

# A Review of Wheel Wear Damage in Railway Vehicle

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## ABSTRAK

Kerusakan akibat keausan pada roda kereta api memiliki dampak signifikan pada keamanan dan kenyamanan perkeretaapian. Tinjauan ini menyelidiki berbagai aspek yang terkait dengan kerusakan akibat keausan roda pada kereta api. Fokus utama tinjauan ini mencakup tiga bidang kritis: jalan rel kereta, interaksi roda-rel, dan kereta api itu sendiri. Bagian pertama membahas struktur dan pemodelan jalur kereta api, sementara bagian kedua mengeksplorasi berbagai tipe interaksi antara roda dan rel serta model matematis yang terkait. Bagian ketiga mengulas jenis kendaraan kereta api, model matematisnya, dan stabilitasnya pada lintasan lurus maupun berkelok. Selain itu, tinjauan ini juga meneliti pengaruh keausan roda terhadap respons dinamis sistem. Diharapkan tinjauan ini dapat memberikan wawasan yang berharga bagi para praktisi dan peneliti dalam memperbaiki dan meningkatkan keandalan serta keselamatan sistem perkeretaapian.

Kata kunci: keausan, kereta, keselamatan

## ABSTRACT

*Damage due to wheel wear on railway trains has a significant impact on railway safety and comfort. This review examines various aspects related to wheel wear damage on trains. The primary focus of this review encompasses three critical areas: railway track, wheel-rail interaction, and the trains themselves. The first section discusses the structure and modeling of railway tracks, while the second section explores various types of interactions between wheels and rails as well as related mathematical models. The third section reviews the types of railway vehicles, their mathematical models, and their stability on straight and curved tracks. Furthermore, this review also examines the influence of wheel wear on the dynamic response of the system. It is hoped that this review will provide valuable insights for practitioners and researchers in improving and enhancing the reliability and safety of railway systems.*

*Keywords: wear, train, safety*

## 1 INTRODUCTION

The railway vehicle is one of the most commonly used ground transportation modes for passengers and goods due to its lower costs [1]. It is a popular choice for many passengers to travel from one city to another. Prior to COVID-19 pandemic in 2019, the Indonesia Railway Company carried a large number of passengers on both intercity and metropolitan routes. The total number of passengers reached approximately 429 million, with 80% of passengers using it in large metropolitan areas such as the capital city Jakarta and its surrounding cities. The rest were intercity railway passengers. The main reason why passengers in large metropolitan areas use the metro railway is due to it has a faster travel time than buses during peak traffic hours.

During congested hours, a large number of passengers arrive at the station at the same time, which can cause a buildup of passengers in the station. He et al presented

effective solutions for railway transportation by either minimizing the headway between railway vehicles or by increasing the speed of the railway vehicles [2]. Minimum headway is the shortest distance between railway vehicles, which can increase the number of railway vehicles and allow more passengers to be transported at similar times. Increasing the speed of railway vehicles depends on the maximum speed at which a rail track and railway vehicle can travel. The speed that can be travelled on the rail track depends on the type of the rail, the rail profile, gauge, the superstructure of the track and the curve radius. The speed that can be traveled by the railway vehicle is affected by the wheel tread profile, flange profile, the suspension design, mass of the bogie and carbody, and the position of the bogie relative to the center of gravity.

As railway vehicle speeds continue to increase, the infrastructure such as railways require intense

engineering work due to vibrations and noise that can reduce passenger comfort [3]. Additionally, railway vehicle speeds need to be reduced when traveling around curves to ensure the safety of the passengers, which increases the travel time. Therefore, it is important to improve passenger comfort and safety by assessing the stability of railway vehicles passing through curved tracks. The dynamic behaviour between railway vehicles and tracks has been studied for a long time.

Both increasing the railway vehicle speed and minimizing the headway can affect the wheel-rail interaction. The curved radius, railway vehicle speed, and the profile of the flange and rail can all influence the wheel-rail interaction. Narrow curves can accelerate excessive wear of the rail head and wheel profile, leading to wear of both the flange and the thread. Morys et al studied the non-rounded wheel wear on a high-speed railway vehicle [4]. Yang et al investigated wheel tread wear resulting from the application of anti-slip control [5]. Fesharakifard studied the effect of wheel irregularities on the dynamic behaviour of railway vehicle [6]. Zhang et al conducted experiments under different operating conditions to study rolling contact fatigue (RCF) on damaged rail-wheels [7]. Finally, Lan et al conducted research on the service life of components in vehicle/track system due to non-rounded wheel wear [8].

