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Developed an Approach to Monitor the Technical Conditions of the Wheels by Measuring the Rolling Stock–track Forces

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Abstract

With the rapid development of railway transportation, there is a growing need to improve the method of measuring the impact force exerted by rolling stock on the rail track. Monitoring the technical conditions of the rail track and wheels is crucial. This research aimed to investigate the improvement of existing systems for wheel monitoring during operation and propose a method to develop rolling stock diagnostic systems while the train is in motion. The study focused on extending the track measuring zone to ensure the comprehensive detection of defects across the entire rail wheel, considering the speed and axle load of the rolling stock. By considering these factors, the researchers aimed to optimize the detection of defects in the rolling stock wheels. The parameters of the inter-sleeper gap on the railway track and the optimal length of the measuring track for defect detection were determined based on the research findings. Furthermore, the study also determined the permissible speeds for rolling stock on the rail-measuring track. This information is crucial for ensuring safe and efficient operations while conducting measurements and diagnostics on the rolling stock. This research contributes to advancing rolling stock monitoring and diagnostics by proposing improvements to existing systems and providing insights into optimizing the measurement process. By accurately detecting defects and determining permissible speeds, this research aids in enhancing the safety and reliability of railway transportation systems.

Keywords: Rolling stock, transportation, railway track, track geometry measurement vehicles (TGMV), Stress

INTRODUCTION

Wheel/rail interaction refers to the complex dynamic relationship between the train wheels and the rail tracks they traverse. Various factors, including the geometrical properties of the rail and wheel, the material characteristics of the rail and wheel, and the operating conditions of the train, influence this interaction. Ensuring proper maintenance and inspection of the rail and wheel is crucial for promoting safe and efficient train operation while minimizing wear and tear.

The maintenance and inspection procedures for the rail and wheel involve continuous measurement and alignment of the rail track and wheels. These procedures help identify any deviations or defects that may affect the performance of the rolling stock. One aspect of concern is the condition of the wheel's tread surface, which can develop issues such as flat spots, scaling, and other defects during

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operation. These defects can significantly increase the dynamic loads exerted on the track and rolling stock [1–3].

Traditionally, the identification of wheel tread defects has relied on a combination of wheel impact load detector (WILD) systems and optical systems. These systems can measure the wheel profile and capture images of the wheel tread condition as the train passes, as observed in Australian rail systems. However, there are limitations associated with this approach in terms of data analysis and drawing conclusive insights. The effectiveness of data collection is heavily dependent on climatic and environmental conditions [4]. Additionally, these systems can be costly and require regular maintenance to ensure accurate and reliable operation.

It is essential to explore alternative approaches and technologies to overcome these limitations and improve the efficiency of wheel tread defect identification and maintenance processes. By leveraging advancements in data analysis, machine learning, and sensor technologies, it may be possible to develop more robust and cost-effective solutions for monitoring and diagnosing wheel tread conditions. These advancements could lead to more accurate and timely detection of defects, enabling proactive maintenance and reducing the risk of operational issues and safety hazards associated with wheel defects in railway systems.

Identifying wheel defects typically involves dynamic testing through noise and sound analysis during operation and static inspection through a visual examination and geometric dimension checks. However, visually inspecting and accurately measuring these defects on a wheel is challenging and prone to imprecision, especially in adverse weather conditions with inadequate lighting. Moreover, the location of the fault on the wheel may be in an inaccessible or unsafe zone, depending on the wheel's position when the train stops.

Given these challenges, developing, and enhancing methods for assessing the impact of wheels on railway tracks and capturing other signals associated with wheel movement along the tracks is imperative. Defective wheels rolling on the rails generate dynamic forces that induce fatigue stress, damaging the rails, wheels, bearings, and other components of the rolling stock.

Numerous methods have been developed for detecting defective wheels, and they are employed in automated systems for diagnosing rolling stock during train operation [5–13]. The diagnostic methods used in different countries vary in measurement techniques, accuracy, and threshold values for indicators that determine whether wheels are deemed defective and need replacement [14]. These systems play a crucial role in identifying and addressing wheel defects, contributing to railway operations' overall safety, reliability, and performance.

METHODS FOR MEASURING THE ROLLING STOCK VERTICAL FORCE IMPACT ON RAILWAY TRACK

Various techniques are available to assess the vertical impact of rolling stock on the track. These techniques can be categorized as follows:

1. *Track geometry measurement:* Track geometry measurement vehicles (TGMV) equipped with sensors are used to measure track geometry. This data is then used to calculate dynamic wheel loads.
2. *Strain gauges:* Strain gauges can be attached to the rail as shear bridges. They measure the vertical wheel load generated by the passing of rolling stock.
3. *Accelerometers:* Accelerometers can be mounted on the rail or the rolling stock. They measure the vertical acceleration of the rail or rolling stock caused by the impact.
4. *Dynamic track stiffness:* This method uses a specially designed vehicle with a dynamic force exciter. The vehicle applies a known force to the rail, and the response of the rail is measured using accelerometers. This data helps infer the vertical stiffness of the track.

5. *Rail deflection measurement:* A laser-based system is used to measure the deflection of the rail caused by the passing of rolling stock. This data calculates the dynamic wheel load and assesses the vertical impact [15].
6. *Wheel impact load detector (WILD):* WILD is a track-based system that consists of instrumented cribs (strain gauges fixed to the rail) configured to measure the entire wheel circumference. It provides information on the impact loads experienced by the wheels.
7. *Combined measurement methods:* These techniques combine various measurements and information, such as vehicle weight, speed, and weather conditions, to obtain a comprehensive understanding of the wheel/rail interaction and monitor the performance of the railway track.

By employing these techniques, railway operators can gather data on the vertical impact of rolling stock, assess the condition of the track, and make informed decisions regarding maintenance and safety measures.

In several countries, two commonly used railway track design and construction methods are the GOST 34759-2021 standard and the piecewise continuous registration of interaction forces method.

