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Railway Dynamics: Global research trends and applications in high-speed railway operation in Vietnam

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ABSTRACT

High-speed railway (HSR) systems operating at velocities up to 350 km/h impose stringent requirements on vehicle–track interaction, wheel–rail contact mechanics, and infrastructure maintenance strategies. At such speeds, railway systems behave as highly coupled nonlinear systems. Small variations in contact conditions or track geometry can significantly amplify dynamic responses. This paper presents a comprehensive review of the theoretical foundations of wheel–rail rolling and sliding contact, with particular emphasis on wear and rolling contact fatigue (RCF). Global research trends in railway dynamics are reviewed, highlighting the increasing integration of multibody dynamics (MBD), advanced contact models, and damage prediction techniques. The applicability of these methodologies to the future high-speed railway system in Vietnam is discussed, and engineering-oriented recommendations and parametric considerations are proposed for the development of simulation-based design and predictive maintenance frameworks.

1. Introduction

The rapid expansion of HSR systems operating at very high speeds has fundamentally transformed the engineering requirements for railway design, operation, and maintenance. At such speeds, vehicle–track interaction becomes highly nonlinear and sensitive to disturbances. Small variations in wheel–rail contact conditions may lead to significant changes in system stability, safety margins, and infrastructure degradation [1], [2], [3], [4], [5].

Over the past decades, numerous studies have investigated individual aspects of railway dynamics, including contact mechanics, MBD, wear modelling, and fatigue prediction. Existing review papers have provided valuable insights into specific domains such as rolling contact fatigue mechanisms, tribological behaviour, or vehicle–track interaction modelling [6], [7], [8], [9], [10], [11], [12]. However, these studies are often fragmented, focusing on isolated phenomena rather than addressing the strong coupling between vehicle dynamics, contact mechanics, wear evolution, and fatigue damage accumulation. In particular, there remains a lack of integrated review frameworks that systematically connect short-term dynamic behaviour with long-

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term degradation processes under high-speed operating conditions.

Moreover, most existing studies primarily target established high-speed railway systems in Europe, Japan, or China, where infrastructure design and maintenance strategies have evolved over decades of operation [13], [14], [15], [16]. In contrast, limited attention has been given to emerging high-speed railway systems, where early-stage design decisions can significantly influence long-term performance, maintenance costs, and operational safety. This gap is particularly relevant for Vietnam, where the planned North–South high-speed railway project presents a unique opportunity to incorporate advanced railway dynamics methodologies at the design stage rather than as a post-deployment optimisation tool [17].

To address these limitations, this paper provides a comprehensive and integrative review of railway dynamics with a particular focus on the coupled mechanisms of wheel–rail contact, wear, and rolling contact fatigue in high-speed railway systems. The novelty of this work lies in three key aspects. First, it establishes a unified conceptual framework that links contact geometry, kinematics, forces, energy dissipation, wear evolution, and fatigue damage within a consistent system-level perspective. Second, it synthesises recent developments in multibody dynamics, contact modelling, and degradation prediction into an integrated simulation paradigm suitable for high-speed applications [3], [18], [19], [20], [21], [22]. Third, it extends the discussion beyond theoretical and numerical modelling by explicitly analysing the applicability of these methodologies to the development of a future high-speed railway system in Vietnam.

2. Wheel–rail contact mechanics

Wheel–rail contact in railway systems is governed by a complex set of geometric, kinematic, force-related, and damage-related quantities. These quantities are strongly coupled and evolve dynamically with vehicle motion, track geometry, operating speed, and material conditions. Classical contact mechanics theories have demonstrated that wheel–rail interaction cannot be fully characterised by contact forces alone but must also account for contact geometry, creepages, stress distributions, and energy dissipation mechanisms [23], [24], [25].

In many studies, wheel–rail interaction is simplified by considering only normal and tangential contact forces. While such simplifications may be acceptable for low-speed or quasi-static analyses, they become inadequate for high-speed applications. Under these conditions, small variations in equivalent conicity, creepages, or contact pressure can lead to significant changes in vehicle stability, wear evolution, and rolling contact fatigue behaviour [26], [27], [28], [29]. Advanced multibody dynamics formulations and numerical contact models further indicate that wear and fatigue processes are governed by frictional work, subsurface stress states, and their accumulation over time, rather than by instantaneous forces alone [30], [31], [32], [33], [34], [35].

To provide a rigorous and systematic description of the wheel–rail contact problem, Table 1 summarises the complete set of physical quantities involved in wheel–rail contact mechanics, classified according to their physical nature and functional role. This comprehensive classification establishes a conceptual framework linking contact geometry, kinematics, forces, energy dissipation, wear, and rolling contact fatigue mechanisms and is consistent with modern railway dynamics modelling practices [34], [36]. Based on this framework, a subset of representative indicators is selected in this study for detailed analysis, as discussed in the subsequent subsection.

Table 1. Comprehensive Set of Physical Quantities in Wheel–Rail Contact Mechanics

Group	Quantity	Symbol	Physical meaning	Role in HSR
Contact Geometry	Contact point	$\boldsymbol{P}$	Instantaneous wheel–rail contact location	Governs force transmission
	Contact patch semi-axes	$\boldsymbol{a}, \boldsymbol{b}$	Dimensions of Hertzian contact ellipse	Affects stress distribution
	Contact area	$\boldsymbol{A_c}$	Area of wheel–rail contact patch	Influences wear & RCF