This review paper aims to review and compile the following topics:

- 1) Railway tracks,
  - 2) Wheel-rail interaction,
  - 3) Railway vehicles,
  - 4) The influence of wheel wear on dynamic response,
- This review is divided into six sections. The first section was an introduction that has already been explained. The second section explains railway tracks, including their types, structures, and foundations, and includes a mathematical model. The third section discusses the interaction that occurs at the contact point between wheels and rails and presents a mathematical model for wheel-rail contact. The fourth section describes different types of railway vehicles, their modelling, and presents a mathematical model for railway vehicles and the stability of railway vehicles on both straight and curved track. The fifth section discusses the various types of wheel wear that occur in railway vehicles and their impact on the behaviour of the railway vehicles. Finally, the review paper concludes in Section 6.

## 2 REVIEW ON RAILWAY TRACK

Several factors that influence track on railway vehicle safety and comfort will be discussed in subsequent sections.

### 2.1 Type of railway track

Rail track infrastructure can be categorized into two types: ballasted and non-ballasted track. Ballasted track is a type of track comprising small, non-uniform stones that distribute the railway vehicle load to the substructure with an acceptable load and can drain water outside the track structure. Ballasted track remains the most preferred option in many countries due to its low construction cost and ease of maintenance [9]. However, in recent decades, increasing railway vehicle speeds and axle loads can permanently degrade the ballast layer and reduce comfort [10].

Non-ballasted track is another type of track where rails are supported and fixed to a concrete slab. Over the last two decades, non-ballasted track has been the main choice in railway construction [11]. Ballasted track typically have lower initial capital costs than non-ballasted tracks typically and have higher operational costs in comparison to non-ballasted track [12]. Ballasted tracks require higher operating costs than non-ballasted tracks due to more frequent maintenance to maintain the track geometry in line with the original design [13].

There are several differences between ballasted and non-ballasted track, including the fastening systems, support layers and bedding conditions. However, both types of tracks share the same component, which is the subgrade. To enhance the subgrade, granular layers are present in both the ballast and sub-ballast layers of the ballasted track [14]. On the other hand, in non-ballasted tracks, the ballast layer is replaced with either asphalt pavement or concrete. Non-ballasted track consist of five layers, namely, the subsoil or subgrade as the foundation, the frost protective layer, the bearing layer bonded hydraulically, bearing layer made of asphalt or concrete (with or without sleepers), and the rails [15]. As the demand for railway vehicle travel increases and the time windows become tighter, the construction of railway tracks has shifted towards non-ballasted tracks. This is because non-ballasted tracks require less maintenance in terms of cost and activity, exhibit better dynamic behaviour, and improve vehicle stability [13].

Today, Japan has approximately 70% of its high-speed railway lines using non-ballasted track systems. The Tokyo and Shin-Osaka route was the first high-speed train route built by Japan using a ballasted track system in 1964. A study on railway construction in Japan,

comparing ballasted and non-ballasted track systems, showed that maintenance cost of the non-ballasted track system has a low value that can offset the construction cost after 9 years [16]. Figure 1 illustrates that maintenance cost on ballasted track four times higher than non-ballasted track due to the need to

maintain the track geometry through activities such as tamping and levelling. According to Tayabji and Bilow, non-ballasted track construction is considered cost-effective if the non-ballasted track has a capital investment cost lower than 30% compared to ballasted track [17].