The GOST 34759-2021 standard for railway track design and construction encompasses several approaches to determine the vertical forces on rails, including:

1. *Analytical method:* This method employs mathematical formulas to calculate the vertical forces based on the track's geometry and loading conditions. It relies on theoretical calculations to estimate the forces acting on the rail/wheel interaction.
2. *Empirical method:* The practical method involves conducting actual tests on a limited rail section to estimate the vertical forces. These tests provide valuable data on the forces experienced by the rail and can be used to make informed decisions regarding track design and construction.
3. *Statistical method:* The statistical method utilizes statistical analysis techniques to estimate the vertical forces based on a sample of data. It involves analyzing the collected data and using statistical models to infer the forces acting on the rail/wheel interaction. However, research has indicated that the above methods may not accurately estimate the forces acting on the rail/wheel interaction, as they do not consider all the relevant factors involved.
4. *Experimental method:* The practical method entails testing actual track sections under realistic loading conditions to measure the vertical forces directly. This method utilizes techniques such as the Schlumpf method and the influence matrices method, which are point methods. These methods allow for the registration of interaction forces only when the wheel is positioned above the strain gauges, as illustrated in Figure 1.

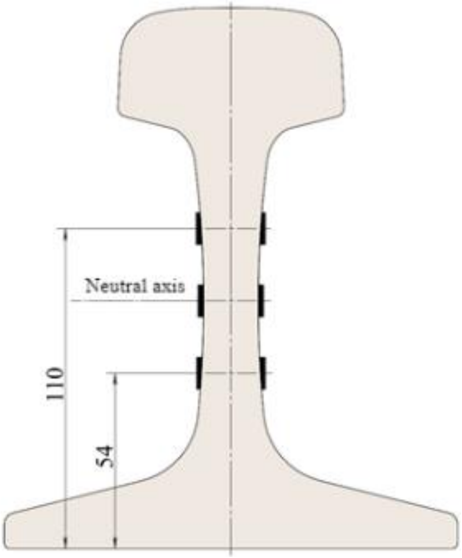


Figure 1. Strain gauges arrangement on rail according to GOST 34759-2021.

By employing these methods, railway engineers and designers can gain insights into the forces acting on the rail/wheel interaction, ensuring the track's safety, stability, and performance.

According to the Schlumpf method [16] for measuring vertical forces, two strain gauges are placed symmetrically on both sides of the rail on the neutral line of the vertical bend at 81 ± 1 mm from the foot (R65 rail). The strain gauges and two compensation strain gauges are connected into one measuring bridge. Following the method of influence matrices [17] for measuring the vertical forces, four strain gauges are installed in the vertical direction on both sides of the rail. Two are glued at 54 ± 1 mm from the base of the rail, the other two at a distance of 110 ± 1 mm. In this method, the readings of each strain gauge are used; therefore, each strain gauge with three compensation strain gauges is connected to four measuring bridges.

The studies carried out [18] on point methods for monitoring the technical condition of rolling stock wheels in motion installing measuring sections with a step of 136 mm over the length of the measuring track section of 25 m. According to the Schlumpf method, the number of strain gauges used is 360 pieces, and by using the influence matrices method - 720 pieces. This arrangement made examining the entire wheel surface impossible after the wheel pair passed the measuring section. Therefore, the "blind" zones on the wheel's surface are up to 90%, depending on its diameter. Thus, the point methods provided in GOST 34759-2021 standard for railway track design and construction are ineffective for monitoring the technical condition of the rolling stock wheels while the train is moving.

Researchers [19–21] theoretically substantiated and experimentally verified the effectiveness of piecewise continuous registration of vertical forces in the wheel/rail contact to continuously measure the vertical impact of the rolling stock on the railway track. According to this method, the length of the measuring zone is 200 mm. This measuring zone is not long enough to capture the entire wheel circumference in one wheel pass; the rolling stock may require several repeated passes along the measuring section, which means more costs and time.

For monitoring the wheel condition of the train [18], an instrumented track section with a length of 12.5 m and 84 strain gauges is proposed using the method of two areas, which made it possible to detect defects of at least 98% of the wheel circumference regardless of diameter.

Monitoring the wheel condition is a significant task with increasing the axle loads and rolling stock speed. Thus, improvement of the wheel/rail forces measurement method is required to monitor the condition of the wheels and detect defects around the entire wheel circumference.

This research aims to improve the method for measuring the rolling stock force impact on the track to monitor the technical condition of the wheels and detect defects entirely at 100% of the entire wheel by extending the measuring zone; therefore, the research will investigate the effect of developing measuring location on the track stresses and rolling stock speed. The piecewise continuous method for measuring vertical forces in the wheel/rail contact by measuring stresses in two rail sections will be developed to monitor the technical condition of the wheels. This method makes it possible to increase the length of the measuring zone, reduce the number of strain gauges and measuring channels, and reduce the size of the measuring railway track.

THE INTER-SLEEPER GAP PARAMETERS SELECTION OF THE RAILWAY TRACK AND DETERMINATION OF THE OPTIMAL MEASURING ZONE LENGTH

In the first stage, a model of a railway track 4600 mm long was developed, in which an R65-type rail was laid on sleepers. This model makes it possible to consider the features of the adopted design solutions for the upper structure of the railway track (Figure 2), increasing the distance between the centers of the sleepers from 544 to 1020 mm, changing the modulus of elasticity of the rail base, and the location of the measuring sections with installed strain gauges.