Group	Quantity	Symbol	Physical meaning	Role in HSR
	Equivalent curvature	R_x, R_y	Combined wheel–rail curvature	Controls pressure level
	Contact angle	γ	Angle between normal and vertical	Critical in curves
	Angle of attack	α	Yaw angle of wheelset	Drives lateral forces
	Equivalent conicity	λ_{eq}	Steering characteristic of wheelset	Determines hunting stability
Normal Contact	Normal force	N	Load transmitted through contact	Dominant stress source
	Contact pressure	$p(x,y)$	Local pressure distribution	Governs subsurface stress
	Maximum pressure	p_0	Peak Hertzian pressure	Triggers RCF initiation
Kinematics	Longitudinal creepage	ξ_x	Slip in rolling direction	Traction/braking
	Lateral creepage	ξ_y	Slip in lateral direction	Curving behaviour
	Spin creepage	ξ_ϕ	Relative rotational slip	Major RCF driver
Tangential Contact	Longitudinal force	F_x	Traction / braking force	Energy dissipation
	Lateral force	F_y	Guiding force	Derailment risk
	Spin moment	M_z	Torsional contact moment	Fatigue contribution
	Friction coefficient	μ	Adhesion condition	Strongly speed-dependent
Energy & Work	Sliding velocity	v_s	Local slip velocity	Wear intensity
	Frictional power	P_f	Rate of energy dissipation	Wear modelling input
	Frictional work	A	Accumulated energy	Governs wear volume
Wear	Wear volume	V	Removed material volume	Profile evolution
	Wear depth	$\delta(s)$	Normal displacement of profile	Geometry degradation
	Wear distribution	-	Spatial wear along profile	Stability variation
RCF	Max. shear stress	τ_{max}	Subsurface stress amplitude	Crack initiation
	Stress tensor	σ	Multiaxial stress state	Fatigue criteria
	Damage index	D	Accumulated fatigue damage	Life prediction
Vehicle–Track Interaction	Lateral wheel force	Y	Lateral load on rail	Track degradation
	Vertical wheel force	Q	Normal wheel load	Safety indicator
	Derailment ratio	Y/Q	Nadal criterion indicator	Safety limit
	Critical speed	v_{cr}	Onset of hunting	HSR stability

Although wheel–rail contact involves a large number of geometric, kinematic, force-related, energetic, and damage-related quantities, the present study is intentionally limited to the investigation of vehicle dynamic stability, wheel–rail contact forces, wear evolution, and rolling contact fatigue mechanisms relevant to high-speed railway operation at 350 km/h. Consequently, only a subset of representative indicators is selected and analysed in detail.

Quantities that primarily act as intermediate variables within the contact formulation or require dedicated material-scale or thermo-mechanical modelling are therefore not explicitly discussed, although their effects are implicitly accounted for in the adopted simulation framework.

2.1. Normal contact forces

The normal contact between wheel and rail is commonly described using Hertzian contact theory [37], [38]. The pressure distribution within the contact patch is given by:

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

where a and b are the semi-axes of the elliptical contact patch. The maximum contact pressure is.

$$\mathbf{p_0} = \frac{3\boldsymbol{N}}{2\boldsymbol{\pi}\mathbf{ab}} \quad (2)$$

where N denotes the normal wheel–rail contact force.

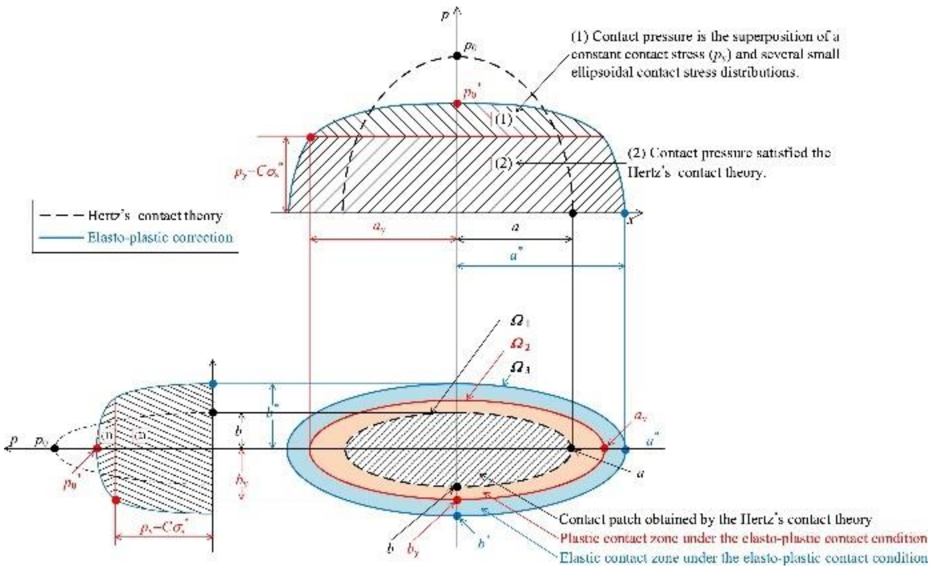

Figure 1. Wheel–rail contact geometry and Hertzian elliptical contact patch, illustrating the distribution of normal pressure under elastic contact assumptions [19]

At speeds of 350 km/h, dynamic amplification may increase normal contact forces by 20–40% compared to static axle loads, especially in the presence of track irregularities [14], [39], [40].

The formulation of the wheel–rail contact problem is strongly dependent on the physical characteristics of the interacting components. In particular, material properties such as elastic modulus, hardness, and yield strength, together with wheel and rail profiles and surface conditions, play a decisive role in determining the appropriate contact modelling approach.

Under ideal conditions with smooth geometries and predominantly elastic behaviour, Hertzian contact theory provides a simplified and efficient representation of the normal contact problem. However, in practical high-speed railway operation, factors such as profile wear, surface roughness, high contact stresses, and potential material nonlinearity may lead to deviations from Hertzian assumptions. In such cases, more advanced non-Hertzian or elasto-plastic contact formulations are required to accurately capture contact pressure distribution and stress states.

Therefore, the selection of contact models in railway dynamics is not universal, but must be adapted according to the combined effects of material characteristics, contact geometry, and operating conditions, particularly in high-speed applications where these factors are strongly coupled.

2.2. Creepage and tangential forces

Relative slip between wheel and rail is described by creepages [36].

$$\boldsymbol{\xi} = [\boldsymbol{\xi_x \xi_y \xi_\phi}] \quad (3)$$

Where $\boldsymbol{\xi_x}$, $\boldsymbol{\xi_y}$, and $\boldsymbol{\xi_\phi}$ represent longitudinal, lateral, and spin creepage, respectively.

Tangential forces are commonly described using the linear creep force formulation derived from Kalker's rolling contact theory [25]. FASTSIM is a numerical algorithm developed to efficiently approximate the nonlinear rolling contact problem and should be distinguished from the linear formulation presented in Eq. (4), an efficient approximation of Kalker's rolling contact theory [36]:

$$\boldsymbol{F_t} = \boldsymbol{C\xi} \quad (4)$$

where C is the creep coefficient matrix.

The FASTSIM algorithm is commonly employed to evaluate tangential forces at the wheel–rail interface.

In the calculation of creep forces, the mechanical properties of the wheel and rail materials, the local contact geometry, and the normal contact force are considered [1], [41], [42]. Based on Hertzian contact theory, the semi-axes of the elliptical contact patch are first determined. Subsequently, the longitudinal creepage, lateral creepage, and spin creepage corresponding to the current contact conditions are evaluated. A schematic illustration of the wheel–rail contact configuration is presented in Figure 2.