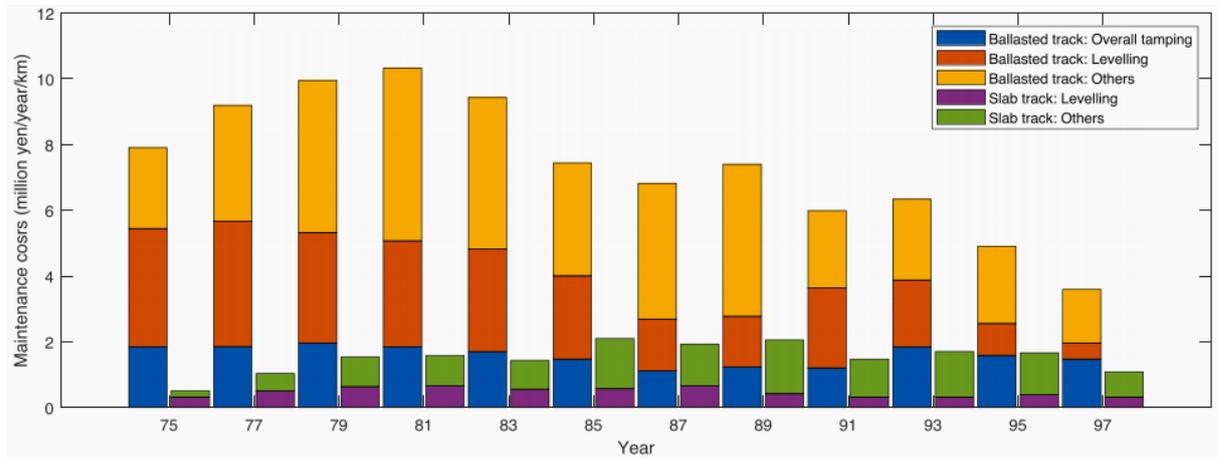


Figure 1 Maintenance Cost on Japanese High Speed Rail – Sanyo Shinkansen (modified from [18]) [12]

## 2.2 Structure of railway track

Railway track infrastructure is usually composed of several components that provide stability and durability for safe travel of railway vehicles [19]. This infrastructure can be categorized into two types, namely ballasted and non-ballasted track. In civil engineering, there are terms such as “superstructure” and “substructure”. Superstructure refers to all components located above ground. The substructure, on the other hand, refers to all components located beneath the ground. Both ballasted and non-ballasted track consist of two main parts, namely the superstructure and substructure.

## 2.3 Superstructure

Superstructure consists of the following components: rails, fastening system, sleeper, ballast bed and sub-ballast bed. When the wheels of the railway vehicle pass through the rails, the rails receive loads and transfer them to the rail pads. The rail pads then transfer the loads to the sleepers. The sleepers, in turn, distribute the load to the ballast bed, sub-ballast bed and subgrade. The stress in the subgrade layer is relatively low as the area increases from the top element to the bottom element in the superstructure [15].

The rails are one of the components of the superstructure and are made of metal, providing continuous support for the wheels of the railway vehicle. Rail pads, made of resilient materials such as rubber, polyurethane, or composite, are installed as an

additional layer between the rail and the fastening system to reduce the vibration and noise. The fastening system holds the rails securely in place, maintains proper alignment and spacing between two sleepers and provides the necessary force for pressing the rails [20]. The fastening system is equipped with insulation to prevent electrical current from the rail to the fastening system. Types of fasteners include clips, bolts, and screws. Sleepers are trapezoidal-shaped elements placed perpendicular to the rails to support them. Sleepers, typically made of wood, concrete, or steel, are spaced almost equally apart and distribute the load from the rails. Ballast, consisting of gravel or rough stones, is located under the sleeper to uniformly distribute the load of the sleeper to the sub-ballast and provide rainwater drainage. The work of Wang and Markine focused on the dynamic responses between the ballast and sleeper, which can be modeled as a nonlinear contact element [21]. They found that the differential settlement, which refers to the difference in structures or material properties between the ballast and sleepers, plays a more important role in track degradation. Meanwhile, Pita et al studied the impact of the track stiffness value in the vertical direction on the speed of railway vehicles. They found that the track stiffness value is influenced by every elastic element under the rail [22].

## 2.4 Substructure

The substructure comprises protection layers and formation, including slopes, verges, and ditches. Sub-ballast is supported by the subgrade, which is the

lowest of the railway track infrastructure and can be categorized as substructure. Using elastic element in the substructure can reduce the degradation of sub-ballast and also the vibrations that are transmitted to the ground [13]. Sub-ballast is an additional layer between the ballast and the underlying soil or subgrade, typically made of a granular material such as gravel or crushed stone, designed to improve the stability and load-bearing capacity of the track. A sub-ballast layer that uses asphalt mixture is known as asphalt underlayment [23], [24], [25]. Bituminous and geogrids sub-ballast are appropriate solutions to improve the bearing capacity of new tracks [13].