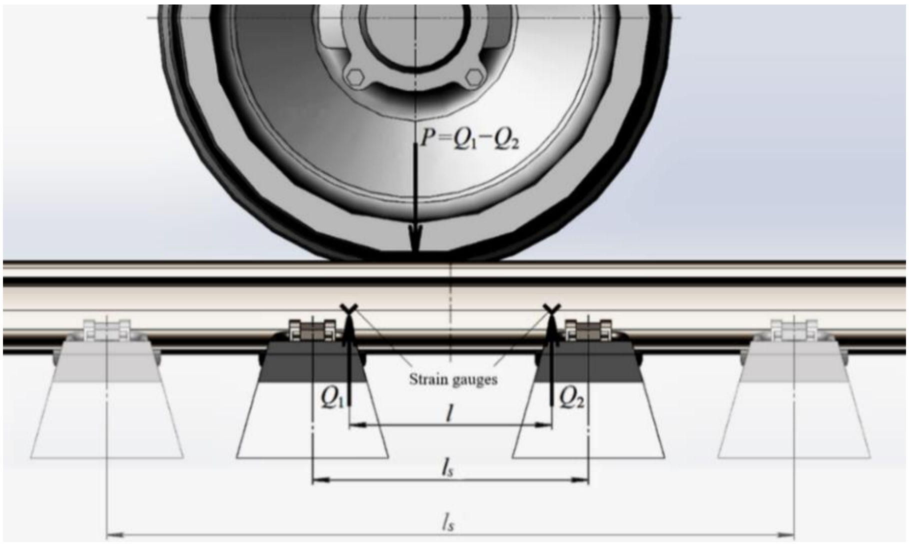


Figure 2. Calculation scheme of the wheel/rail interaction.

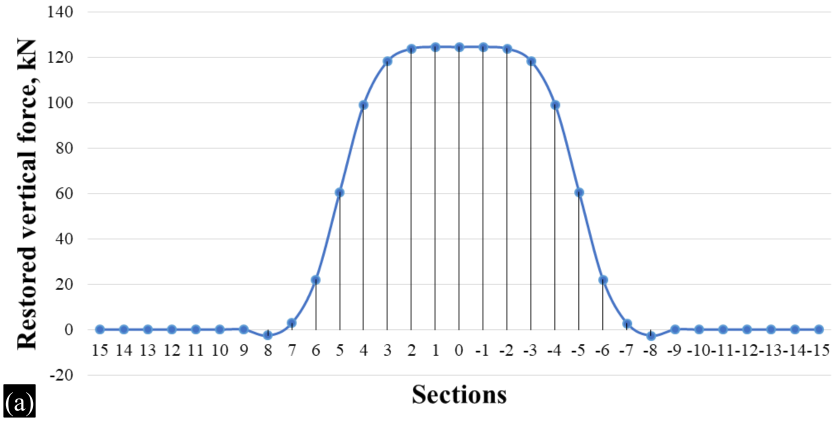
Where, P is the vertical force from the wheel to the rail; Q_1, Q_2 are shear forces; L is the distance between the measuring sections with installed strain gauges; L_s is the distance between the centers of the sleepers.

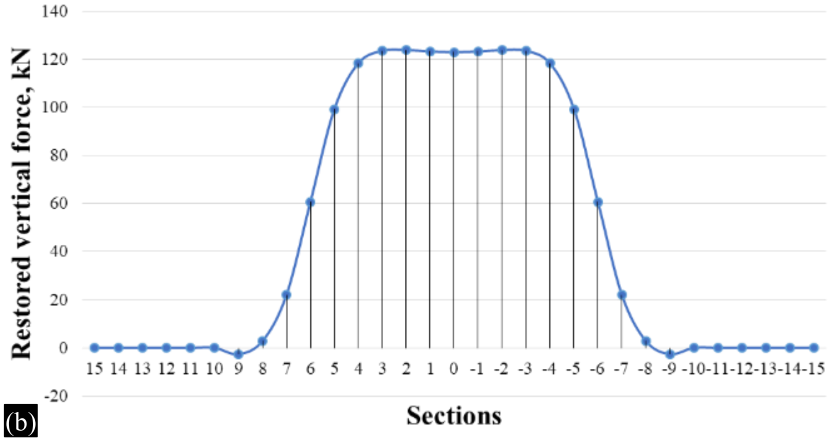
At the same time, the design characteristic of the track's structure in the calculations was chosen: the R65 rail laid on reinforced concrete sleepers on the ballast. The ballast layer under the sleeper was assumed to be 55 cm, with a sub-ballast layer of sand extending a further 20 cm.

The rail analysis model was created using SolidWorks 2021, and the finite element analysis was performed using ANSYS Workbench version 2021.

The values of the calculated vertical forces were determined using the method of two sections (Figure 3). One of the best options for increasing the length of the measuring zone according to this method is increasing the distance between the sleepers. At the same time, it was found that the relationship between the length of the measuring zone and the distance between the sleepers is linear (Figure 4).

As a result of the theoretical analysis performed using the finite element model of a rail with sleepers, it was determined that the increase in the length of the measuring zone on the rail when using the method of the two sections could be achieved by increasing the distance between the sleepers. However, the impact of the rolling stock on the components of the rail track and structures grows. Then the stress increased in the rail, sleeper, ballast under the sleeper, and on the subgrade (formation).