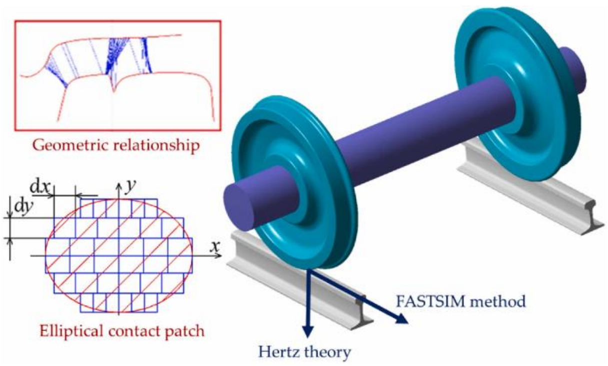

Figure 2. Schematic representation of wheel–rail contact modelling, showing geometry determination, contact patch discretisation, and tangential force evaluation using the FASTSIM method [2]

Despite the widespread adoption of simplified contact and wear modelling approaches, their applicability to high-speed railway systems requires careful evaluation. The FASTSIM algorithm, for instance, offers high computational efficiency and is well suited for large-scale multibody dynamics simulations. However, it relies on simplified assumptions regarding contact conditions and may not accurately capture complex phenomena such as partial slip, material plasticity, and non-Hertzian contact effects under severe loading conditions.

Archard-based wear models provide a practical and efficient framework for predicting material removal. However, their empirical nature limits their ability to capture transient conditions, temperature effects, and evolving material properties. Energy-based wear models partially address these limitations by incorporating frictional work, but they still depend on calibration parameters that may vary significantly with operating conditions.

For RCF, cumulative damage models offer a computationally tractable approach for long-term simulations. However, such models often rely on simplified stress indicators and linear damage accumulation assumptions, which may not fully represent the complex multiaxial stress states and crack propagation mechanisms observed in real railway systems.

Table 2. Comparison of modelling approaches for wheel–rail contact, wear, and RCF

Method	Accuracy	Computational cost	Advantages	Limitations	Suitability for HSR
Hertz's theory	Medium	Very low	Simple, analytical	No plasticity, simplified geometry	Limited
FASTSIM	Medium–high	Low	Efficient for MBD simulations	Limited in severe contact conditions	High
FEM contact models	Very high	Very high	Detailed stress analysis	Not suitable for long-term simulations	Low
Archard wear model	Medium	Very low	Simple and robust	Empirical, lacks physics detail	Medium
Energy-based wear	Medium–high	Medium	Accounts for frictional work	Requires calibration	High
Fatigue index models	Medium	Low	Suitable for long-term prediction	Simplified damage representation	High
Multiaxial fatigue models	High	High	Physically accurate	Computationally expensive	Medium

The comparison highlights a fundamental trade-off between model fidelity and computational efficiency. While high-fidelity approaches such as finite element methods provide detailed insight into contact stress distributions, they are not practical for system-level or long-term simulations required in high-speed railway applications. Conversely, simplified models such as FASTSIM and Archard-based formulations offer sufficient accuracy with significantly lower computational cost, making them more suitable for integrated simulation frameworks. Therefore, hybrid modelling strategies that combine efficient contact models with calibrated wear and fatigue laws are increasingly adopted in modern railway dynamics studies.

3. Wear and rolling contact fatigue

Wheel–rail wear and RCF are among the most critical degradation mechanisms affecting the safety, reliability, and lifecycle cost of railway systems, particularly in high-speed railway operation. At operating speeds up to 350 km/h, the wheel–rail interface is subjected to extremely high normal contact pressures, significant tangential stresses, and complex rolling–sliding kinematics, which together create severe conditions for material degradation [36].

Wear and RCF are not independent phenomena. Wear progressively modifies wheel and rail profiles, thereby altering contact geometry, equivalent conicity, creepages, and stress distributions. These changes directly influence the initiation and propagation of fatigue cracks, while fatigue-induced surface damage may in turn accelerate material removal by wear mechanisms [27], [36]. This strong coupling between vehicle dynamics, contact mechanics, wear evolution, and fatigue damage renders the prediction of wheel–rail degradation a highly nonlinear and path-dependent problem.

Despite extensive research, the accurate prediction of wear and RCF remains challenging due to the coexistence of elastic–plastic contact behaviour, evolving contact geometry, multiaxial stress states, and uncertainties in frictional and material properties. Under high-speed conditions, dynamic force amplification further accelerates damage accumulation, making simplified or quasi-static approaches inadequate [25], [43], [44], [45]. Consequently, modern studies increasingly rely on integrated simulation frameworks combining multibody dynamics, wheel–rail contact models, wear laws, and fatigue damage criteria [27], [32], [33], [34].

3.1. Governing wear laws and energy dissipation mechanisms

The quantitative description of wheel–rail wear is commonly based on phenomenological laws derived from experimental observations. One of the most widely adopted formulations is Archard's wear law, which relates the wear volume to the normal contact force and sliding distance:

$$\boldsymbol{V = k\frac{Ns}{H}} \tag{5}$$

where V denotes the wear volume, k is the wear coefficient, N is the normal contact force, s is the sliding distance, and H represents the hardness of the softer contacting material [46], [47], [48]. Although originally developed for dry sliding contacts, this formulation remains widely used in railway applications due to its physical transparency and numerical robustness.

For high-speed railway operation, where contact conditions are inherently non-stationary, wear is more appropriately described in terms of frictional energy dissipation. Energy-based wear models express material removal as a function of the accumulated frictional work:

$$\boldsymbol{V = k_V \int P_f dt} \tag{6}$$

with the frictional power defined as:

$$\boldsymbol{P_f = \tau v_s} \tag{7}$$

Where τ is the tangential traction and v_s is the local sliding velocity within the contact patch [49].