### 2.5 Track modelling

The accuracy of the simulation was affected by the track model and its supports. The infinite rail can be modeled using the Euler-Bernoulli beam, which has been studied by several authors [26][27][28][29][6]. The beam can be continuously supported, and its vertical vibration can be modeled up to about 1000 Hz. For rails that are discretely supported, a flexible approach can be used for the range 1000 up to 6500 Hz, and the degree of freedom for the support can result in differences [30]. Zhai and Cai examined track modeling by modeling the rail pads, ballast, and subgrade as cross-linked springs and dampers [31]. Assumptions were made on the track model due to the separate definition of substructure parameters, such as sleeper mass, ballast mass, rail pads stiffness, rail pads damping, ballast stiffness, and damping stiffness.

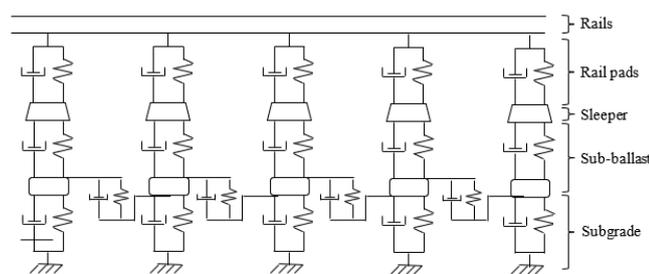


Figure 2 Beam with discretely support [30]

### 2.6 Mathematical representation model of railway track

The track can be modeled as a layered structure that has flexible deformation which involves two rails, rail pads, rail fasteners, sleeper, ballast, sub-ballast, and subgrade. The vertical vibration of the track can be modeled as the Kirchhoff plate [5]. Deformations that occur under subgrade are neglected and not considered in equations.

The track can be modeled as a mathematical representation model as follows.

$$M_T \ddot{x}_T + C_T \dot{x}_T + K_T x_T = F_T \quad (1)$$

Where  $M_T$  represent the mass matrices of the track,  $C_T$  represent the damping matrices of the track,  $K_T$  represent the stiffness matrices of the track.  $x_T$  represents the track displacement vector.  $F_T$  is vector of track bed interaction. Zhai completed the calculation of spatial vibration on the track [32].

There are two types of railway track infrastructure: ballasted and non-ballasted track. Each type of railway track consists of two main structures: the superstructure and the sub-structure. The superstructure comprises several components, including rails, a fastening system, sleepers, a ballast bed and a sub-ballast bed. The sub-structure consists of the subgrade. Each component of railway track infrastructure has stiffness that can affect the wheel-rail interaction.

## 3 REVIEW ON WHEEL-RAIL INTERACTION

The interaction between the wheel and rail will be reviewed and discussed in this section. The behavior of wheel-rail interaction is determined by the contact between the wheel and rail. The interface between the vehicle and tracks is also known as the contact patch. The interaction between the wheel and rail contact interface can be controlled by controlling the size and position of the contact patch on both wheel and rail. The contact between the wheel and rail is studied to understand overall vehicle dynamics and to assess the force in the contact surface material.

### 3.1 Type of wheel-rail interaction

Small quasi-horizontal contact patches occur when the wheel and rail interact. When there is contact pressure on a small surface area, it can lead to a larger stress concentration. The tangential forces, such as traction or braking  $F_x$ , or guiding force  $F_y$ , acting on that surface can be seen in Figure 3. These forces affect the vehicle's dynamic behavior. There are two procedures to determine the contact: normal contact (Hertz theory) and tangential contact (Kalker's theory).

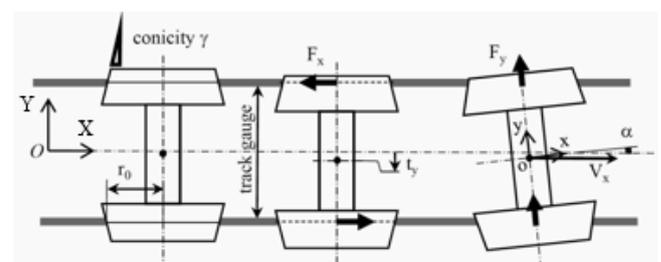


Figure 3 Degree of freedom on wheelset [33]

To speed up and simplify numerical calculations, various modifications have been made to the classical

Hertzian contact theory, which is used to describe normal contact between the wheel and rail. Pombo et al used computational tools to predict wear in a specific railway system based on Hertzian wheel-rail contact, and validated the results by applying them to real operations [34]. However, non-Hertzian contact models have been found to provide better accuracy in predicting wheel or track wear in railway vehicle interactions [35][36][37][38]. Ye et al proposed a non-Hertzian model that considers yaw motion in predicting wheel wear in different types of railway vehicles and operating environments, using simulation and field tests to validate the model [35]. Sun et al simplified the model by considering yaw motion and used non-Hertzian normal rail-wheel contact to validate the results against the Kalker variational method, showing high accuracy in predicting normal stresses and the contact patch [37]. Y. Yang, Guo, et al investigated the wheel-rail interaction of a heavy transport locomotive under various conditions using a non-Hertzian contact method [38].

