fewer than 4 sleeper-ballast interface losses occurred, the gap resulted in a notable 30% increase in wheel-rail impact load. However, the rate of change diminished when more than 4 sleepers were involved.
- Moreover, gap size emerged as a critical factor, with sizes ranging from 0.2 mm to 1.6 mm leading to a load increase exceeding 65%. Beyond 1.6 mm, the increase rate decreased.
- Escalation in speed leads to a noticeable amplification in wheel-rail interaction force variations, suggesting a heightened sensitivity to speed changes.

These findings underscore the importance of considering various factors to uphold railway infrastructure integrity and safety.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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