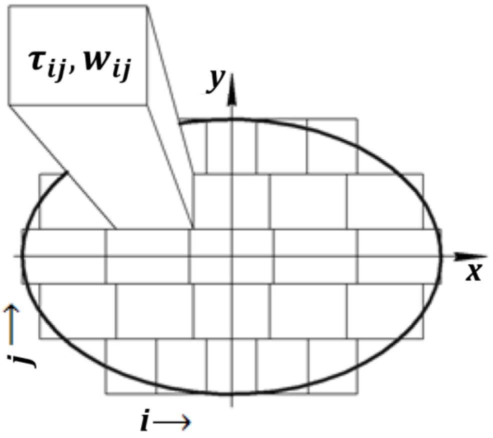

Figure 3. Discretisation of the contact patch in the FASTSIM algorithm [49]

This formulation explicitly accounts for variations in contact forces and sliding conditions and is therefore particularly suitable for HSR systems operating under dynamically varying loads.

3.2. Spatial wear distribution and profile evolution dynamics

Wear develops in a highly non-uniform manner along the wheel and rail profiles. Localised wear concentrations typically emerge in regions subjected to elevated creepages and contact stresses, such as the gauge corner of rails and the flange or tread transition zones of wheels. The location and severity of these wear zones are governed by track curvature, suspension characteristics, and vehicle dynamic behaviour [27], [50], [51], [52], [53].

To capture spatially varying material removal, the local wear depth along the wheel or rail profile is expressed as:

$$\delta(s_i) = \frac{V_i}{A_i} \tag{8}$$

where V_i is the local wear volume associated with a discretised contact element and A_i is the corresponding contact area [33].

Progressive profile evolution modifies contact geometry, equivalent conicity, and steering characteristics, thereby feeding back into wheelset kinematics and contact force generation.

In practical railway operation, wear and rolling contact fatigue are not uniformly distributed but tend to concentrate in specific regions of the wheel–rail interface. The most frequently affected areas include the wheel tread–rail head contact zone and the gauge corner, where high contact stresses and creepage are present. These regions are particularly susceptible to material removal and crack initiation due to combined rolling–sliding conditions.

Fatigue damage in wheels is closely related to the accumulation of cyclic contact stresses, leading to subsurface crack initiation and subsequent propagation toward the surface. The interaction between wear and fatigue is complex: moderate wear may remove surface-initiated cracks and delay fatigue progression, while excessive wear or changes in contact geometry may increase stress concentration and accelerate crack growth.

Therefore, accurate prediction of degradation requires simultaneous consideration of both wear distribution and fatigue mechanisms, especially under high-speed operating conditions.

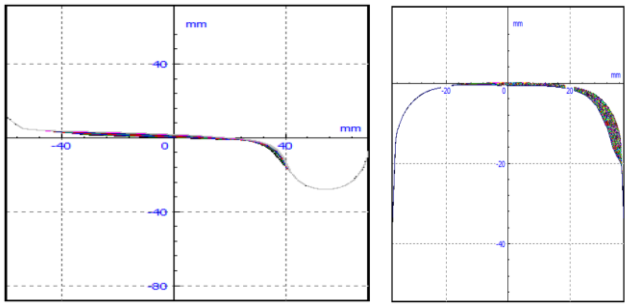

Figure 4. Evolution of wheel/rail profiles due to cumulative wear [33]

3.3. Rolling contact fatigue as a cyclic stress accumulation process

Rolling contact fatigue arises from cyclic stress states generated beneath the wheel–rail contact surface during repeated rolling–sliding contact. Unlike wear, which is governed by material removal, RCF is driven by the accumulation of cyclic shear and normal stresses that may lead to crack initiation and propagation within the surface or subsurface layers [44].

The initiation of RCF damage is closely related to the amplitude of subsurface shear stresses and multiaxial stress states. These stresses depend on normal contact forces, tangential tractions, contact geometry, and friction conditions, all of which are influenced by vehicle dynamic behaviour. In high-speed railway operation, dynamic force amplification significantly increases stress amplitudes, accelerating RCF damage accumulation [6], [27], [33], [44], [54].

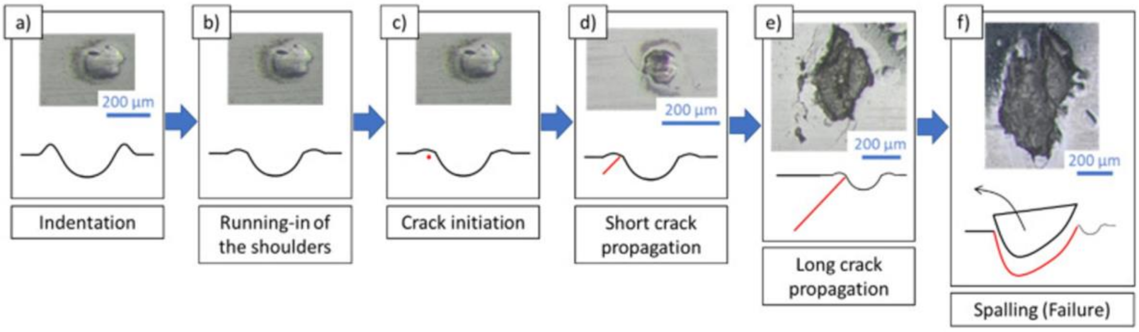

Figure 5. Evolution of rolling contact fatigue (RCF), illustrating crack initiation, propagation, and spalling under repeated rolling–sliding contact conditions [55]

3.4. Governing criteria and damage accumulation in RCF modelling

From a modelling perspective, RCF is commonly evaluated using fatigue criteria based on contact stress histories. A widely adopted approach employs a linear cumulative damage rule:

$$D = \sum_{i=1}^{n} \frac{\Delta N_i}{N_f(\sigma_i)} \quad (9)$$

where D is the accumulated damage index, ΔN_i denotes the number of load cycles at a given stress level σ_i, and N_f represents the number of cycles to failure under that stress state. Fatigue failure is assumed to occur when $D \geq 1$ [44], [56].

More advanced RCF models employ multiaxial fatigue criteria, such as maximum shear stress or Dang Van–type criteria, to account for the combined influence of normal and tangential stresses within the contact zone [33], [44], [56]. These formulations are particularly relevant for high-speed railway systems, where complex stress paths arise due to varying creepages and evolving contact geometry.

The selection of an appropriate rolling contact fatigue damage model requires a balance between prediction accuracy and computational feasibility. Figure 6 illustrates a hierarchical classification of RCF damage models with respect to model complexity and system-level applicability.

