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Review

From track to stability: A review of vibration behavior, structural reliability, and dynamic performance in railway vehicles

Yana Li*, Yunxiao Chen

Zhan Tianyou College, Dalian Jiaotong University, Dalian 116028, China
* **Corresponding author:** Yana Li, 13504891087@163.com

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Abstract: Railway vehicles operate under continuously changing wheel-rail contact, track geometry, loading, speed, and environmental conditions, making vibration behavior a direct driver of ride comfort, running safety, structural fatigue, and maintenance demand. Existing studies often examine vehicle vibration, structural reliability, and dynamic performance separately, which can obscure the causal path from track excitation to vehicle response, fatigue damage, performance degradation, and maintenance action. This review synthesizes these topics within an integrated life-cycle framework. It first examines major vibration excitation mechanisms, including track irregularities, wheel and rail defects, turnouts, transition zones, traction and braking forces, and aerodynamic disturbances. It then reviews modeling and analysis methods, including multibody dynamics, finite element analysis, vehicle–track coupled models, co-simulation, monitoring-based validation, and uncertainty analysis, with emphasis on their ability to connect dynamic loads with stress histories and fatigue reliability. Structural reliability is discussed as the mechanism by which vibration-induced loads become service risk, while dynamic performance is evaluated through ride comfort, running safety, hunting stability, vibration control, and multi-objective optimization. Furthermore, key limitations such as simplified contact assumptions, insufficient full-scale validation, weak coupling between monitoring data and fatigue models, limited interpretability of AI diagnosis and immature digital-twin implementation are identified in this review. Finally, future directions are proposed toward physics-informed modeling, uncertainty-aware reliability assessment, intelligent monitoring, adaptive vibration control and reliability-centered maintenance for safer, more durable, and sustainable railway vehicles.

Keywords: railway vehicles; vehicle track interaction; vibration behavior; structural reliability; dynamic performance

1. Introduction

Railway transport has become one of the most important modes of modern mobility owing to its high carrying capacity, energy efficiency, safety and suitability both for passenger and freight transport [1]. With the development of high-speed, heavy-haul, urban, and intelligent railway systems, railway vehicles are required to operate at increasingly high speeds, under heavier axle loads, on denser timetables, and with more variable infrastructure conditions [2–4]. These trends increase the need for stable vehicle operation, improved ride comfort, reduced vibration and noise, increased component life and reliable structural performance. Consequently, vibration behavior, structural reliability, and dynamic performance have become main topics in railway vehicle research [5–7].

A railway vehicle is not an isolated mechanical system. In normal operation, it is in continuous interaction with the track, the wheel-rail contact interface, suspension system, bridges, tunnels, transition zones and environmental disturbances. Track irregularities, rail corrugation, wheel flats, wheel polygonization, turnouts, rail joints, traction and braking forces, aerodynamic loads, and crosswinds are all sources of dynamic excitation. These excitations are transferred from the wheel–rail contact to wheelsets, axle boxes, bogie frames, suspension elements, the carbody, onboard equipment and passengers. Therefore, the vibration of the railway vehicles should be considered as a source-path-response problem, where the excitation is created at the vehicle-track interface, transmitted through the vehicle structure, transformed into acceleration and stress responses and finally reflected on comfort, safety, fatigue, reliability and maintenance demand [8, 9]. Studies on railway vehicle vibration monitoring further demonstrate that this sequence is increasingly investigated through onboard and wayside sensors, signal processing, machine learning, and life-cycle monitoring frameworks [10–12].

Among the various dynamic phenomena noticed in railway vehicles, vibration-induced instability and fatigue damage are particularly important. Low frequency vibration is related to ride comfort, hunting motion, carbody swaying and running stability, while high frequency vibration is often correlated with wheel-rail impact, structural resonance, noise radiation and local dynamic stress. Small variations of the wheel profile, equivalent conicity, suspension parameters or track irregularity can have a strong impact on the critical speed and stability of high-speed vehicles. In heavy-haul vehicles, increased axle loads, longitudinal train dynamics, and repeated wheel-rail impacts can accelerate fatigue in wheelsets, axles, bearings, bogie frames, welded joints, and suspension brackets [13]. In urban rail systems, frequent acceleration and braking, tight curves, and complex track conditions may cause significant vibration, wear, noise, and maintenance challenges [14, 15].

Structural reliability is another crucial concern because railway vehicles are expected to maintain safe operation over long service lives under extremely variable loading conditions. Dynamic loads depend on various factors such as speed, track quality, wheel-rail contact state, loading conditions, environmental conditions, degradation state, and maintenance history. Such uncertainties complicate reliability assessment compared with deterministic strength analysis. Fatigue failure, crack initiation, crack propagation, local stress concentration and resonance-induced damage may develop gradually and remain difficult to detect at early stages. As a result, probabilistic reliability analysis, vibration-based health monitoring, remaining useful life prediction, and reliability-centered maintenance have become progressively significant for railway vehicle design and operation [16]. However, monitoring data do not automatically provide reliable knowledge unless vibration signals are connected to load paths, stress histories, validated structural models, and interpretable degradation mechanisms [17, 18].

