ACTA TECHNICA JAURINENSIS
Vol. 18, No. 1, pp. 38-45, 2025
10.14513/actatechjaur.00769

Research Article

Quasi-static methods for determining the calculated wheel load on the railway track

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Submitted: 10/02/2025 Revised: 21/02/2025 Accepted: 21/02/2025 Published online: 26/02/2025

Abstract: This paper analyzes existing quasi-static methods for determining the wheel load on the railway track and provides recommendations for their application under various operating conditions. The study examines the influence of train speed, track design, and track condition on the calculated dynamic load values. The results indicate that at high speeds, additional dynamic components must be considered for a more accurate load assessment. A comparative analysis of the examined methods demonstrates their equivalence within specific speed ranges, enabling their synthesis to expand applicability and improve calculation accuracy. The study also includes calculations for ballastless track, considering its increased stiffness. It was found that for such structures, the load calculation equations need to be adjusted, as ballastless track exhibits reduced deflection but higher transmitted dynamic loads. The updated equations proposed in this paper allow for a more precise determination of wheel loads for different types of rolling stock and track structures. The results can be integrated into mathematical models of railway track behavior to refine external load parameters. Additionally, reference load values are essential for railway track condition monitoring systems.

Keywords: Railway; Quasi-static method; Wheel-rail interaction; Dynamic load assessment; Railway track monitoring

I. INTRODUCTION

A significant number of scientific and practical calculations related to railway track design are based on various mathematical models. Among the most widely used methods for analyzing track–vehicle interaction, the following can be distinguished:

Analytical Methods: These methods rely on classical approaches in mechanics and elasticity theory, utilizing simplified mathematical models to describe the interaction between rails, sleepers, and rolling stock. One such approach is the beam on an elastic foundation method. This model considers the rails as beams resting on an elastic foundation, represented by ballast or a ballastless structure. It enables the assessment of stresses and deformations in the track. For instance, in [1], the primary equation for rail deflection is used to determine rail stresses as an auxiliary tool for analyzing wear accumulation. In [2], the Zimmermann-Eisenmann quasi-static design method has been refined to account for dynamic factors. In [3], fundamental analytical relationships are applied to analyze load distribution in railway track reinforcement.

Finite Element Method (FEM): This modern and highly accurate numerical analysis method is used to model complex systems. It allows for the analysis of stresses and deformations in railway tracks by discretizing them into numerous small elements. FEM enables the consideration of various materials, geometries, load types, and even the impact of temperature conditions. In [4], the influence of different design parameters and damper materials on rail vibration damping characteristics is investigated. Study [5] examines the behavior of the railway embankment under dynamic loads from high-speed train movement. In [6], FEM is applied to analyze the reinforcement of the subgrade using micropiles. Due to its widespread application, numerous other studies have also utilized this method. In [7], modeling shows optimized transportation routes could cut costs and carbon emissions.

Multibody Dynamics (MBD) Models: This method is based on modeling the motion of a system comprising multiple bodies (such as wagons, axles, and wheels) while accounting for their dynamic interactions. A crucial aspect of MBD modeling is the simulation of wheel-rail contact. This approach enables the study of complex motion scenarios, including oscillations, wear, and impact loads. For instance, in [8], an analysis of freight wagon body deformations is conducted. Study [9] investigates train passage through railway sections with varying stiffness characteristics. In [10], the impact of track irregularities on train dynamics is analyzed.

Multilayer System Models: These models are used to analyze the railway track as a multilayer system, where each layer (rails, sleepers, ballast, and subgrade) is modeled separately. This approach accounts for the influence of each layer on track behavior. Such models are based on elasticity theory, particularly in modern implementations that focus on dynamic elasticity problems. In [11], a model of the railway track's stress-strain state is developed based on the dynamic elasticity problem. Study [12] presents a periodic model that incorporates the complex geometry of the track to analyze its response at low frequencies. In [13], the load-bearing capacity of metal corrugated structures in the multilayer sub-rail space is investigated.