### 3.2 Mathematical representation model of wheel-rail interaction

The interaction between the wheel and the rail can cause unstable vibration and adverse conditions. Both wheel and rail surface can cause very complicated wheel-rail interactions [5]. There are two types of wheel-rail interaction that will be discussed in this section, namely Hertzian and Non-Hertzian contact method.

de Pater and Johson predicted the shape and size of the contact area and the normal pressure for Hertzian contact method [39]. Hertz analytically solved the normal problem assuming that the contact surface is elliptic in shape. The normal contact pressure in the elliptical contact surface is semi-ellipsoidal can be expressed as follows:

$$p(x, y) = p_0 \sqrt{1 - \left(\frac{x}{a}\right)^2 - \left(\frac{y}{b}\right)^2} \quad (2)$$

Where  $p_0$  represents maximum value of the contract stress,  $a$  represents semiaxes in the rolling direction,  $b$  represents semiaxes in the lateral direction.

The normal force that occurs at the center of elliptical contact surface can be expressed as follows:

$$F_z = \frac{2}{3} p_0 ab \quad (3)$$

Y. Yang et al proposed predicting wheel profile wear and fatigue damage by accurately modelling the

interaction between the wheel and the rail in the simulation for non-Hertzian contact method. The distribution of pressure that occurs in the normal contact  $p_{(i)}$  under multi-point wheel and rail contact can be expressed as follows:

$$p_{(i)}(x, y) = \frac{\pi E}{2(1 - \nu^2)} \frac{(\delta - z_{wr}^{(A)}(y)) \sqrt{x_{1(i)}^2(y) - x^2}}{\sum_{i=1}^{N_c} \int_{y_{r(i)}}^{y_{l(i)}} \int_{-x_1(i)(\eta)}^{x_1(i)(\eta)} \frac{\sqrt{x_{l(i)}^2(\eta) - \xi^2}}{\sqrt{\xi^2 + (\eta - y)^2}} d\eta} \quad (4)$$

Where  $N_c$  is the number contact points between the wheel and rail;  $E$  is Young's modulus;  $\nu$  is Poisson's ration of the wheel material;  $x_1(i)(y)$  represents the longitudinal edges of the contact patch between the wheel and rail.  $y_{l(i)}$  represents the contact patch on the left edge of the wheel-rail and  $y_{r(i)}$  represents the contact patch on the right edge of the wheel-rail.

The force that occurs in the normal contact between wheel and rail  $N_{wr(i)}$  can be further expressed as

$$N_{wr(i)} = \int_{C_{(i)}} p_{(i)}(x, y) \quad (5)$$

$$p_{(i)}(x, y) = \frac{\pi^2 E}{4(1 - \nu^2)} \int_{y_{r(i)}}^{y_{l(i)}} \frac{x_{1(i)}^2(y) \sqrt{x_{1(i)}^2(y) - x^2}}{\sum_{i=1}^{N_c} \int_{y_{r(i)}}^{y_{l(i)}} \int_{-x_1(i)(\eta)}^{x_1(i)(\eta)} \frac{\sqrt{x_{l(i)}^2(\eta)}}{\sqrt{\xi^2 + (\eta - y)^2}} d\eta} d\eta$$

Where  $C_{(i)}$  represents the contact patch area.

**Error! Reference source not found.** illustrates the simulation of wheel-rail tangential contact, which includes various wheel-rail adhesion conditions such as dry, wet, and greasy. The corresponding parameters are listed in Table 1.