Dynamic performance connects vibration behavior with reliability consequences. Indicators such as ride comfort, derailment coefficient, wheel unloading rate, lateral wheel-rail force, critical hunting speed, carbody acceleration, vibration exposure, and fatigue damage index are commonly used to evaluate railway vehicle operation. However, these indicators are interdependent and may conflict. For instance, a suspension design that can improve comfort but may decrease stability under some conditions, while a lightweight design may decrease energy consumption but increase structural flexibility, vibration amplification, and fatigue sensitivity [14, 19]. Thus, rather than focusing on optimizing a single performance indicator, vehicle design should balance among comfort, safety, stability, reliability, energy efficiency and life-cycle maintenance costs.

Although numerous studies have addressed railway vehicle dynamics, vibration control, fatigue analysis, structural reliability, and condition monitoring, many existing reviews remain focused on a single aspect of the problem [1, 17, 18]. They have discussed various aspects such as impact vibration, vibration measurement, track structural health monitoring, AI-enabled predictive maintenance, and digital twin-based railway maintenance [20–22]. These studies provide important foundations, but the engineering problem is more tightly coupled than separate categories suggest. Vibration is not only a comfort issue; it is also a source of dynamic stress, fatigue accumulation, structural degradation, noise, and safety risk. Reliability is not only a material strength issue; it depends on service-induced dynamic loads, track conditions, wheel-rail interaction, uncertainty, and maintenance history. Dynamic performance cannot be fully evaluated without considering both vehicle vibration response and structural reliability.

Accordingly, this review follows an integrated life-cycle framework that tracks and addresses operational excitation, wheel-rail interaction, vibration transmission, structural stress and fatigue damage, reliability degradation, dynamic performance response, monitoring, control, and maintenance decision-making. It further contributes by linking vibration excitation mechanisms with fatigue-relevant structural responses, connecting vehicle-track dynamic modeling with reliability assessment through multibody dynamics, finite element analysis, coupled simulation, uncertainty quantification, monitoring data, and validation, and discussing dynamic performance from the broader perspective of comfort, running safety, vibration control, life-cycle reliability, intelligent monitoring, and maintenance optimization.

This integrated logic is illustrated in **Figure 1**, which presents track-induced excitation, vehicle vibration response, structural reliability, dynamic performance, and maintenance feedback within one life-cycle framework. The same logic is used throughout the review; Section 2 explains how excitation is generated and transmitted, Section 3 evaluates modelling approaches for representing this process, Section 4 links vibration-induced loads to fatigue and reliability, Section 5 examines performance and control interdependencies, Section 6 discusses future directions for intelligent and reliability-centered railway vehicle systems, and Section 7 concludes the article.

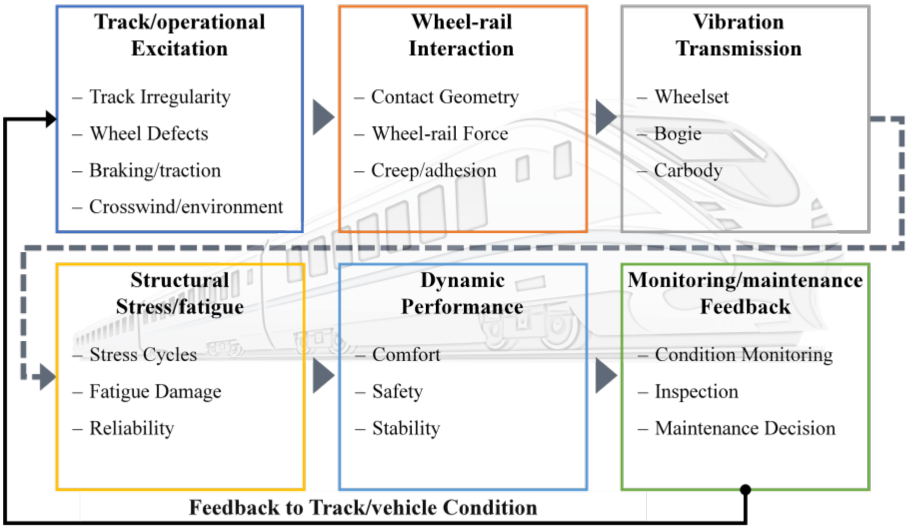

Figure 1. Integrated framework linking track-induced excitation, vibration response, structural reliability, dynamic performance, and maintenance feedback in railway vehicles.