Statistical and Stochastic Methods: These methods account for the random nature of track and rolling stock parameters, such as track irregularities or rail wear. The model can incorporate load distribution and dynamic effects associated with random deviations, helping to assess the impact of system inhomogeneities and uncertainties. In [14], a decision-making model based on fuzzy data is described. In [15], an intelligent model for efficient power supply in transport systems. Study [16] presents mathematical methods for processing recorded data to monitor electromagnetic interference in rails.

Experimental (Empirical) Methods: These methods involve field studies or tests conducted on specialized test benches. They provide real-world data on track–vehicle interaction using sensors and measurement systems. Experimental methods are applied to measure dynamic loads by installing sensors on rails, wheelsets, and other components. In [17], the results of stress assessment in railway track elements, particularly at high speeds, are presented. Study [18] reports on in-situ measurements of rail deflection in areas where ballast layer deformations occur. In [19], an autonomous railway track monitoring system based on a measurement complex is proposed.

In most cases, when studying the behavior of the railway track itself, the rolling stock is represented in a simplified manner. This is primarily due to the complexity of simultaneously modeling both a system of moving and oscillating bodies (rolling stock) and a system of compressed and deformed layers (railway track) using uniform mathematical approaches. Additionally, optimizing the mathematical model by excluding (or simplifying the consideration of) elements that are not directly investigated in a given research focus is often beneficial.

In such cases, the load from the rolling stock is replaced by a force (or a system of forces) acting from the wheel onto the rail. Naturally, the magnitude of this load depends on various factors, such as axle load, train speed, the condition of the rolling stock, and the state of the track. It must account for both static and dynamic components.

The determination of wheel-rail loads is fundamental in railway track design and maintenance. With the growing demand for high-speed rail and heavier freight transportation, accurate assessment methods are critical to ensure track safety, longevity, and cost-effective maintenance. Traditional methods often rely on simplified static calculations.

Numerous studies have explored methods for calculating wheel-rail loads. Analytical methods, such as the beam on an elastic foundation approach [1-3], have been widely used for their simplicity. Finite Element Method (FEM) models offer high accuracy but at the expense of increased computational effort [4-7]. Multibody dynamics models [8-10] enable a more comprehensive understanding of vehicle-track interactions, particularly for high-speed applications. Works [11-13] have focused on modeling the subgrade and ballast layers to capture the complex behavior of granular materials under dynamic loads. Dynamical loads also influence the settlement behavior of ballasted railway tracks [20].

Several analytical methods are currently available for determining the load level on the track. Despite the advancements, there remains a gap in practical and computationally efficient methods that balance accuracy and simplicity. Existing models either oversimplify the dynamic components or require extensive computational resources, which are not always practical for routine engineering applications. The need for a robust, adaptable approach that considers high-speed passenger and heavy freight train operations is evident, especially as railway networks modernize.

The objective of this study is to analyze these methods and provide recommendations regarding their application, particularly extending their use to high-speed railway sections and ballastless track structures. This study introduces improved quasi-static methods that integrate dynamic load factors while maintaining computational efficiency. The novelty lies in refining existing analytical models to account for high-speed conditions and variations in track structures, including ballastless tracks. Compared to conventional approaches, the proposed methods offer enhanced accuracy without significantly increasing complexity, making them suitable for both design and real-time monitoring applications.

II. Methods for determining the calculated wheel-rail load

A direct method for determining the dynamic force exerted by the wheel on the rail through static load assessment is described in [21–23] and expressed by equations (1) to (3).

$$Q_{dyn} = Q_{stat} + t\bar{s}Q_{stat} \quad (1)$$

$$\bar{s} = \text{n}\varphi \quad (2)$$

$$\varphi = 1 + \frac{V - 60}{140} \quad (3)$$

where Q_{stat} is the static wheel load on the rail (kN); t is the statistical distribution coefficient, for t=3 the calculation accuracy is 99.7 %; n is a coefficient accounting for track condition, typically within the range of 0.1–0.3; φ is the speed factor; V is the train speed (km/h).