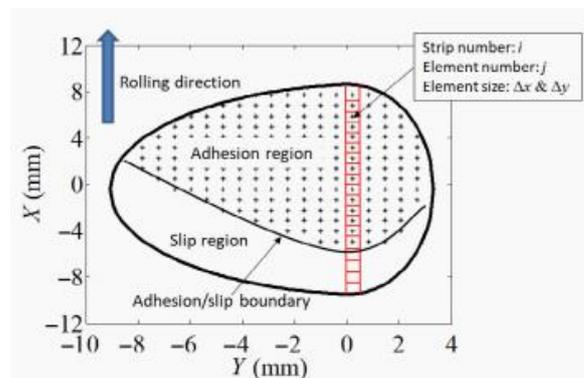


Figure 4 MKP-FaStrip model schematic diagram [5]

Table 1 Wheel-rail adhesion parameter [5]

Notation	Contact condition		
	Dry	Wet	Greasy
$\mu_0$	0.30	0.12	0.08
$A_p$	0.40	0.40	0.50
$B_p$	0.60	0.20	0.10

Contact between the wheel and rail can significantly impact the behavior of wheel-rail interaction. When contact pressure is exerted on a small surface area, it can result in a higher concentration of stress. The tangential forces, such as traction or braking  $F_x$ , or guiding force  $F_y$ , acting on that surface, have an effect on the vehicle’s dynamic behaviour. There are two types of wheel-rail interaction: Hertzian and non-Hertzian contact method. It has been found that the non-Hertzian model of wheel-rail interaction is more accurate than the Hertzian model.

#### 4 REVIEW ON RAILWAY VEHICLE

The dynamic behaviour of railway vehicles is strongly influenced by the interaction between the wheel and rail, as the forces that occur in this contact interface are transmitted to the bogie and carbody through the suspension system [40]. In this section, we will review and discuss the different types of railway vehicles that exist and their respective characteristics.

##### 4.1 Type of railway vehicle

The selection of railway vehicles depends on various factors such as the intended use, the type of goods or passengers being transported, the distance to be covered, the infrastructure available on the railway network, and many other factors. There are several types of railway vehicles that have different purposes such as locomotives are designed to pull and push the trains over long distance, while freight wagons are specialized for carrying various types of cargo, such as bulk goods, containers, or heavy machinery. Passenger coaches, on the other hand, are designed to provide comfortable and safe transportation for passengers. Special-purpose vehicles are designed for specific purposes such as track maintenance, while high-speed railway vehicles are designed for high-speed travel on dedicated tracks. Metro railway vehicles are designed for urban transit systems with frequent stops, while trams are designed for use in cities with street-level tracks. Overall, the type of railway vehicle used depends on the purpose of the journey, the type of cargo or passenger being transported, and the infrastructure available on the railway network.

##### 4.2 Railway vehicle modelling

In general, railway vehicles are modelled with two main components based on the principle of multi-body dynamics which consists of:

1. Vehicle structure involves the carbody, bolster, bogie frame, and axle box. Each component has six degrees of freedom and can be modeled as rigid bodies,
2. Suspension system, which involves the primary suspension system, secondary suspension system, and draft gear in coupler system. These components can be modeled with consideration of nonlinear characteristics as spring-damper elements.

##### 4.3 Mathematical representation model of the railway vehicle

The vehicle subsystem has equation of motion that can be derived easily to D’Alembert’s principle and can be expressed as a second-order differential equation in the time domain:

$$M_V \ddot{x}_V + C_V \dot{x}_V + K_V x_V = F_V \quad (6)$$

Where  $M_V$  represents the mass matrices of the railway vehicle,  $C_V$  represents the damping matrices of the railway vehicle and  $K_V$  represents the stiffness matrices of the railway vehicle.  $x_V$  represents the railway vehicle’s displacement vector.  $F_V$  is vector of interaction between the wheel and rail. Zhai solved the spatial vibration of the railway vehicle [32].

##### 4.4 Stability of railway vehicle

Stability of railway vehicle refers to its ability to maintain a steady and controlled motion while traveling on both straight and curved track, without exhibiting uncontrollable or unstable behaviour such as excessive vertical or lateral vibration, derailment, or excessive guiding forces. This is an essential aspect of railway vehicle performance, as it directly impacts the safety, comfort, and reliability of the railway vehicle. Stability can be categorized as straight track stability and curved track stability.