2. Vibration behavior and excitation mechanisms in railway vehicles

Vibration behavior in railway vehicles arises from the continuous interaction between the moving vehicle, the wheel-rail contact interface and the supporting track system. Unlike mechanical systems with relatively stable boundary conditions, railway vehicles are exposed to spatially varying track geometry, evolving wheel-rail contact states, changing speeds, and environmental loads. These factors produce vibration responses that influence ride comfort, running stability, structural fatigue, noise generation, and maintenance demand. Therefore, Section 2 focuses on the physical mechanisms by which excitation is generated, transmitted through the wheelset-bogie-carbody system, and transformed into measurable acceleration, force, stress, and damage-related indicators. The vibration data become useful for engineering decisions only when they are connected to vehicle state, track condition, component health, and maintenance planning [11].

The vibration response of a railway vehicle is not governed by a single excitation source or structural mode. Instead, it is the result of coupled interactions among wheelsets, bogies, suspension systems, carbodies, track structures, and infrastructure components. Low-frequency vibration is mainly associated with comfort, carbody motion, and running stability, whereas high-frequency vibration is more closely related to wheel–rail impact, structural resonance, rolling noise, and local stress fluctuation. The coexistence of these frequency ranges makes railway vehicle vibration a multi-scale dynamic problem. It is an important distinction because low-frequency responses are commonly evaluated through comfort and stability indicators, while high-frequency responses are more closely linked to impact loading, fatigue damage, wear, and noise.

2.1. Sources of vibration excitation

The main excitation source in railway vehicle operation is track irregularity. Vertical irregularities result in bounce and pitch motions, while lateral alignment errors excite sway, yaw and hunting-related responses [4]. Cross-level irregularities and track twist can induce roll motion and uneven wheel loading. As train speed increases, the same spatial irregularity is transformed into a higher-frequency temporal excitation, which may amplify vehicle responses when excitation frequencies approach the natural frequencies of vehicle or track components. Track irregularity is therefore not merely a geometric defect; it is a speed-dependent dynamic input whose effect depends on vehicle mass distribution, suspension properties, wheel-rail contact state, and track support stiffness [5–7].

Wheel and rail defects provide another important type of excitation [7]. Wheel flats, wheel polygonization, rail corrugation, local rail dents, and welded rail joints exert periodic or impulsive loads at the wheel-rail interface. These excitations could lead to huge dynamic wheel loads, high-frequency vibration, and accelerated degradation of both vehicle and track components [4–6]. Impact-vibration studies classify these defects as wheel-rail contact irregularities, including wheel out-of-roundness, wheel flats, tread spalling, polygonization, rail joints, corrugation, switches, and local rail defects [23–25]. Their severity is governed not only by defect size but also by speed, axle load, contact stiffness, and the dynamic compliance of the track. For example, the same wheel flat may be a minor comfort issue at low speed but a fatigue-critical impact source at high speed.

Vibration behaviour is also influenced by operational conditions. Traction and braking forces influence longitudinal dynamics and may interact with wheel-rail adhesion variation. Curving induces lateral creep forces, flange contact, wheel unloading, and unequal suspension deformation. Turnouts and crossings produce discontinuous contact conditions and impact loads. Bridge expansion joints, track transition points, tunnels, and viaducts can further modify the dynamic boundary conditions of the track, producing further excitation and response amplification [26–28]. In freight and heavy-haul operations, longitudinal impulses during traction, braking, and coupler interaction are especially important because they can couple with lateral curving behavior, wheel-rail adhesion, and wagon hunting stability [13, 29]. Aerodynamic loads, crosswinds, and tunnel pressure waves also disturb carbody motion and wheel unloading, especially for high-speed vehicles [30,31]. These examples demonstrate that vibration excitation is determined by vehicle and infrastructure conditions, operating scenario, and environment. **Table 1** shows how these excitation sources propagate into vehicle response, reliability degradation, and maintenance implications. The excitation sources should not be ranked only by vibration amplitude; their engineering significance depends on how they modify wheel-rail forces, stress cycles, comfort, safety margins, and maintenance demand.

Table 1. Source-to-consequence map of vibration excitation mechanisms in railway vehicles.

Excitation source	Typical origin	Dominant vibration response	Reliability/Performance consequence	Monitoring or mitigation implications
Track geometry irregularity	Vertical profile, alignment error, cross-level, twist	Low-frequency bounce, pitch, sway, roll, and wheel-load variation	Reduced ride comfort, increased wheel unloading, higher safety risk, fatigue load amplification	Track geometry monitoring, speed-dependent response assessment, targeted track maintenance