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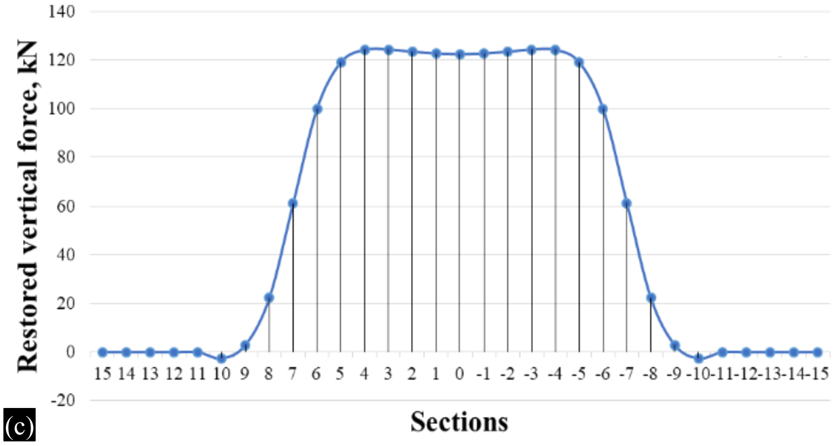
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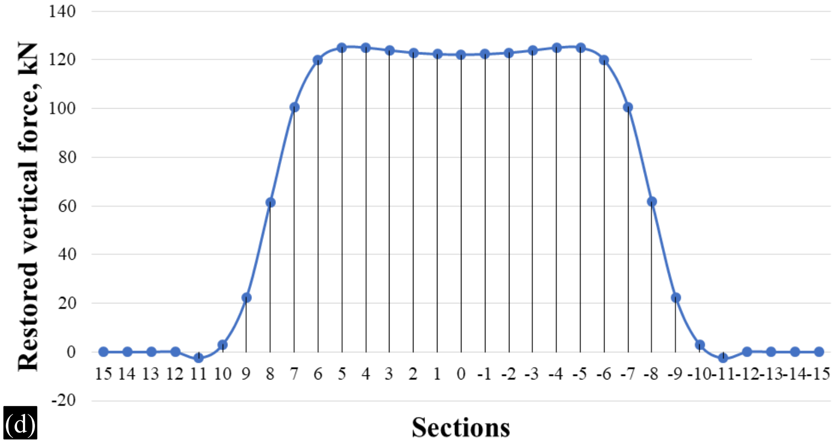
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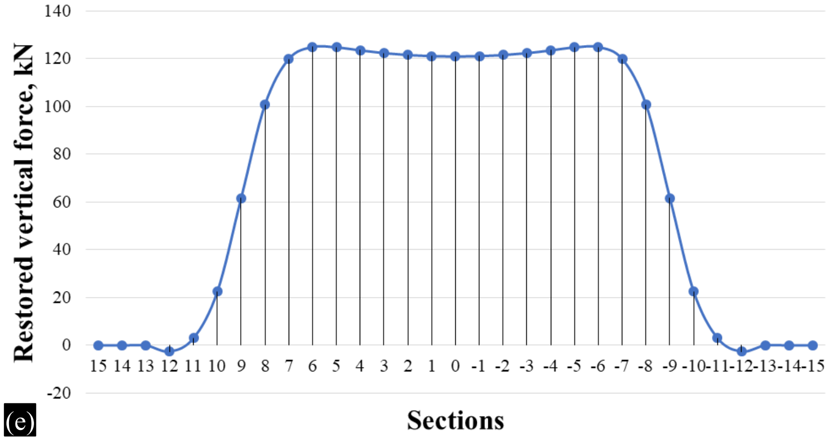
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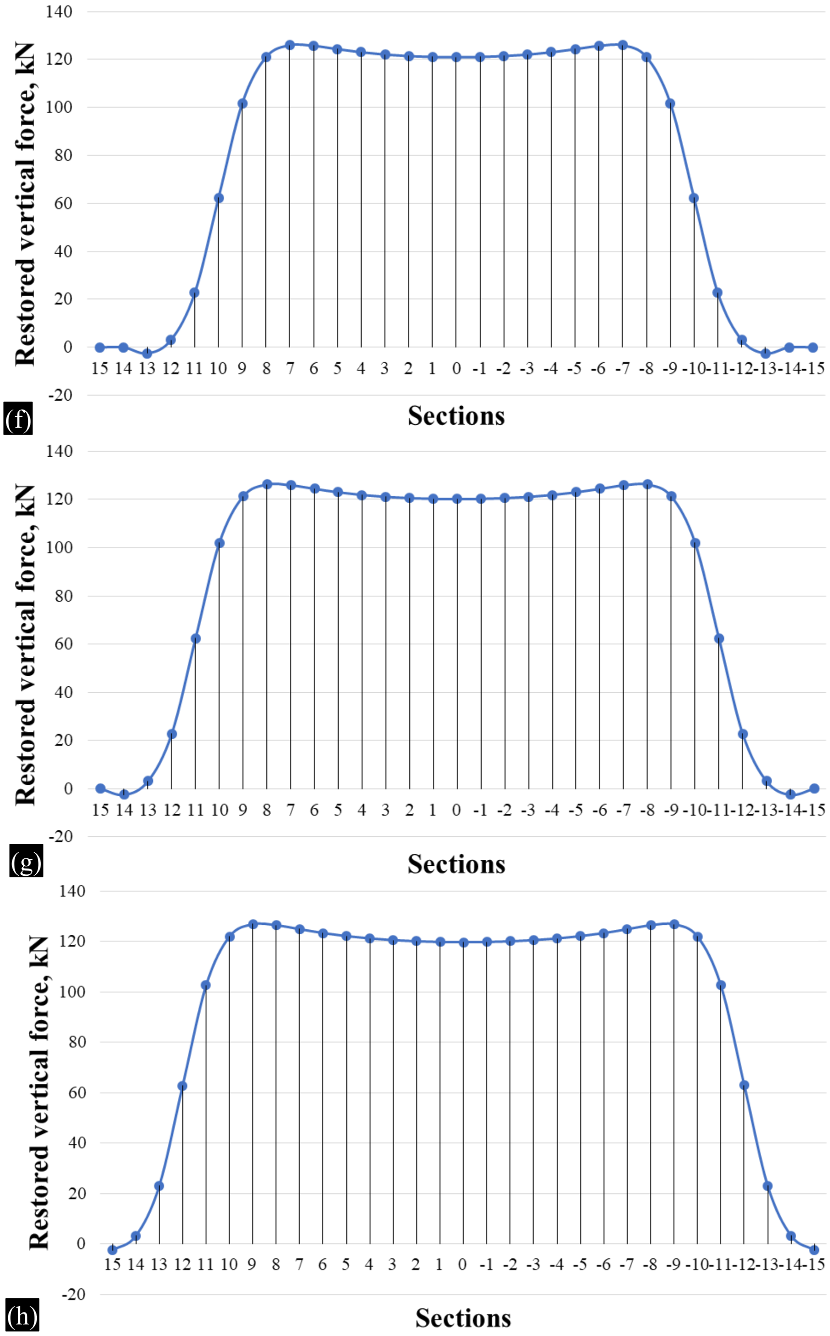

Figure 3. Measured vertical forces using the method of two sections at (a) distance between sleepers. (a) 544 mm, (b) 612 mm, (c) 680 mm, (d) 748 mm, (e) 816 mm, (f) 884 mm, (g) 952 mm, (h) 1020 mm.