##### 4.5 Stability on the straight track

When a railway vehicle is in motion, the wheelset oscillates at a frequency proportional to its velocity. At low speeds, the spring connecting the wheelset to the carbody through the bogie restores the force acting on the wheelset and reduces the lateral oscillation. However, at high speeds, the inertia forces increase and the frequency of oscillation, resulting in a progressive increase in lateral oscillation. Generally, at low speeds, the railway vehicle is stable and undergoes decaying oscillation, returning the wheelset to the center of the

track. As the speed increases, the oscillation becomes larger, and the decay rate decreases, making the railway vehicle less stable. Researcher such as Silva e Silva et al examined the effect of worn wheel profiles on the probability of derailment based on Nadal's Criterion [41]. Jönsson et al studied the variation of suspension characteristics of two-axle freight wagons that affect the wagon's behaviour on tangent track, including the effects of geometrical tolerances, corrosion, and wear on suspension characteristics [42]. Zhu et al examined the stability of high-speed trains under polygonal wear caused by disc brakes [43]. While Jin et al conducted extensive experiments on the polygonal wear of metro train wheels and analyzed its effect on dynamic behaviour [44].

#### **4.6 Stability on the curved track**

On sharply curved track, the wheel-rail interaction generates lateral forces that can cause the railway vehicle to turn. To prevent derailment, a large flange clearance is required according to Redtenbacher's formula, which allows the wheelset to move outwards. However, the leading wheelset still generates a significant lateral force, which is guided by the flanges and contributes to the turning of the vehicle.

There are several types of railway vehicles, including locomotives, freight wagons, passenger coaches, special purpose vehicles, and metros. Based on the principle of multi-body dynamics, railway vehicles consist of two main components: the vehicle structure and the suspension system. Some railway vehicles have one-stage suspension, while others have two-stage suspension. One-stage suspension vehicles feature a primary suspension, while two-stage suspension vehicles have both primary and secondary suspension. The stability of a railway vehicle can be categorized into straight track stability and curved track stability. Straight track stability occurs when the wheelset oscillation decays after several cycles. On curves, lateral forces are produced due to centrifugal force, and the flange plays a crucial role in preventing derailment.

### **5 REVIEW ON THE INFLUENCE OF WHEEL WEAR ON DYNAMIC RESPONSE**

Wheel wear refers to the gradual loss of material from the surface of railway vehicle wheels that occurs during contact with the rail. This is a normal and expected occurrence in the operation of any railway. The friction that occurs between the wheel and rail causes a certain amount material to be removed from the surface of the wheel, which can lead to a decrease in the wheel's diameter and a change in its profile. As the wheel wears, the stability of the railway vehicle can be affected, noise levels may increase, and braking

performance may decrease. This section will review and discuss the topic of wheel wear in railway vehicles.

#### **5.1 Type of wheel wear**

There are several types of wheel wear that can affect the dynamic behaviour of a railway vehicle, namely flange wear, thread wear, shelling, out of roundness, and flat spots. Thread wear, also known as rolling contact fatigue, has a significant impact on the efficiency of operation and safety [45]. Fröhling et al examined the stress conditions that occur at the wheel-rail interaction using contact stress analysis on heavy haul railways that have heavy axle loads and large carrying capacities over many years of operation [45]. Fergusson et al investigated the minimization of wheel wear on three-piece bogie equipped with a self-steering mechanism, as a result of the selection of lateral and longitudinal primary suspension stiffness and friction coefficient at the center pivot [46]. The optimal result for minimizing wheel wear was found to be a low coefficient of friction at the center pivot, low stiffness of primary suspension in lateral direction, and low stiffness of primary suspension in longitudinal direction. Vér et al studied the wheel flat defect, which can decrease the critical speed of the railway vehicle [47].

#### **5.2 Influence of wheel wear on dynamic response**

The dynamic response of a railway vehicle is influenced by various factors, such as the railway track, wheel-rail interaction, vehicle design, and operating conditions. Wheel wear is one of the factors that can significantly affect the dynamic behavior of a railway vehicle [30]. Moreover, the wheel-rail interaction is also influenced by the track design. Improper rail and wheel profile can lead to accelerated wear of both wheels and rails due to increased wheel-rail interaction.