Table 1. *Cont.*

Excitation source	Typical origin	Dominant vibration response	Reliability/Performance consequence	Monitoring or mitigation implications
Wheel defects	Wheel flat, polygonization, tread spalling, out-of-roundness	Periodic or impulsive wheel-rail impact, axle-box vibration, high-frequency stress	Accelerated wheel/rail wear, bogie-frame fatigue, bearing damage, and noise increase	Axle-box acceleration, wayside wheel impact load detection, wheel reprofiling
Rail surface defects	Rail corrugation, joints, weld irregularities, and local dents	Repeated high-frequency excitation and vibration transmission through the bogie and carbody	Rolling noise, fatigue stress concentration, passenger discomfort, component loosening	Rail grinding, corrugation monitoring, vibration-spectrum tracking
Turnouts and crossings	Discontinuous wheel-rail contact and variable support stiffness	Transient impact, lateral force fluctuation, wheel unloading	Localized wear, reduced running safety, high maintenance demand	Instrumented turnout monitoring, impact-load measurement, optimized crossing geometry
Transition zones and bridges	Abrupt stiffness change between embankment, bridge, tunnel, or slab track	Dynamic load amplification, resonance, vertical acceleration peaks	Track settlement, wheel–rail force increase, comfort reduction, fatigue accumulation	Stiffness transition design, bridge–vehicle dynamic evaluation, long-term monitoring
Traction and braking forces	Acceleration, deceleration, adhesion variation, coupler interaction	Longitudinal vibration, wheel–rail creepage variation, load redistribution	Wheel slip/slide risk, wear, instability in heavy-haul or urban operation	Adhesion monitoring, traction/braking control, wheel condition inspection
Aerodynamic and environmental loads	Crosswind, tunnel pressure waves, temperature, rain, snow, contamination	Carbody sway, pressure-induced vibration, adhesion change	Comfort degradation, wheel unloading, overturning risk, uncertain load conditions	Wind monitoring, tunnel-pressure assessment, environmental-condition-based operation

2.2. Wheel rail interaction and vibration generation

Wheel-rail interaction is the basic mechanism through which track excitation enters the vehicle system. The contact patch between the wheel and rail is small, but it transmits large normal, tangential and creep forces. The nonlinear nature of this contact makes railway vehicle vibration intrinsically complex. Contact stiffness varies with load, profile geometry, wear state and local surface defects. The tangential forces depend on creepage, adhesion, contamination and friction conditions. As a result, small changes in wheel or rail profile may produce large changes in vibration response and running stability [32].

In the vertical direction, wheel-rail contact converts track irregularities and surface defects into dynamic wheel loads. When excitation is smooth and moderate, the wheel remains in continuous contact with the rail, and the response can often be described using linear or weakly nonlinear models. But severe defects, rail joints, or transition zones might cause impact-like responses, leading to sudden load amplification and high-frequency vibration. In worse cases, partial loss of contact or wheel unloading may occur, reducing running safety and increasing fatigue damage. This vertical load amplification is critical because it determines the stress cycles transmitted to axles, bearings, bogie frames, welded joints, and suspension brackets, from a reliability perspective.

In the lateral direction, wheel-rail contact governs guidance and stability. The conicity of the wheel tread produces a self-centering mechanism, but it also contributes to hunting motion at high speed. The balance among wheelset guidance, suspension restraint, creep force saturation, and flange contact establishes whether the vehicle runs stably or develops unstable oscillation. This makes wheel-rail interaction not only a vibration transmission mechanism but also a stability-determining mechanism. Degraded wheel-rail contact can worsen hunting stability, wheel-rail wear, rolling contact fatigue, and running safety, while accurate modeling of contact geometry, normal force, creep force, and adhesion remains a persistent challenge [13]. Heavy-haul vehicle-track interaction further illustrates this coupling by linking wheel-rail forces, vehicle response, track vibration, wear, fatigue, safety, and maintenance consequences [13, 29]. Thus, the wheel-rail interface is the physical link between vibration excitation, dynamic performance, and structural reliability.

A critical point is that improving wheel-rail interaction is not always a one-directional objective. Higher guidance stiffness may improve curving or suppress lateral motion, but it may also increase wheel-rail forces and wear. Lower equivalent conicity may improve high-speed hunting stability, but it may reduce curving performance. Better vibration isolation may reduce carbody acceleration but increase bogie loads. Therefore, wheel-rail interaction should be evaluated through coupled criteria rather than through a single comfort, force, or stability index.

2.3. Vibration transmission paths

Once the vibration is generated at the wheel-rail interface, the vibration propagates through several transmission paths. The most direct path is from the wheelset to the axle box, primary suspension, bogie frame, secondary suspension, carbody, and finally to passengers and onboard equipment. Along this sequence, every component acts as both a vibration transmitter and a dynamic filter. The stiffness and damping characteristics of the primary suspension influence wheelset stability and bogie vibration. On the other hand, secondary suspension mainly directs carbody vibration and ride comfort.

The bogie also plays a crucial role in the transmission of vibration. It fastens the wheelsets to the carbody and meets the contending requirements of stability, curving ability, comfort, and structural strength. A bogie with insufficient damping may allow excessive vibration to reach the carbody, whereas excessive damping may increase wheel-rail forces and reduce isolation performance. Similarly, suspension nonlinearities, clearances, friction elements, and degradation can alter vibration transmission in ways that are tough to capture with simplified models [33].