DETERMINATION OF THE RAILWAY TRACK COMPONENTS LOADING

At the subsequent stage, calculations were conducted to assess the loading of the structural elements of the railway track, considering different axle loads of the rolling stock [22].

The calculations were performed using a multivariate approach based on the "Methodology for assessing the impact of rolling stock on the track in terms of ensuring its reliability" [23]. This methodology considers various factors, such as the distances between sleepers and the axle loads of the rolling stock, measured in ton-force (tf). By considering these factors, the methodology enables the determination of the loading experienced by the structural elements of the rail track.

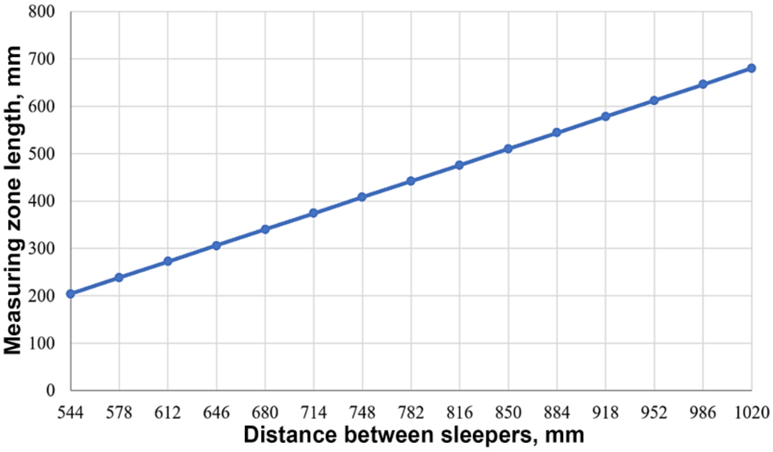

Figure 4. The relationship between the measuring zone length and the distance between the sleepers.

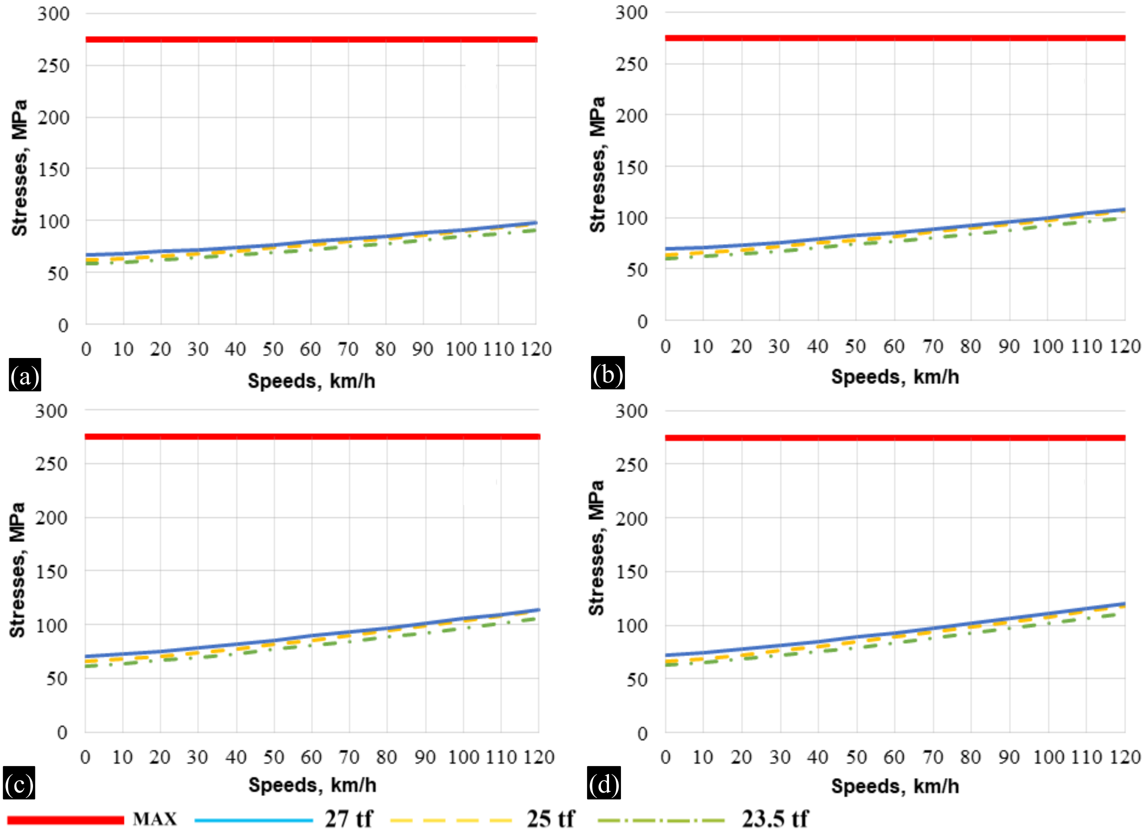

Figure 5. The relationship between the maximum rail stresses and the rolling stock speed with different axle loads. (a) with a distance between sleepers 544 mm; (b) with a distance between sleepers 748 mm; (c) with a distance between sleepers 884 mm; (d) with a distance between sleepers 1020 mm.