For speeds up to 60 km/h, the speed factor can be assumed as φ=1. For instance, in [22, 23], the speed factor calculation accounts for train type, where equation (4) is proposed for freight trains and equation (5) for passenger trains.

$$\varphi = 1 + \frac{V - 60}{160} \quad (4)$$

$$\varphi = 1 + \frac{V - 60}{360} \quad (5)$$

This methodology is based on the widely accepted hypothesis that the statistical distribution of wheel-rail load values follows a Gaussian distribution. Eq. (1) and its graphical representation in **Fig. 1** and **Fig. 2** illustrate the range of load values, where the width corresponds to three standard deviations from the mean value (for t=3 in Eq. (1)). This implies that the probability of exceeding the calculated dynamic load is three occurrences per 1,000 measurements.

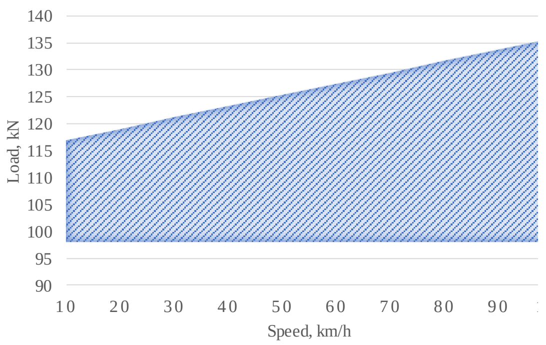

***Figure 1.** Calculated wheel-rail load for a freight train*

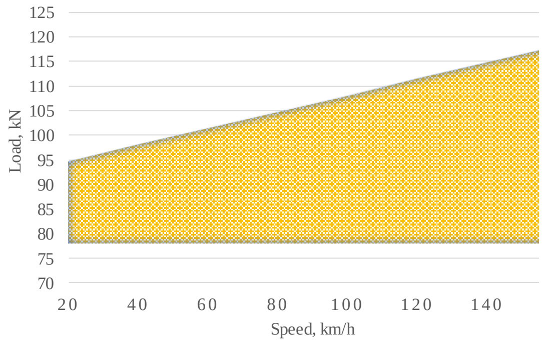

***Figure 2.** Calculated wheel-rail load for a passenger train*

For the creation of **Fig. 1** and **Fig. 2**, the static load was assumed to be 98 kN for a freight train, corresponding to an axle load of 20 t/axle, and 78 kN for a passenger train, corresponding to an axle load of 16 t/axle under normal track conditions.

Other alternative methods exist for calculating the dynamic wheel-rail load, each with its own specific features. One such approach determines the dynamic load as the statistical sum of multiple dynamic force components, as referenced in various studies, including [3, 13, 24]. This method can be concisely expressed by equations (6) to (8), allowing for the additional consideration of certain rolling stock and track parameters.

$$Q_{dyn} = \bar{Q} + \lambda S \quad (6)$$

$$\bar{Q} = Q_{stat} + \bar{Q}_s \quad (7)$$

$$S = \sqrt{S_s + S_r + 0.05S_i + 0.95S_c} \quad (8)$$

where $\bar{Q}$ – mean dynamic wheel-rail load (kN); λ=2.5 – coefficient accounting for a 0.994 probability of not exceeding the dynamic load; S – standard deviation of the force acting from the wheel to the rail (kN); $\bar{Q}_s$ – mean force due to the oscillation of the sprung mass of the vehicle (kN); S_s – standard deviation of the force from the oscillation of the sprung mass (kN); S_r – standard deviation of the force due to wheel rolling over rail irregularities (kN); S_i – standard deviation of the force caused by an isolated irregularity on the wheel (kN); S_c – standard deviation of the force caused by a continuous irregularity on the wheel (kN).

The characteristics of the force accounting for oscillations from the sprung mass of the vehicle are determined by equations (9) to (12).

$$\bar{Q}_s = 0.75Q_{s\,(\max\ )} \quad (9)$$

$$S_s = 0.08Q_{s\,(\max\ )} \quad (10)$$

$$Q_{s\,(\max\ )} = k_d(Q_{stat} - q_k) \quad (11)$$

$$k_d = 0.1 + 0.2\frac{V}{f_{st}} \tag{12}$$

where $Q_{s\,(\max)}$ – maximum force value due to oscillations of the sprung mass of the vehicle (kN); k_d – vertical dynamic coefficient, which depends on the specific type of wagon or locomotive; q_k – weight of the unsprung portion of the vehicle per wheel (kN); f_{st} – static deflection of the suspension springs (mm).