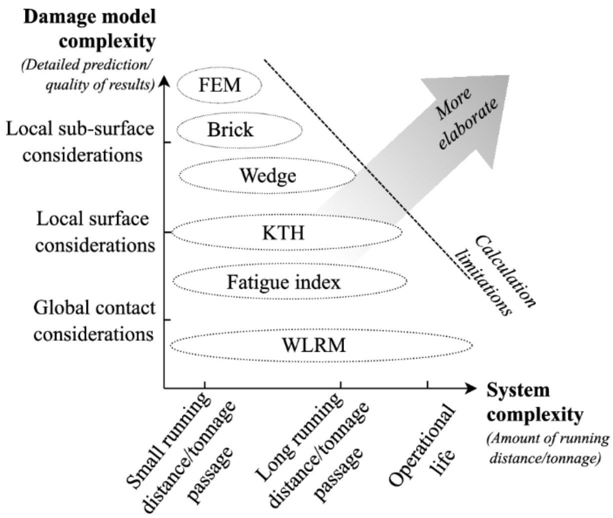

Figure 6. Hierarchical classification of rolling contact fatigue damage models illustrating the trade-off between model complexity and system complexity, ranging from local subsurface approaches to whole-life rail models [7]

3.5. Coupling between wear, RCF, and vehicle dynamics

Wear and RCF are strongly coupled through their mutual dependence on wheel–rail contact conditions. Progressive wear modifies contact geometry and stress distributions, thereby influencing RCF initiation and propagation. Conversely, fatigue-induced surface damage may accelerate wear by promoting material removal or, in some cases, delay fatigue progression by removing damaged layers [6], [27], [44], [54].

From a dynamic standpoint, this coupling necessitates integrated simulation strategies in which vehicle dynamics simulations provide contact forces and creepages, wear models update wheel and rail profiles, and fatigue criteria evaluate RCF damage accumulation over successive operating intervals [32], [33], [34], [35]. Such coupled approaches are essential for realistic long-term degradation assessment in HSR systems.

The strong coupling between vehicle dynamics, wear evolution, and fatigue damage accumulation necessitates an iterative simulation framework. Figure 7 illustrates the adopted coupled vehicle–wear simulation scheme used for long-term degradation analysis.

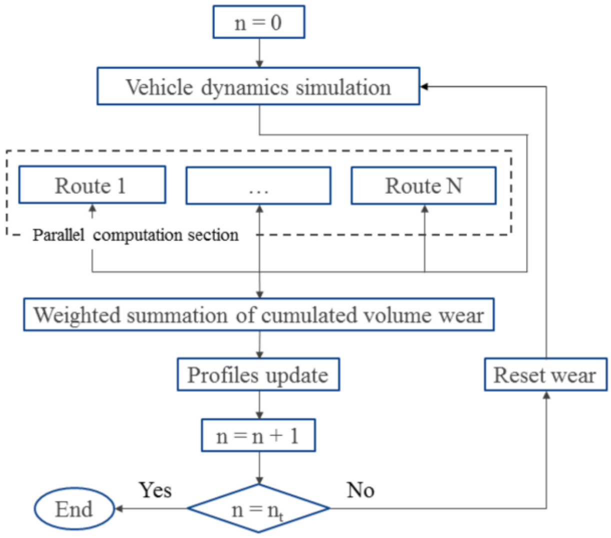

Figure 7. Iterative simulation framework for coupled vehicle dynamics and wheel–rail wear prediction, including parallel route computation, cumulative wear evaluation, and profile update for long-term degradation analysis [33]

3.6. Factors considered in high-speed railway dynamic simulations

In the context of wear and RCF analysis, HSR dynamic simulations must account for several key factors, including vehicle speed, axle load, suspension characteristics, wheel and rail profiles, friction conditions, track irregularities, and operating scenarios. At speeds around 350 km/h, dynamic amplification of contact forces and sensitivity to equivalent conicity variations play a decisive role in governing both wear rates and RCF damage accumulation [27], [57], [58], [59], [60].

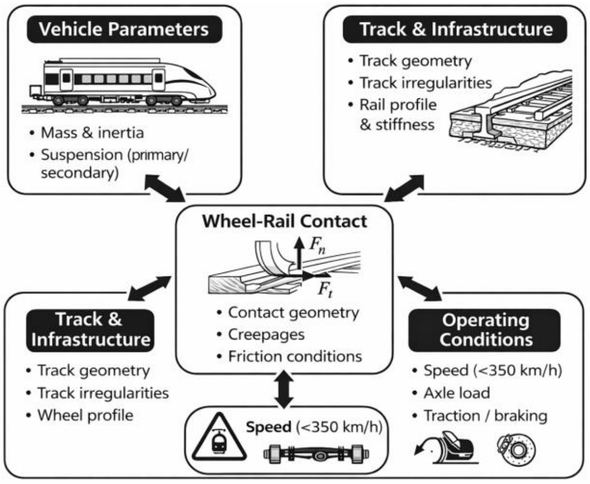

Figure 8. System-level framework of high-speed railway dynamic simulation, including vehicle parameters, track characteristics, contact conditions, and operating factors governing vehicle–track interaction

HSR dynamic behaviour is governed by the coupled interaction between vehicle characteristics, track and infrastructure properties, wheel–rail contact conditions, and operating scenarios. To ensure a realistic representation of vehicle–track interaction at very high operating speeds, all these factors must be simultaneously considered within the dynamic simulation framework. Figure 8 provides a system-level overview of the key factors incorporated in HSR dynamic simulations and their mutual interactions through the wheel–rail contact interface.

4. Global research trends in railway dynamics

The rapid development of HSR systems over the past three decades has placed railway dynamics at the core of modern rail engineering research. As operating speeds continue to increase, the dynamic interaction between vehicles and track infrastructure becomes increasingly complex, nonlinear, and sensitive to degradation mechanisms such as wear and RCF. Consequently, railway dynamics research has progressively shifted from simplified analytical models toward integrated numerical simulation frameworks capable of capturing vehicle–track interaction, wheel–rail contact mechanics, and long-term degradation processes [5], [27], [54].

Recent studies and bibliometric analyses indicate a substantial growth in research output in this field, with a significant proportion of publications emerging after 2015, driven by rapid expansion of HSR networks, particularly in Asia and Europe. It has been reported that more than 60% of railway dynamics-related publications have been produced within the last decade, highlighting a transition from theoretical modelling toward application-orientated and lifecycle-based research frameworks [6], [8], [15], [16].

This section reviews major global research trends in railway dynamics, with particular emphasis on modelling evolution, wheel–rail contact and damage assessment, and system-level lifecycle analysis, which together form the methodological foundation for HSR applications worldwide [15], [16], [27], [54].