Structural transmission is also significant. Flexible distortion of the bogie frame, carbody, wheelset, and suspension brackets can cause additional vibration modes. Modern lightweight car bodies are especially sensitive to elastic vibration because reduced structural mass may lower natural frequencies and increase susceptibility to bending or torsional responses. Therefore, vehicle vibration should not be observed only as rigid-body motion. Flexible-body effects must be considered when assessing high-speed vehicles, lightweight structures, and fatigue-sensitive components [13]. The same vibration path that transmits acceleration to passengers can also transmit dynamic stress to fatigue-sensitive structural details. Therefore, vibration isolation, structural durability, and comfort evaluation are inseparable.

2.4. Vehicle vibration modes and frequency characteristics

Railway vehicles exhibit different vibration modes including vertical, lateral, longitudinal, pitch, roll, yaw, bending and torsional motion. Vertical bounce and pitch are closely linked to tracking vertical irregularities and passenger comfort. Lateral sway and yaw are related to alignment irregularities, wheel-rail conicity and hunting stability. Roll vibration may occur from cross-level irregularity, curving, wind loading, or irregular suspension characteristics. Longitudinal vibration can occur during traction, braking, coupler interaction and train formation dynamics [1,29].

Carbody vibration is specifically important, as it directly affects passenger comfort and onboard equipment reliability. At low frequencies, carbody rigid-body motion controls perceived ride quality. At higher frequencies, elastic bending and torsion may develop significantly, especially in long and lightweight car bodies. If excitation from track irregularity, wheel polygonization, or rail corrugation coincides with carbody, bogie, or wheelset modes, resonance-like amplification may occur. Such amplification may increase floor acceleration, degrade comfort, and increase local stress at joints and interfaces.

Wheel-rail force variation and running stability are closely related to bogie and wheelset vibration [34]. Wheelset lateral motion, yaw motion, and rotational dynamics are essential to hunting behavior. Bogie frame vibration can impact suspension loads, fatigue stress and vibration transmission to the carbody. Axle box acceleration is often used as an indicator of wheel-rail influence, track defects and bearing faults. However, interpreting such signals requires caution because measured vibration may contain overlapping contributions from track irregularities, wheel defects, suspension dynamics, and structural resonance [12,35,36]. The onboard and wayside measurements provide valuable information, but sensor placement, calibration drift, environmental variability, and signal ambiguity can limit direct fault attribution [12,37].

Low-frequency vibration, typically associated with vehicle rigid-body motion, has a strong influence on ride comfort and running stability. High-frequency vibration is more localized but is often more damaging to components because it is associated with wheel–rail impact, corrugation, wheel flats, polygonal wear, and structural resonance. The two ranges are not independent. Repeated high-frequency impact can accelerate wheel or rail wear, which later modifies low-frequency vehicle dynamics; conversely, poor hunting stability can intensify irregular wear and generate new high-frequency excitation. This coupling explains why railway vehicle vibration should be interpreted across frequency ranges and evaluated through comfort, safety, fatigue, and maintenance consequences together.

2.5. Experimental characterization of vibration behavior

Experimental investigation remains vital because railway vehicle vibration is influenced by several factors (nonlinear and uncertain) that cannot be fully estimated by analytical models alone. Field tests using accelerometers, displacement sensors, strain gauges, axle box sensors, force measurement wheelsets and onboard monitoring systems provide direct information about vehicle response under real operating conditions. Such data are valued for recognizing vibration sources, validating dynamic models, assessing ride comfort, and detecting abnormal structural behavior [38].

Roller-rig tests and laboratory experiments offer restrained conditions. They allow researchers to examine wheelset stability, suspension behavior, wheel–rail contact characteristics and vibration control strategies under repeatable excitation. Modal testing and operational modal analysis are used to identify natural frequencies, mode shapes, and damping ratios of carbodies, bogie frames, and other structural components. However, laboratory tests cannot fully replicate the mutual effects of long-term wear, environmental variability, mixed excitation, infrastructure degradation, and real operating uncertainty [22].

Onboard and wayside monitoring provide complementary information. Onboard monitoring offers broad spatial coverage from in-service vehicles, whereas wayside monitoring provides high-precision local information for passing vehicles [10–12]. Neither approach is sufficient alone. Onboard accelerometers may detect track defects and vehicle anomalies, but localization and source separation remain difficult. Wayside sensors may precisely detect wheel-impact loads, track geometry, or rail defects, but their coverage is restricted to instrumented sites. IoT-based sensing, fiber-optic sensing, distributed acoustic sensing, and smart composite materials can expand monitoring ability, but they also introduce additional practical concerns related to durability, calibration, interoperability, data quality and cybersecurity [20,22].