The standard deviations of dynamic forces are determined by equations (12) to (15).

$$S_r = 1.788 \cdot 10^{-7}\alpha_1\beta\varepsilon\gamma l\sqrt{\frac{Uq_k}{k}}\bar{Q}V \tag{12}$$

$$S_i = 0.05\alpha_0\xi e_0\frac{U}{k} \tag{13}$$

$$S_c = \frac{1.63 \cdot 10^{-2}\alpha_0 U\sqrt{q_k}V^2}{d^2\sqrt{kU - 32k^2 q_k}} \tag{14}$$

$$k = \sqrt[4]{\frac{U}{4EI}} \tag{15}$$

where α_1 – coefficient accounting for the weight of the track superstructure involved in wheel interaction, 0.403 for concrete sleeper; β – coefficient accounting for rail type, 0.9 for UIC60 rails; ε – coefficient depending on the type of rail supports, 1.0 for concrete sleepers; γ – coefficient depending on the type of ballast, 1.0 for crushed stone ballast; l – sleeper spacing (cm); U – subgrade stiffness modulus (MPa); E – rail steel stiffness modulus (MPa); I – rail moment of inertia (cm^4); α_0 – coefficient depending on the type of rail supports, 1.0 for concrete sleepers; ξ – ratio of additional rail deflection due to the presence of an isolated irregularity on the wheel to the depth of this irregularity, 1.47 under most conditions; e_0 – depth of the isolated irregularity on the wheel (cm); d – wheel diameter (cm).

The calculation results based on equations (6) to (15) are presented in **Fig. 3** for a freight train and in **Fig. 4** for a passenger train.

It should be noted that this method additionally determines the mean probable wheel-rail load. This load depends on the train speed and is therefore a function not only of the static load but also of the dynamic contributions from wagon body oscillations – Eq. (7). The calculated value is set at a level of 2.5 standard deviations from the mean probable value – Eq. (6). This implies that the adopted load value may be exceeded in 6 out of 1,000 measurements. The standard deviation accounts for the dynamic contributions from both the rolling stock oscillations and the railway track.

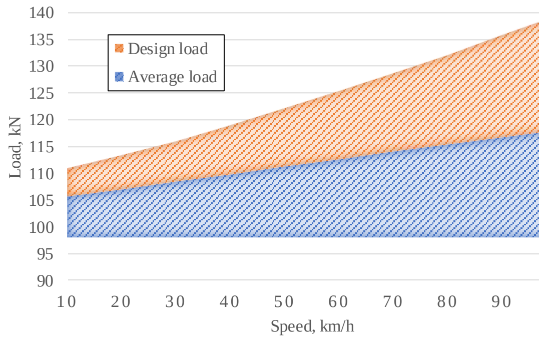

Figure 3. *Calculated wheel-rail load for a freight wagon, Eq. (6)*

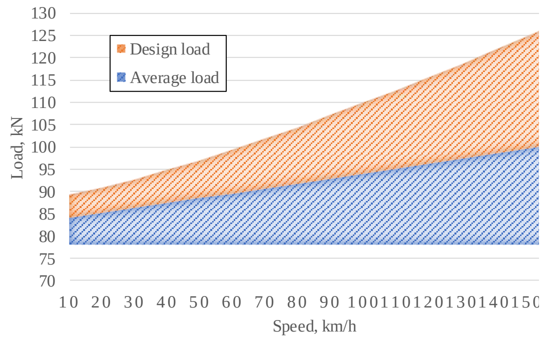

Figure 4. *Calculated wheel-rail load for a passenger wagon, Eq. (6)*

Despite some differences in approaches, both considered methods can be regarded as equivalent within the range of values presented in **Fig. 1–4**. This enables their synthesis to expand and refine the methodology.

III. Results

Equations (6) to (15) constitute a more complex and, consequently, less commonly used methodology. However, this approach allows for the consideration of the type of rolling stock, as well as the design and condition of the railway track.