4.1. Evolution of railway dynamics modelling

Early railway dynamics research relied primarily on linearised vehicle models and simplified track representations to investigate basic stability and ride quality issues. While these models provided valuable theoretical insight, they were unable to capture the nonlinear effects arising from suspension characteristics, wheel–rail contact behaviour, and track irregularities at high speeds, particularly under conditions where dynamic amplification becomes significant [27], [52].

With advances in computational power, MBD has become the dominant modelling paradigm. Modern MBD frameworks enable the simultaneous modelling of carbody, bogie, wheelsets, suspension systems, and flexible track components, allowing for a realistic representation of system-level dynamics. This evolution has enabled researchers to analyse complex phenomena such as hunting instability, wheel unloading, and nonlinear vehicle–track coupling under high-speed conditions [5], [21], [22], [50].

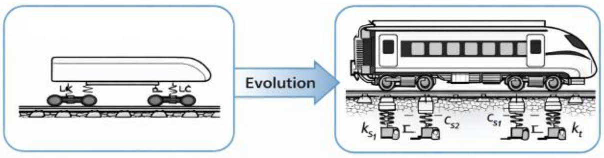

Figure 9. Evolution of railway dynamics modelling from simplified vehicle representations to integrated multibody vehicle–track interaction models

This transition toward high-fidelity multibody modelling reflects a broader shift in railway engineering from simplified analytical approaches to integrated system-level simulations. Such models are now considered essential for evaluating stability margins and dynamic performance in high-speed railway systems, particularly for operating speeds approaching 350 km/h.

4.2. Advances in wheel–rail contact and damage modelling

A central research focus in railway dynamics concerns the accurate modelling of wheel–rail contact. Early linear creep force models have gradually been replaced by nonlinear formulations that account for partial slip, saturation, and spin creepage. Efficient numerical algorithms, such as FASTSIM, have been widely adopted due to their ability to balance computational efficiency and acceptable accuracy in large-scale simulations [3], [41], [42], [61].

However, despite their efficiency, simplified contact models exhibit limitations when dealing with severe loading conditions or non-Hertzian contact geometries. As a result, more advanced approaches, including non-elliptical contact models and finite element methods, have been developed to improve stress prediction and fatigue assessment, albeit at significantly higher computational cost [19], [31], [51].

In parallel, research on wear and RCF has evolved from empirical observations toward semi-mechanistic and physics-based models. Contemporary studies emphasise that wear and RCF originate from the same contact mechanics but follow different degradation pathways, namely material removal and cyclic damage accumulation. This unified understanding has led to the development of coupled modelling strategies capable of capturing both short-term contact behaviour and long-term degradation processes [6], [7], [9], [28], [29].

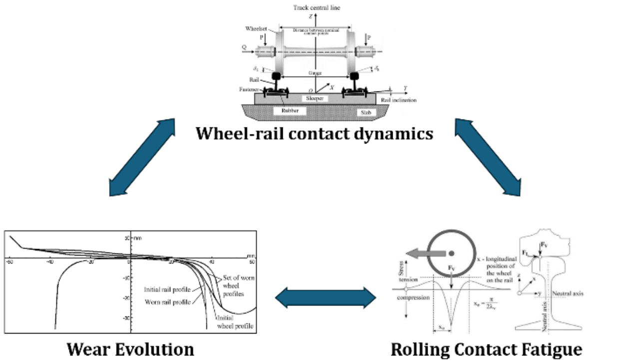

Figure 10. Evolution of railway dynamics modelling from simplified vehicle representations to integrated multibody vehicle–track interaction models [8], [62], [63]

4.3. System-level and long-term degradation assessment

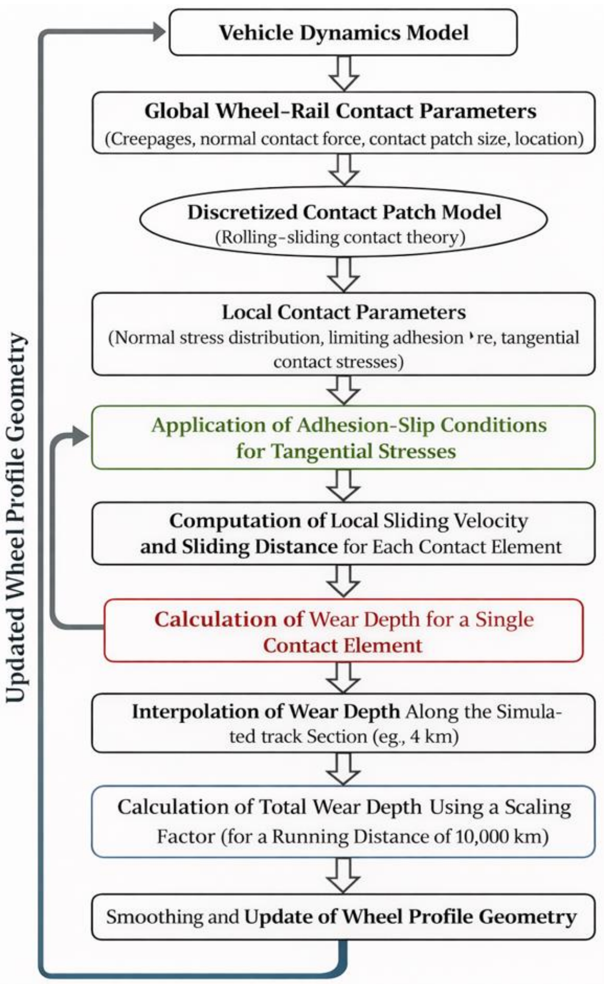

Figure 11. Flowchart of the Iterative Wheel Wear Prediction Framework Coupled with Vehicle Dynamics [64]

A notable global trend is the transition from short-term dynamic response analysis toward system-level and long-term degradation assessment. High-speed railway operation requires not only stable dynamic behaviour but also predictable lifecycle performance of wheels and rails. Consequently, recent research increasingly adopts iterative simulation strategies that couple vehicle dynamics, wear evolution, and fatigue damage accumulation over extended operational periods [20], [33], [35], [64].

These approaches highlight the inherent trade-off between model fidelity and computational efficiency. While high-fidelity methods such as finite element analysis provide detailed insight into stress distributions and crack initiation mechanisms, they remain impractical for long-term simulations. Therefore, engineering-orientated models, including Archard-based wear formulations and fatigue indices, are widely used to support lifecycle prediction and maintenance planning [30], [46], [48].