The results of these calculations are presented in Figures 5–8, illustrating the distribution of loading across the rail track’s structural elements. Figures 5–8 provide visual representations of the calculated loading, offering insights into the areas that experience higher or lower loading levels.

By employing this methodology and conducting these calculations, evaluating, and understanding the loading patterns and stresses imposed on the rail track’s structural elements is possible. This information is crucial for ensuring the reliability and integrity of the track, enabling appropriate maintenance and design decisions to be made.

Rail Stress

Figure 5 shows that as the distance between the centers of the sleepers increases, the maximum stress values in the rail remain below the allowable stress limits for all the considered axle load cases.

Figure 5 provides a graphical representation of the maximum stress distribution in the rail for different distances between the sleeper centers. The stress values are compared against the allowable stress limits, which serve as a criterion for determining the rail's structural integrity.

The analysis indicates that even with increased distance between the sleepers, the maximum stress levels experienced by the rail do not surpass the specified allowable stress limits. This finding suggests that the rail structure can withstand the applied loads without exceeding the acceptable stress thresholds.

Ensuring that the stress levels remain within the allowable limits is crucial for maintaining the integrity and longevity of the rail. By observing the results presented in Figure 5, it can be concluded that the considered axle load cases, in conjunction with the varying sleeper distances, do not impose excessive stress levels on the rail.

Sleeper Stress

Considering the maximum stress values in the sleeper, Figure 6 illustrates the impact of different inter-sleeper gap lengths on the top allowable speeds, particularly concerning an axle load of 27 tons [22].

Figure 6 demonstrates that when the inter-sleeper gap is 748 mm, even with an axle load of 27 tons, the speed does not fall below the recommended maximum rates. This indicates the track can support the given load and allows safe train operations at optimal speeds.

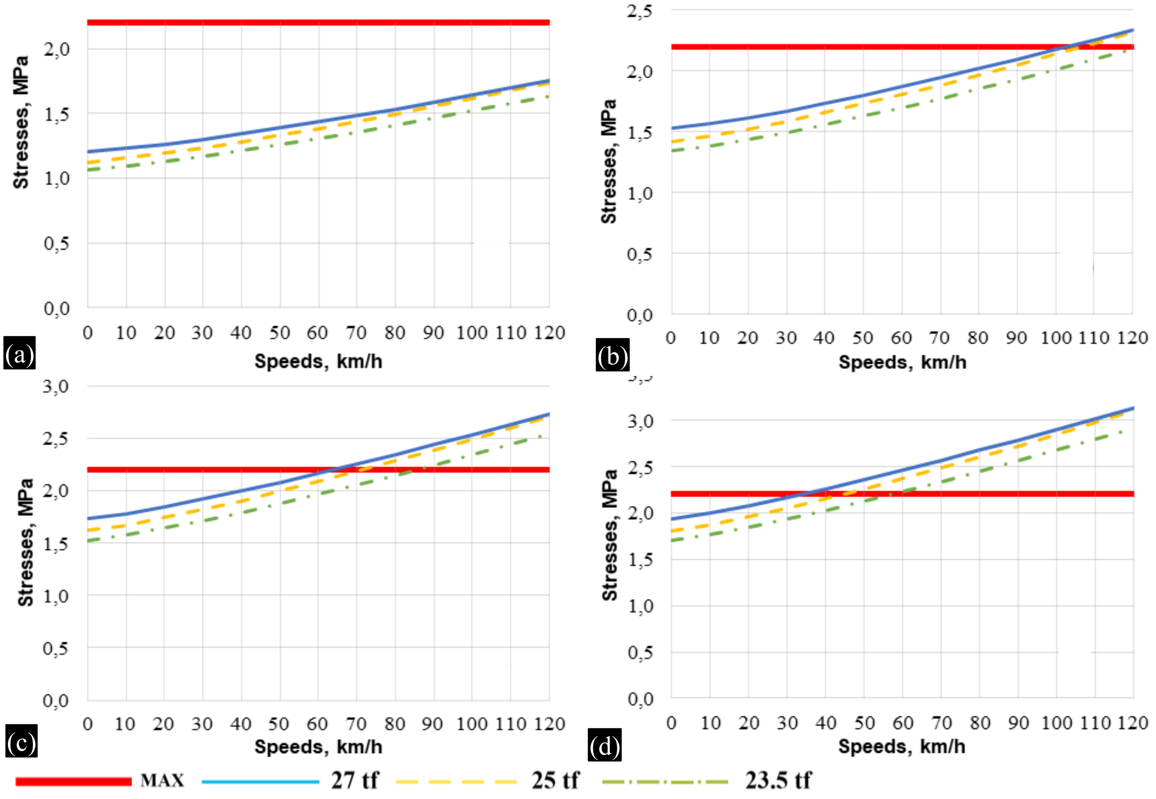

Figure 6. The maximum sleeper stresses and the rolling stock speed with different axle loads. (a) with a distance between sleepers 544 mm; (b) with a distance between sleepers 748 mm; (c) with a distance between sleepers 884 mm; (d) with a distance between sleepers 1020 mm.

However, when the distance between the centers of the sleepers increases to 884 mm, the maximum allowable speed is significantly reduced compared to the cases with inter-sleeper gaps of 544 mm and 748 mm. This reduction is expected as the longer inter-sleeper gap leads to increased stresses in the sleeper, thereby imposing limitations on the maximum speed at the measuring section.

Furthermore, the situation worsens when the sleeper spacing reaches 1020 mm. In this scenario, the maximum stresses in the sleeper escalate significantly, further constraining the full allowable movement speed across the measuring section.

Figure 6 visualizes the relationship between the inter-sleeper gap length, maximum sleeper stresses, and the corresponding limitations on speed. It highlights the importance of considering these factors in track design and maintenance to ensure safe and efficient train operations.