To initiate the proposed wheel-rail load calculation algorithm, several input parameters must be defined. These include: static wheel load determined by the axle load and wheel configuration, train speed (a critical parameter affecting the dynamic load component), the current state of the railway track, subgrade stiffness, rail properties (including the modulus of elasticity and moment of inertia), sleeper spacing and ballast characteristics to capture structural influences on load distribution, suspension parameters and unsprung mass by important for modeling the vehicle’s dynamic response. The outcome of the algorithm is sensitive to the initial conditions specified. Notably, variations in train speed significantly affect the dynamic amplification factor, track irregularities and their initial amplitudes alter load distribution outcomes, suspension settings influence the interaction between rolling stock and track. Sensitivity analyses were conducted to determine how deviations in initial conditions impact the final calculated loads. By carefully defining these quantities, the proposed algorithm ensures reliable and repeatable results across various operating conditions.

For calculations based on this methodology, the authors combined the characteristics of common freight and passenger wagons used in European countries, as presented in **Table 1**.

Table 1. *Generalized wagon characteristics for calculations*

Characteristic	***Freight Wagon***	***Passenger Wagon***
Static wheel-rail load (Q_{stat}), kN	98	78
Weight of the unsprung part of the running gear per wheel (q_k), kN	14.7-24.5	11.8-17.7
Static suspension deflection (f_{st}), mm	90-120	90-110
Wheel diameter (d), cm	92	92

The results of parametric calculations considering different combinations of rolling stock and railway track characteristics are presented in **Fig. 5** for a freight train and in **Fig. 6** for a passenger train.

As seen in **Fig. 5**, the calculated wheel-rail load for freight wagons, determined using Eq. (1), aligns with other calculations within the considered speed range, particularly for speeds of 60–80 km/h, which are among the most common on the mainline corridors of European railways.

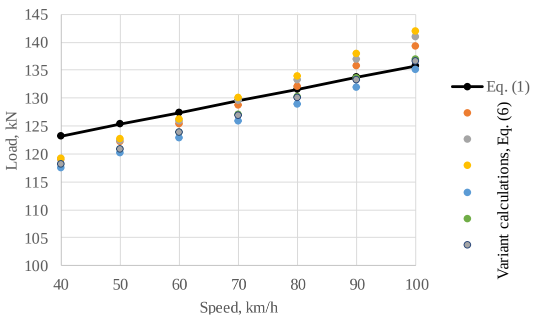

Figure 5. *Wheel-rail load for a freight wagon*

For passenger wagons, the calculated wheel-rail load (**Fig. 6**) obtained using a method with a more flexible consideration of dynamic processes results in higher values at high speeds compared to Eq. (1). Therefore, starting from speeds of 140–160 km/h, Eq. (3) is recommended to be applied in the form of Eq. (16).

$$\varphi = 1 + \frac{V - 90}{70} \tag{16}$$

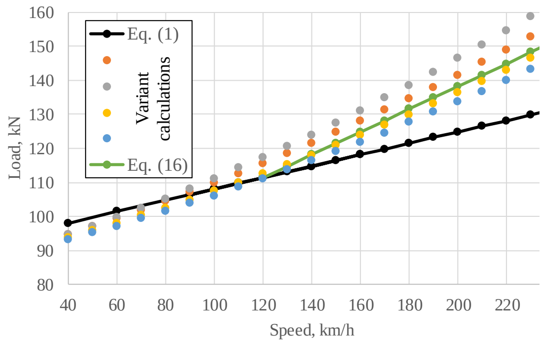

Figure 6. *Wheel-rail load for a passenger wagon*

The calculations and results presented above by the authors apply exclusively to ballasted track structures. Slab track is significantly stiffer because it rests directly on a rigid foundation (concrete slabs or a monolithic structure). This reduces rail deflection but increases the transmission of dynamic loads, primarily due to reduced energy dissipation.

To account for these differences, the previous calculations were repeated considering the structural and physico-mechanical characteristics of slab track. The generalized results are presented in **Fig. 7** for a freight wagon and in **Fig. 8** for a passenger wagon.