Nevertheless, experimental characterization has limitations. Field data are affected by mixed excitation sources, variable operating conditions, sensor noise, and limited measurement locations. Laboratory tests may not fully reproduce real track irregularities, environmental effects, long-term degradation, or full vehicle–infrastructure coupling. Therefore, the most reliable understanding of vibration behavior is obtained by combining field measurement, laboratory testing, numerical simulation, and statistical analysis. In this review framework, the role of experimental characterization is to support the transition from vibration observation to model validation, reliability assessment, and performance evaluation.

3. Modeling and analysis methods for vehicle–track dynamic systems

Accurate modeling of railway vehicle–track dynamic systems is fundamental for understanding vibration behavior, predicting structural loads, evaluating running safety, and optimizing vehicle performance. Because railway vehicles operate through continuous wheel–rail interaction, their dynamic response cannot be fully described by considering the vehicle alone. The track, foundation, bridges, tunnels, turnouts, and transition zones all influence excitation input and vibration transmission. Therefore, vehicle-track dynamic analysis increasingly requires coupled modeling strategies that can represent vehicle motion, structural flexibility, wheel-rail contact, and track response within a consistent framework [39]. The modeling objective is not simply to increase detail, but to represent the physical link between excitation, vibration response, stress history, reliability degradation, and dynamic performance indicators.

However, modeling railway vehicle dynamics involves a fundamental compromise between accuracy and computational efficiency. Highly detailed models can capture nonlinear contact, flexible structures, suspension characteristics, and local defects, but they are computationally expensive and often difficult to validate. The simplest models are efficient and useful for parametric studies, but they may fail to notice important nonlinear or high-frequency phenomena. The selection of a suitable modeling method should therefore be directed by the research objective, frequency range, component of interest, and required level of prediction accuracy [17]. Quasi-static, multibody, finite element, dynamic finite element, wave-propagation, and hybrid models each have distinct strengths, but their value depends on whether they support the specific part of the vibration-reliability-performance chain being investigated [40].

3.1. Multibody dynamic modeling of railway vehicles

Multibody dynamics is a widely used method for railway vehicle analysis. In conventional multibody models, the carbody, bogie frames, wheelsets and suspension elements are signified as interconnected rigid bodies. These models are effective for analyzing running stability, ride comfort, curving performance, wheel-rail forces and vehicle response to track irregularities. They can also incorporate nonlinear suspension elements, bump stops, friction dampers, yaw dampers, and wheel -rail contact models.

The major strength of multibody modeling lies in its ability to describe system-level vehicle motion with reasonable computational cost. It allows researchers to investigate how suspension parameters, vehicle speed, wheel profile, equivalent conicity and track irregularities influence dynamic performance. For studies focused on low-frequency rigid-body motion, such as hunting stability and ride comfort, multibody models are often sufficient. This makes multibody dynamics particularly useful for generating comfort indices, wheel–rail force histories, derailment-related indicators, and stability margins.

Nevertheless, rigid multibody models do have obvious shortcomings, such as being unable to accurately characterize elastic deformation of carbodies, bogie frames, axles, or wheelsets. This limitation particularly becomes critical for lightweight railway vehicles and high-speed trains, where structural flexibility can significantly affect vibration transmission and fatigue loading. Rigid models may also underestimate local dynamic stress and fail to capture resonance between structural modes and external excitation. Therefore, flexible multibody models have become increasingly important. These models can better represent carbody bending, bogie frame vibration, and wheelset deformation while maintaining system-level dynamic simulation capability by the introduction of modal flexibility or finite element-based component flexibility [1]. Rigid-body performance indicators are therefore useful but not sufficient for reliability assessment, because acceptable comfort or wheel unloading does not necessarily exclude fatigue-critical elastic modes in the bogie frame or carbody.

3.2. Finite element modeling of vehicle structures

Finite element modeling is essential for the assessment of structural stress, fatigue behavior, modal characteristics and local deformation of railway vehicle components. Carbodies, bogie frames, axles, wheels, welded joints, suspension brackets and equipment support are usually analyzed using finite element approaches. These models provide detailed information on stress concentration, natural frequencies, mode shapes and structural stiffness distribution.

Finite element analysis is particularly valuable for structural reliability assessment because fatigue damage often initiates at local stress concentration zones rather than at locations of maximum global displacement. Welded joints, bolted connections, axle transitions, and bracket interfaces are typical examples where local modeling detail strongly affects predicted fatigue life. In addition, finite element models support lightweight design by identifying redundant material regions and evaluating the control interdependencies between weight reduction and vibration resistance [41]. In the integrated vibration–reliability–performance chain, finite element modeling acts as the conversion tool that transforms dynamic loads into stress histories and fatigue-relevant damage indicators.