Sleeper-Ballast Contact Pressure

Figure 7 illustrates the relationship between the distance between the centers of the sleepers and the maximum sleeper-ballast contact pressure at different axle loads and speeds [22]. It provides valuable insights into the impact of these factors on the permissible pressure values and the condition of the track.

Figure 7 shows that when the distance between the centers of the sleepers is 1020 mm, the maximum sleeper-ballast contact pressure exceeds the permissible pressure values at speeds of 100 km/h for axle loads of 25 t and 27 t. This indicates that under these conditions, the contact pressure between the sleeper and the ballast exceeds the recommended limit, potentially leading to track instability and increased risk of track deterioration.

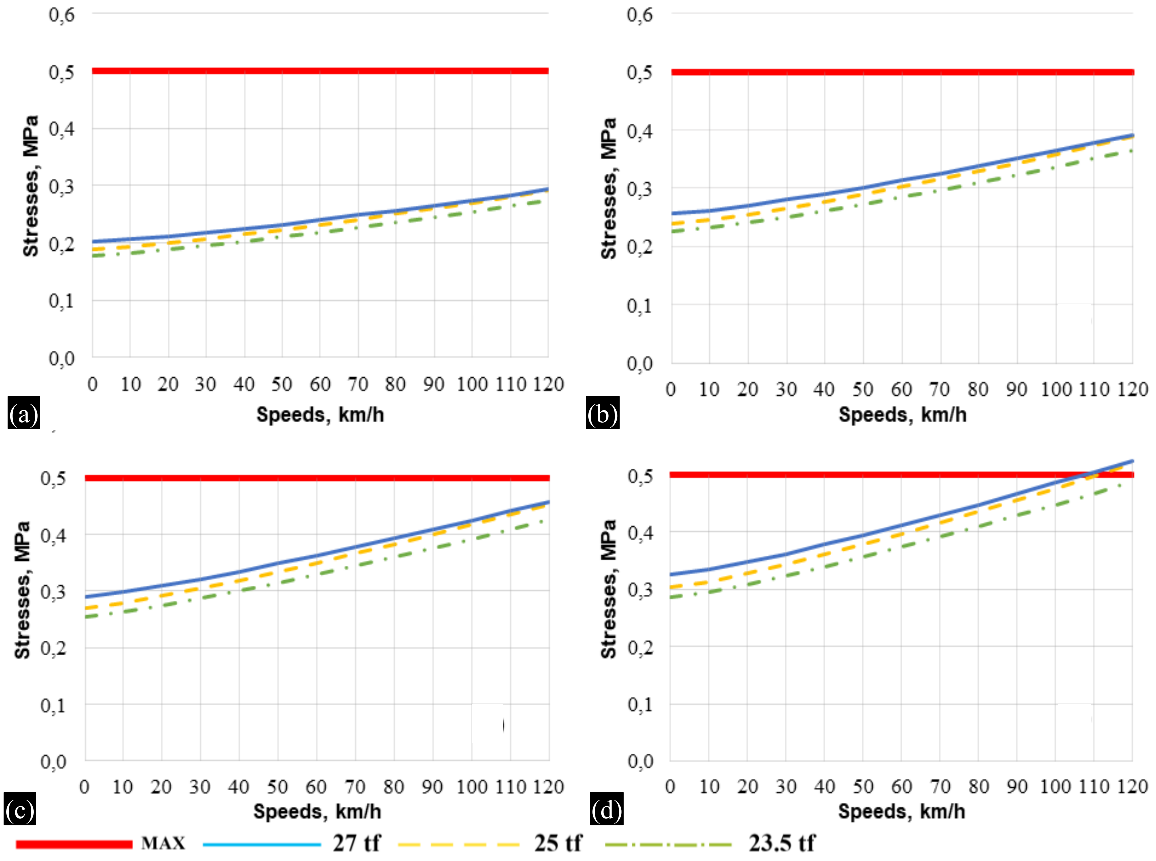

Figure 7. The influence of speed and axle load on the maximum sleeper-ballast contact pressure. (a) with distance between sleepers 544 mm; (b) with distance between sleepers 748 mm; (c) with distance between sleepers 884 mm; (d) with distance between sleepers 1020 mm.

On the other hand, Figure 7 also shows that the maximum stresses in the ballast underneath the sleeper, resulting from an increase in the distance between the centers of the sleepers, do not significantly impact the current allowable speed of the rolling stock along the measuring section. This implies that the current speed limits can still be maintained despite the increased stresses in the ballast.

However, it is essential to note that the increased sleeper/ballast contact pressure resulting from more significant inter-sleeper gaps will lead to accelerated track deterioration and higher maintenance requirements. It highlights the need for regular track inspections, maintenance activities, and potential adjustments to the permissible pressure values to ensure the long-term reliability and safety of the railway track.

Overall, Figure 7 provides valuable information regarding the relationship between the distance between sleepers, sleeper-ballast contact pressure, and track conditions, serving as a reference for track design, maintenance, and optimization efforts.

Subgrade Bearing Pressure

Figure 8 presents the maximum bearing pressure at the sleeper-subgrade interface for different distances between the sleepers and various axle load values [4]. This information is crucial for evaluating the structural integrity and performance of the track.

Upon analyzing Figure 8, it is evident that for inter-sleeper distances of 544 mm and 748 mm, the maximum bearing pressure at the sleeper-subgrade interface remains within acceptable limits for all considered axle load values. This result indicates that the pressure exerted on the track structure is within the permissible range at these distances, even considering the established network speeds.