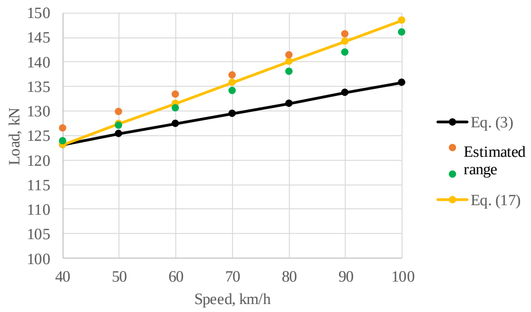

Figure 7. *Calculated wheel-rail load for a freight wagon on slab track*

For determining the wheel-rail load on slab track, it is recommended to use equation (17) for a freight wagon, equation (18) for a passenger wagon at speeds up to 120–140 km/h, equation (19) for a passenger wagon at higher speeds.

$$\varphi = 1 + \frac{V - 50}{70} \tag{17}$$

$$\varphi = 1 + \frac{V - 40}{80} \tag{18}$$

$$\varphi = 1 + \frac{V - 70}{50} \tag{19}$$

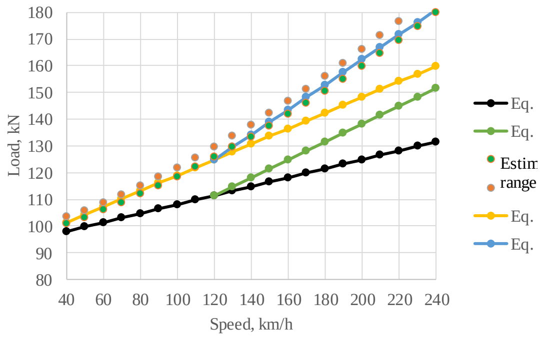

Figure 8. *Calculated wheel-rail load for a passenger wagon on slab track*

For better visual analysis, **Fig. 7–8** present the calculated load range obtained from parametric studies, along with results based on the previously established dependencies and those obtained using the adjusted equations (17) to (19) proposed by the authors.

IV. CONCLUSION

The study analyzes existing quasi-static methods for determining the wheel-rail load and provides recommendations for their application under various operating conditions.

While the proposed quasi-static methods improve accuracy over traditional static approaches, certain limitations exist: simplified representation of track irregularities may not capture all localized effects, assumptions regarding uniform material properties can lead to deviations under varying real-world conditions, environmental factors like temperature fluctuations and ballast degradation are not fully modeled, the methods primarily address vertical loads, with lateral forces considered beyond the current scope.

The influence of train speed, track structure, and track condition on the calculated values of dynamic loading has been investigated. It has been established that at speeds exceeding 140–160 km/h, additional dynamic components must be considered to achieve more accurate load estimation.

A comparative analysis of the examined methods has shown their equivalence within certain speed ranges, allowing for their synthesis to expand applicability and improve calculation accuracy.

Calculations have been performed for ballastless track, considering its stiffness characteristics. It has been found that for such structures, the load calculation equations need adjustment, as ballastless track exhibits reduced deflection but an increased level of transmitted dynamic loads.

Updated equations have been proposed for determining the wheel-rail load for various types of rolling stock and track structures.

The obtained results can be applied in various mathematical models of railway track behavior to justify the external loading parameters. Significant loads acting on the railway track may be caused also by machinery being used on the tracks [25].

Furthermore, reference loads are a crucial component of railway track condition monitoring systems. The authors intend to apply this development as a foundational element for training railway track monitoring systems with intelligent coverage, which analyze large datasets on loads and track conditions in real time [26, 27]. This opens opportunities for developing intelligent platforms for railway infrastructure diagnostics and predictive maintenance.

ACKNOWLEDGEMENT

The research was conducted as part of the implementation of the project "Decentralized System for Monitoring the Condition of Critical Transport Infrastructure Facilities with Intelligent Cover" (project registration number 0124U000744). The authors express gratitude to the employees of the Ukrainian State University of Science and Technologies and the members of the "SZE-RAIL" research team and the Vehicle Industry Re-search Center at Széchenyi István University.

AUTHOR CONTRIBUTIONS

D. Kurhan: Conceptualization, Supervision, Review and editing.

D. Kovalskyi: Theoretical analysis and calculations., Writing, Review and editing.

DISCLOSURE STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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