However, finite element models are associated with several challenges. Detailed models may contain millions of degrees of freedom, making direct coupling with vehicle-track dynamic simulations computationally demanding. Boundary conditions are another source of uncertainty. The way loads, constraints, contact interfaces, and suspension connections are represented can substantially influence results. Moreover, material properties, weld quality, residual stress and manufacturing inadequacies are often simplified or ignored. These uncertainties can limit the reliability of purely deterministic finite element predictions. Therefore, finite element modeling should be combined with experimental modal analysis, strain measurement and probabilistic methods when used for design verification or fatigue assessment [42]. A refined finite element mesh does not guarantee a reliable fatigue prediction if the input load spectrum, boundary conditions, damping assumptions and material uncertainties are poorly characterized.

3.3. Vehicle-track coupled dynamic models

Vehicle-track coupled models extend the analysis from the vehicle subsystem to the complete wheel-rail-track interaction system. In such models, the vehicle is usually represented using multibody dynamics, while the track is modeled as rails, rail pads, sleepers, ballast, slab layers, fasteners and foundation supports. The wheel-rail interface connects the two subsystems through nonlinear normal contact and tangential creep forces.

These models are necessary because track flexibility can strongly influence wheel-rail forces and vibration response. A vehicle running on a rigid track will not exhibit the same dynamic behavior as one running on a flexible ballasted track, slab track, bridge or transition zone. Track support stiffness, damping, rail pad properties, ballast degradation and foundation settlement all affect vibration transmission and dynamic load amplification. Coupled models are therefore widely used to study track irregularity response, wheel-rail impact, bridge-vehicle interaction, transition zone dynamics and rail corrugation-related vibration [43, 44]. Quasi-static excitation mainly represents moving axle loads, whereas dynamic excitation arises from wheel and rail unevenness, defects and system flexibility; the latter is more relevant to impact amplification and fatigue-relevant stress cycles [45–47].

A critical issue in vehicle-track coupled modeling is the representation of track irregularities and defects. Measured track geometry provides realistic excitation, but it may not be available for all operating conditions. Artificially generated irregularities allow standardization but may fail to reproduce local defects and degradation patterns. In addition, wheel and rail surface defects such as wheel flats and rail corrugation require fine spatial resolution and accurate contact modeling. Consequently, the quality of excitation input is often as important as the sophistication of the dynamic model itself. Therefore, coupled models should be evaluated not only by mathematical complexity, but also by whether they reproduce the excitation environment that drives comfort loss, wheel-rail force amplification, structural stress, and maintenance demand.

3.4. Time-domain and frequency-domain analysis

Time-domain analysis is widely used because railway vehicle dynamics are nonlinear and often involve transient events. It is suitable for studying wheel-rail impact, hunting instability, curving, braking, traction, turnouts, track transitions and degraded track conditions. Time-domain simulation can capture nonlinear suspension behavior, contact loss, flange contact, creep force saturation and speed-dependent effects. It is also useful for evaluating safety indices such as derailment coefficient, wheel unloading rate and lateral wheel-rail force.

Frequency-domain analysis, by contrast, is efficient for studying vibration transmission, modal response, resonance and random vibration under linear or weakly nonlinear assumptions. It is useful for identifying dominant frequency bands, evaluating ride comfort, analyzing structural resonance and interpreting measured vibration spectra. Frequency-domain methods also support transfer function analysis between wheel-rail excitation and carbody or bogie response [48].

However, finite element models also encounter several challenges. For example, time-domain analysis is not only computationally expensive but also sensitive to input uncertainty. Whereas frequency-domain analysis may not capture strong nonlinearities or transient impacts. A combined approach is often most effective for railway vehicle systems. Time-domain simulations can reveal nonlinear and transient behavior, whereas frequency-domain analysis can clarify resonance mechanisms and vibration transmission characteristics. From a reliability perspective, this combined approach is useful because fatigue damage depends on time histories of stress cycles, while resonance mechanisms and vibration transfer paths are often more clearly diagnosed in the frequency domain.

3.5. Co-simulation and multi-physics modeling

Co-simulation and multiphysics modeling are increasingly used in practice, as railway systems become sophisticated. These approaches integrate multibody dynamics, finite element analysis, control systems, aerodynamics, acoustics, thermal effects, and electrical traction models. For example, active suspension analysis requires coupling vehicle dynamics with control algorithms. Crosswind stability assessment may require coupling vehicle dynamics with aerodynamic loading. Noise prediction requires linking wheel–rail vibration with acoustic radiation. Fatigue evaluation may require transferring dynamic loads from multibody simulations to finite element stress models.

The advantage of co-simulation is that it allows each subsystem to be modeled using the most suitable method. However, it also introduces challenges in numerical stability, data exchange, time-step coordination, and model validation. Coupling errors may arise when one subsystem is simplified excessively or when incompatible assumptions are used across domains. Therefore, co-simulation should not be treated as a simple combination of software tools. It requires careful definition of interfaces, consistent parameter exchange, and validation against physical measurements [15, 49]. This requirement is especially important when dynamic loads are transferred from a vehicle model to a structural model, because loss of phase, amplitude, boundary-condition, or frequency information can lead to misleading fatigue predictions.