The occurrence wear on the wheel can cause changes in the contact area between the wheel and the rail. These changes can, in turn, affect the distribution of contact force, leading to changes in the vehicle dynamic response. As wheel wear increases, the contact area between the wheel and rail decreases, resulting in an increase in contact pressure and higher forces acting on the rail in both vertical and lateral directions. These higher forces can cause the railway vehicle to experience increased vibration and noise. Additionally, as the wheel wear diameter decreases due to wear, it can affect the stability and ride comfort of the vehicle, especially in lateral direction, causing increased lateral vibration and reduce ride comfort. Moreover, wheel wear can also affect the wear on the rail and the wheel-rail interaction conditions. As wheel wear increases, the surface-roughness of the wheel tread also increases, which can affect the adhesion of

the wheel-rail interaction, traction, and braking performance of the vehicle [48].

Corrêa et al examined the parameter that affected the wheel wear that occurs in heavy wagon with meter and broad gauge, running on tangent and curve track [49]. Primary suspension longitudinal clearance and stiffness affect the wheel wear. Wheel Wear is the highest affected parameter, with up to 42% higher wear for the broad-gauge car running on an ideal track through a curve of 860 m of radius and up to 172% higher for the meter gauge car, on a sharper curve of 371 m of radius.

Bian et al. examined the impact of wheel flat conditions on dynamic response using finite element analysis. The wheel flat can cause a large dynamic impact force as well as a forced vibration with a high frequency, which can cause damage to the track structure [50]. Therefore, monitoring and managing wheel wear is crucial to ensure the safe and comfortable operation of railway vehicles. It is important to minimize the occurrence wear and take timely actions, such as periodic maintenance and wheel profiling, to reduce its negative effects on the vehicle's dynamic behaviour and overall performance [41].

When a railway vehicle comes into contact with the railway track, material loss occurs on the surface of the wheel, leading to a decrease in diameter and a change in the wheel's profile. Railway vehicles can experience various types of wheel wear, including flange wear, thread wear, shelling, out-of-roundness, and flat spots. Wheel wear is a significant factor that can affect the dynamic behavior of a railway vehicle. The occurrence of wheel wear can result in changes to the contact area between the wheel and the rail, which in turn affects the distribution of contact force and leads to alterations in the vehicle's dynamic response. As wheel wear increases, the contact area between the wheel and rail decreases, resulting in higher contact pressure and forces acting in both the vertical and lateral directions. This can lead to increased vibration and noise, as well as potentially impacting the stability and ride comfort of the vehicle, particularly in the lateral direction.

## 6 CONCLUSION

This paper reviews and discusses past research on railway track infrastructure. Each component of railway track infrastructure, such as rail, rail pads, fastening systems, sleepers, ballast, sub-ballast, and subgrade, has a stiffness that can affect the wheel-rail interaction. There are three components of railway track infrastructure that have a significant influence on wheel-rail interaction, namely rail pads, fastening system and ballast. There are two types of wheel-rail

interaction discussed in this review, namely Hertzian and Non-Hertzian contact method. It has been found that the non-Hertzian model of wheel-rail interaction is more accurate than the Hertzian model. Railway vehicles are categorized into types such as locomotives, freight wagons, passenger coaches, special purpose vehicles, and metros. These vehicles can be equipped with either a one-stage suspension or a two-stage suspension. One-stage suspension vehicles have primary suspension, which guides the wheelset and isolates dynamic loads. In contrast, two-stage suspension vehicles have primary and secondary suspension. The secondary suspension absorbs smaller vibrations and shock, enhancing comfort and stability. There are several wheel wears such as flange wear, thread wear, shelling, out-of-roundness, and flat spots. Wheel wear is a significant factor that can affect the dynamic behavior of a railway vehicle. The occurrence of wheel wear can result in changes to the contact area between the wheel and the rail, which in turn affects the distribution of contact force and leads to alterations in the vehicle's dynamic response.

However, there is still ongoing work to be done regarding the journey of metro trains in urban environments. Currently, metro trains play a crucial role in passenger mobility in metropolitan cities. However, there are several factors that affect the journey of metro trains in urban environments, such as rail geometry, smaller curve radii, and the complexity of routes due to the presence of urban buildings and existing infrastructure. Load variations, including normal and overload conditions during peak hours or special events, must be considered for evaluating stability and comfort. The suspension system and dynamic characteristics of electric trains should be adaptable to ensure optimal performance and safety. Research on operational speed in dense urban environments can provide insights into maintaining safe and efficient speeds while considering factors like safety, stability, and passenger comfort. These research studies aim to enhance understanding and contribute to the development of effective metro train systems in metropolitan cities, ensuring sustainable and environmentally friendly transportation options in crowded urban areas.

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