Such iterative frameworks form the numerical backbone of modern railway dynamics simulations, enabling the integration of short-term vehicle dynamics with long-term degradation behaviour in a computationally efficient manner.

Despite the extensive development of modeling approaches, validation remains a critical aspect of railway dynamics studies. Model validation is typically performed by comparing simulation results with experimental measurements obtained from full-scale tests, roller rigs, or in-service monitoring data. Key validation metrics include contact forces, acceleration responses, wear profiles, and fatigue damage patterns.

Recent studies emphasize the importance of combining numerical simulation with field data to ensure model reliability, particularly for high-speed railway applications where dynamic amplification and nonlinear effects are significant. However, the availability of high-quality validation data remains a major challenge, especially for emerging railway systems.

4.4. Implications for high-speed railway systems

Global research experience demonstrates that railway dynamics plays a decisive role in the safety, reliability, and maintenance cost of high-speed railway systems. Integrated simulation frameworks enable engineers to evaluate stability margins, identify critical degradation zones, and optimise vehicle and track design parameters prior to system deployment [5], [50], [54].

At operating speeds around 300–350 km/h, the coupling between vehicle dynamics, wear, and rolling contact fatigue becomes particularly significant. Small variations in wheel–rail contact geometry, suspension characteristics, or track conditions may lead to substantial differences in degradation rates and maintenance requirements. This sensitivity underscores the necessity of adopting holistic, system-level modelling approaches that integrate dynamics, contact mechanics, and material degradation processes [6], [7], [52].

These findings indicate that future high-speed railway systems, particularly in emerging contexts such as Vietnam, should incorporate integrated simulation frameworks at the design stage to ensure both dynamic stability and long-term sustainability.

5. Implications and application to high-speed railway operation

5.1. Role of railway dynamics in high-speed operation

In high-speed railway (HSR) systems operating at speeds up to 300–350 km/h, vehicle–track dynamic interaction plays a decisive role in ensuring operational safety, ride comfort, and infrastructure longevity. At such speeds, minor variations in contact geometry or track irregularities can significantly amplify dynamic forces. This leads to accelerated wear and rolling contact fatigue (RCF) [1], [5], [50]. Consequently, railway dynamics should not be treated as a secondary design consideration but rather as a core component of high-speed railway engineering.

The integrated modelling framework discussed in the previous sections provides a systematic means to capture these interactions by coupling vehicle dynamics, wheel–rail contact mechanics, and degradation processes within a unified computational environment. Compared with conventional quasi-static or decoupled analyses, such approaches enable a more realistic representation of high-speed operational conditions and their long-term implications [5], [22], [51].

In practical high-speed railway systems, trains typically operate as multi-car configurations rather than isolated vehicles. This introduces additional dynamic coupling effects that significantly influence wheel–rail interaction and system stability.

Interactions between adjacent vehicles, variations in axle loads, and the distribution of forces along the train length can lead to cumulative dynamic responses on the track. These effects may alter wheel–rail contact forces, increase dynamic amplification, and affect the onset of hunting instability, particularly at high operating speeds.

Consequently, accurate assessment of wheel–rail system behaviour requires system-level modelling approaches that account for the full train configuration, rather than simplified single-vehicle representations. This highlights the importance of MBD simulations in capturing the collective behaviour of multi-car trains under realistic operating conditions.

5.2. Implications for wheel and rail degradation management

The strong coupling between vehicle dynamics, wear evolution, and RCF damage accumulation has direct implications for wheel and rail maintenance strategies. Wear-induced profile evolution alters equivalent conicity and steering behaviour, which in turn affects contact forces and stress distributions. Depending on operating conditions and maintenance interventions, these changes may either accelerate or mitigate RCF development [6], [7], [55].

These degradation processes exhibit inherently nonlinear behaviour due to the coupling between contact mechanics, material response, and evolving surface conditions. In particular, nonlinear effects arise from creep force saturation, sensitivity of contact conditions to small variations in wheel and rail profiles, and redistribution of contact stresses under repeated loading.

As operating speeds increase, these mechanisms lead to nonlinear growth in wear rates and fatigue damage accumulation, rather than proportional relationships with speed or load. In the context of this study, such nonlinear behaviour is interpreted based on existing literature from a system-level perspective, rather than being explicitly quantified through dedicated numerical simulations, in order to remain consistent with the review-oriented scope of the paper.

Simulation-based wear and RCF prediction enables the identification of degradation hotspots along representative routes and allows for the evaluation of long-term consequences of design and operational decisions. By integrating cumulative wear and fatigue damage within iterative simulation loops, it becomes possible to move beyond reactive maintenance toward predictive and condition-based strategies. This approach helps reduce lifecycle costs and improve system reliability [20], [64].

5.3. Application to high-speed railway development in Vietnam

Vietnam's planned high-speed railway system [17] represents a unique opportunity to embed advanced railway dynamics methodologies at an early stage of development. This enables the integration of vehicle–track interaction modelling, wear prediction, and fatigue analysis into system design and operation under realistic operating conditions.

To provide a more realistic engineering perspective, typical operating conditions for modern high-speed railways can be considered. These include operating speeds in the range of 300–350 km/h, axle loads of approximately 14–17 tons, and the use of standard gauge (1435 mm) track systems. Under such conditions, wheel–rail contact forces and dynamic responses become highly sensitive to track irregularities, suspension characteristics, and wheel–rail profile geometry [3], [19], [52].

Parametric analyses reported in the literature indicate that increasing operating speed leads to nonlinear increases in dynamic forces and contact stresses, thereby accelerating wear and fatigue damage accumulation. These nonlinear trends are primarily associated with creep force saturation and the sensitivity of contact conditions to small variations in geometry and loading, and are interpreted from a system-level perspective based on existing literature, rather than being explicitly quantified through dedicated numerical simulations, in order to support engineering decision-making within the scope of this review.

Similarly, higher axle loads increase normal contact forces, while track structure influences stiffness and stress distribution. These behaviours are consistent with findings from recent studies on contact mechanics and creep force modelling [3], [31], [41].

By applying coupled vehicle dynamics and wear–RCF simulation frameworks, these factors can be systematically evaluated during the design phase, enabling informed decision-making regarding vehicle specifications, suspension design, wheel and rail profiles, and maintenance planning.