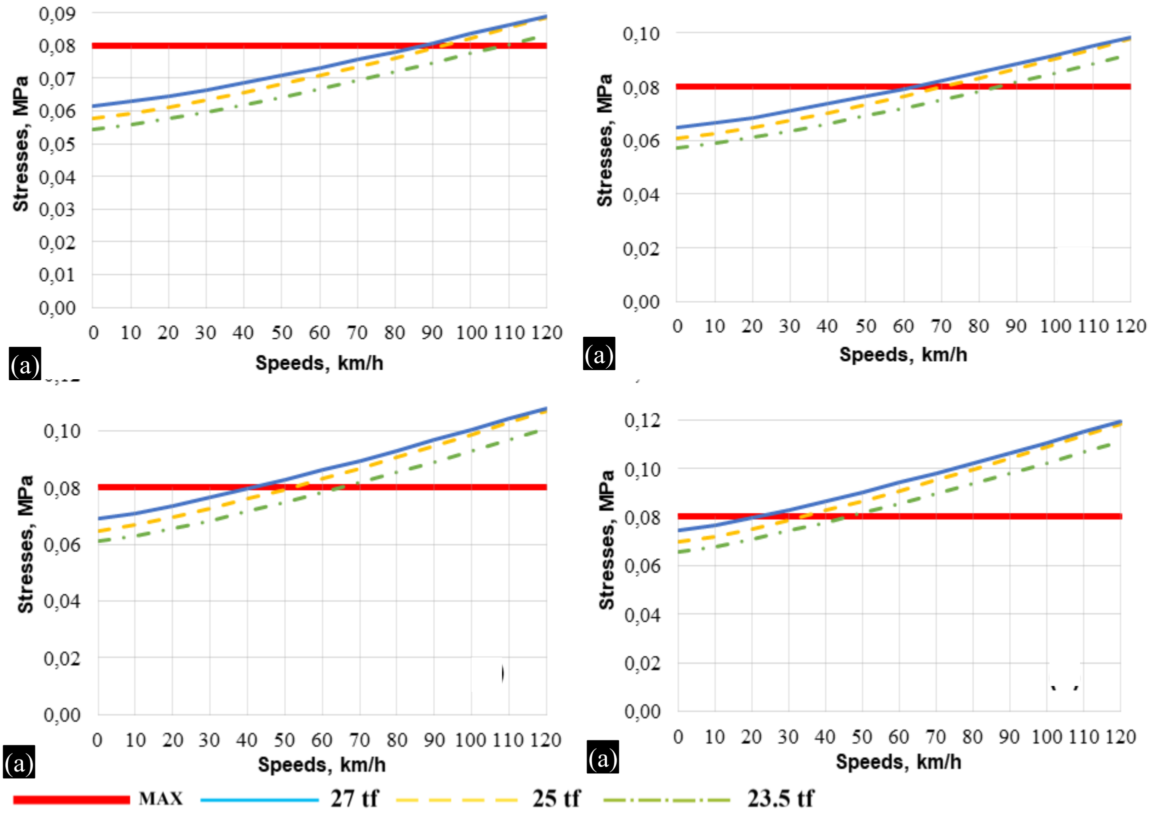

Figure 8. Maximum track subgrade stresses and the speed of the rolling stock with different axle loads. (a) with a distance between sleepers 544 mm; (b) with a distance between sleepers 748 mm; (c) with a distance between sleepers 884 mm; (d) with a distance between sleepers 1020 mm.

Table 1. Recommended speeds of rolling stock (km/h) at different distances between sleepers.

Distance between sleepers, mm	Axle load		
	23.5 tf	*25 tf*	*27 tf*
544	105	90	85
612	100	85	80
680	90	75	70
748	80	70	60
816	75	60	50
884	65	50	40
952	55	40	30
1020	45	30	20

However, when the distance between the sleepers is increased to 884 mm and 1020 mm, the maximum bearing pressures at the sleeper-subgrade interface exceed the recommended limits, resulting in lower permissible speeds. This signifies that the pressure exerted on the track structure is significantly higher than acceptable for the distance between sleepers.

The findings from Figure 8 highlight the importance of maintaining appropriate distances between sleepers to ensure that the bearing pressures at the sleeper-subgrade interface remain within safe and permissible levels. When the inter-sleeper gap exceeds certain thresholds, the track's structural integrity and performance may be compromised, necessitating speed restrictions and potential track maintenance activities.

In summary, Figure 8 provides valuable insights into the relationship between inter-sleeper distances, maximum bearing pressures at the sleeper-subgrade interface, and permissible speeds. It serves as a reference for optimizing track design, maintenance practices, and operational considerations to ensure the long-term reliability and safety of the railway track.

Based on the values of the maximum stresses arising in the track components, the maximum permissible speeds of the rolling stock on the measuring section of the railway track were determined (Table 1).

CONCLUSIONS

Considering the results presented above, the study has yielded several significant findings:

1. Theoretical studies conducted using finite element modeling of a rail with sleepers have demonstrated the feasibility of increasing the distance between sleepers along the instrumented track section equipped with strain gauges. This finding substantiates the possibility of extending the length of the measuring zone on the rail. However, it is essential to note that increasing the inter-sleeper gap can lead to a higher impact of the rolling stock on the various components of the railway track, potentially causing the degradation of the track structure.
2. The research has confirmed that it is possible to appropriately select the length of the measuring zone and the parameters of the inter-sleeper gap when designing the measuring section of the railway track to monitor the condition of the rolling stock in motion. It is crucial to ensure that the speed of the rolling stock passing through the measuring section does not exceed the recommended allowable speeds, considering the different distances between the sleepers and the axle load of the rolling stock.
3. The study has improved the piecewise continuous method for measuring vertical forces in the wheel/rail contact by incorporating stress measurements in two rail sections to detect defects on the wheel tread surface. This enhanced approach increases the length of the measuring zone, saving time and reducing the number of strain gauges and measuring channels required.

These findings collectively contribute to the understanding and development of effective techniques for monitoring the condition of rolling stock and assessing the impact of wheel/rail interaction. They provide insights into optimizing the design and operation of measuring sections in railway tracks, ensuring safe and reliable performance while minimizing maintenance requirements.

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