From an engineering perspective, addressing these challenges requires a structured approach integrating modelling, design, and maintenance. First, advanced multibody dynamics simulations should be applied to evaluate vehicle–track interaction under representative operating conditions. Second, optimisation of wheel and rail profiles, together with appropriate material selection, should be implemented to control contact stresses and wear. Finally, predictive maintenance strategies based on simulation results and condition monitoring data should be adopted to manage long-term degradation and ensure safe operation.

This integrated framework provides a practical pathway for improving system reliability, controlling wear and fatigue, and supporting the sustainable development of high-speed railway systems in Vietnam.

5.4. Practical challenges and limitations

Despite its advantages, the application of advanced railway dynamics simulation to high-speed railway systems faces several practical challenges. These include the availability of high-quality input data, such as accurate material properties, friction coefficients, and track irregularity spectra. In addition, long-term degradation simulations remain computationally demanding and require careful calibration and validation to ensure credible results [51], [62].

Another limitation arises from the inherent uncertainty associated with wear and RCF processes, which are influenced by stochastic operating conditions and environmental variability. Therefore, simulation results should be interpreted as indicative trends rather than exact predictions, highlighting the importance of sensitivity analysis and probabilistic modelling approaches [46], [48].

5.5. Integration with digital engineering and future practice

Recent developments in digital engineering and data-driven methodologies provide new opportunities to enhance railway dynamics applications. The integration of numerical simulations with condition monitoring data enables the development of digital twin frameworks for high-speed railway systems. Within such frameworks, simulation models can be continuously updated and validated using operational data, thereby improving the accuracy of wear and RCF predictions over time [16], [53].

For emerging high-speed railway networks, including those planned in Vietnam, this integrated approach offers a pathway toward sustainable operation by aligning design, operation, and maintenance within a unified digital ecosystem.

Overall, the application of advanced railway dynamics frameworks provides a critical link between fundamental contact mechanics, long-term degradation assessment, and practical engineering decision-making in high-speed railway systems.

6. Limitations and future research directions

Despite the advances discussed in this paper, several limitations remain. Wear and RCF processes are inherently influenced by uncertainties in material properties, friction conditions, environmental factors, and operational variability. As a result, deterministic simulation results should be interpreted as indicative trends rather than absolute predictions.

Future research should focus on the integration of probabilistic and data-driven methods with physics-based railway dynamics models to better quantify uncertainty and variability. The incorporation of condition monitoring data into numerical simulations offers promising opportunities for the development of digital twin frameworks for high-speed railway systems. Such approaches will enable continuous model updating, improved prediction accuracy, and more effective lifecycle management.

7. Conclusions and recommendations

7.1. Conclusions

This paper has presented a comprehensive review of railway dynamics with a particular focus on wheel–rail wear and rolling contact fatigue (RCF) in high-speed railway systems. It has been shown that wear and RCF originate from the same wheel–rail contact mechanisms but evolve through different physical pathways, namely material removal and cyclic fatigue damage accumulation. Both processes are strongly coupled with vehicle dynamics through evolving contact geometry, creepages, and stress distributions.

At operating speeds up to 350 km/h, these interactions become highly nonlinear and sensitive to small variations in vehicle parameters, track conditions, and wheel–rail profiles. Simplified or decoupled modelling approaches are therefore insufficient to capture the true dynamic behaviour and long-term degradation characteristics of high-speed railway systems. Instead, integrated simulation frameworks that combine multibody vehicle dynamics, advanced wheel–rail contact modelling, and iterative wear–RCF assessment are required.

Global research trends clearly indicate a transition toward system-level and long-term degradation analysis, where lifecycle performance, rather than short-term dynamic response alone, becomes the primary evaluation criterion. The iterative computational framework discussed in this study provides a consistent numerical backbone for linking vehicle dynamics with progressive wheel–rail degradation under realistic operating conditions.

7.2. Engineering and practical implications

From an engineering perspective, the results of this study highlight the importance of incorporating railway dynamics considerations early in the design and planning phases of high-speed railway projects. Integrated wear and RCF simulations enable engineers to identify potential degradation hotspots, assess the sensitivity of dynamic behaviour to profile evolution, and evaluate the long-term consequences of design and operational decisions.

Such simulation-based approaches support the transition from reactive maintenance strategies toward predictive and condition-based maintenance, contributing to improved safety, reduced lifecycle costs, and enhanced operational reliability. Moreover, the use of standardised simulation frameworks facilitates transparent communication between infrastructure managers, vehicle manufacturers, and regulatory authorities.

7.3. Recommendations for high-speed railway development in Vietnam

The development of high-speed railway systems in Vietnam presents a strategic opportunity to integrate advanced railway dynamics methodologies from the earliest stages of planning and design. Given the operating speeds envisaged, reaching up to 350 km/h, vehicle–track interaction must be treated as a central engineering concern rather than a secondary verification step. The adoption of multibody vehicle dynamics models, combined with advanced wheel–rail contact formulations, is therefore essential to accurately capture dynamic behaviour and assess long-term infrastructure performance.

Equally important is the systematic consideration of wheel–rail degradation mechanisms, particularly wear and rolling contact fatigue. Rather than being evaluated independently, these phenomena should be analysed within coupled simulation frameworks that account for profile evolution, stress redistribution, and their feedback on vehicle dynamics. Such integrated approaches enable the identification of degradation-prone operating regimes and support the development of maintenance strategies that are both technically robust and economically sustainable.

To ensure the reliability of simulation-based assessments, dedicated investment in computational infrastructure and specialised expertise is required. High-speed railway dynamics and degradation modelling demand significant computational resources as well as domain-specific knowledge in contact mechanics and numerical simulation. Strengthening national research capacity through targeted training programmes and collaboration with established international research centres will play a key role in building a sustainable technical foundation.

Finally, a progressive validation strategy should be adopted as the high-speed railway network evolves. Numerical models must be continuously refined using field measurements, inspection data, and monitoring results obtained during operation. This iterative validation process will not only improve predictive accuracy but also facilitate the long-term integration of simulation tools into asset management and decision-making frameworks, thereby contributing to the safe, efficient, and sustainable development of high-speed railway systems in Vietnam.

Author Contributions

Huu Phuoc Nguyen: Conducted the literature review, developed the conceptual framework, and wrote the manuscript. **Duy Nam Ngo:** Contributed to reviewing the manuscript, correcting technical and language issues, and providing guidance on the research content and structure. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Disclosure and Copyright Disclaimer

The authors declare that there are no potential conflicts of interest arising from this research and that the article has not been previously published.

Sharing data on demand

Data will be provided upon request.

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