Multi-physics modeling is especially important for next-generation railway vehicles because vibration behavior is increasingly linked with energy consumption, noise emission, structural durability, and intelligent control. However, as model complexity increases, interpretability may decrease. A highly complex model is not necessarily more useful if its parameters cannot be identified or its predictions cannot be validated. Thus, model complexity should increase only when it improves physical insight or engineering decision-making [50]. Accordingly, model integration must be accompanied by data consistency, validation, uncertainty awareness, and clear decision rules.

3.6. Model validation and uncertainty analysis

Model validation is a critical step in railway vehicle dynamics because many model parameters are uncertain or time-varying. Suspension stiffness and damping, wheel–rail friction, track support stiffness, vehicle loading condition, wheel and rail profiles, and structural damping can all change during service. Without validation, numerical models may produce results that appear precise but are not physically reliable [39].

Experimental validation can be performed using field tests, roller-rig tests, modal testing, axle-box acceleration measurement, strain monitoring, and force measurement on wheelsets. Validation should include not only global responses such as carbody acceleration and wheel–rail force but also local quantities such as structural strain and component vibration where reliability assessment is required. The usefulness of validation data depends on sensor placement, calibration, signal quality, data synchronization, and the ability to separate vehicle faults from track-induced excitation [10–12].

Uncertainty analysis is therefore not an optional extension but a necessary part of realistic modeling. Track irregularity spectra, wheel defects, friction conditions, suspension degradation, payload variation, support stiffness, material variability, and measurement noise all influence predicted responses. Deterministic simulations based on nominal parameters may be useful for comparison, but they cannot quantify the probability that a vehicle will remain comfortable, stable, safe, and fatigue-resistant under real operating variability. Simulations provide mechanistic interpretation, whereas monitoring and AI models can support prediction; both remain limited when long-term field validation data are scarce [51–55].

Hybrid modeling offers a promising response to these limitations. Physics-based models can define the causal structure of vehicle-track interaction, while monitoring data can update uncertain parameters, detect deviations, and support remaining useful life prediction. Machine learning may improve anomaly detection and degradation forecasting, but purely data-driven models can fail when applied outside their training domain or when their outputs are not physically interpretable. Thus, the most useful future models are likely to be physics-informed, data-updated, and validation-oriented rather than purely deterministic or purely data-driven. Digital-twin frameworks may support this transition only when they provide bidirectional updating, transparent uncertainty treatment, and verified links between measured vibration, structural stress, reliability state, and maintenance decisions [21,22,56].

4. Structural reliability and fatigue performance of railway vehicles

Structural reliability is a fundamental requirement for railway vehicles because their components are expected to withstand millions of load cycles over long service periods while maintaining safe and stable operation. Unlike static structures, railway vehicles experience continuously varying dynamic loads caused by wheel-rail interaction, track irregularities, braking, traction, curving, vibration resonance and environmental effects. These loads are transmitted through wheelsets, axles, bogie frames, suspension systems, carbodies, welded joints and equipment supports, producing complex stress histories. Therefore, structural reliability in railway vehicles should not be regarded merely as a strength verification problem, but as a dynamic, probabilistic, and life-cycle issue [57].

A critical feature of railway vehicle structures is that damage usually accumulates gradually. Fatigue cracks may initiate at stress concentration regions and propagate under repeated vibration loading before becoming visible or safety-critical. This makes early detection and life prediction difficult. Moreover, the actual service environment is often more variable than design assumptions. Track degradation, wheel wear, suspension aging, temperature variation, corrosion, overload operation, and maintenance quality can all change the structural load path and damage accumulation rate. Consequently, reliability assessment must consider not only nominal design loads but also real dynamic operating conditions [58]. In this section, structural reliability is treated as the intermediate link between vibration behavior and service risk: vibration excitation generates load histories, load histories generate stress cycles, and stress cycles govern fatigue damage, reliability degradation, remaining useful life, and maintenance decisions.

4.1. Dynamic loads and structural damage mechanisms

Dynamic loads are the direct link between vehicle vibration behavior and structural reliability. Track irregularities and wheel-rail defects generate fluctuating wheel loads, lateral forces, and impact forces that propagate into the bogie and carbody. Vertical dynamic loads are commonly associated with wheel flats, rail joints, track settlement, and transition zones, while lateral loads are closely related to curving, hunting motion, flange contact and alignment irregularities.

These dynamic loads produce stress cycles in structural components. In many cases, fatigue damage is not caused by the largest single load but by the cumulative effect of repeated moderate-amplitude loads. This is particularly important for bogie frames, axles, welded joints, and suspension brackets, where local stress concentration can amplify nominal loads. Impact excitation may also introduce high-frequency stress components, which are sometimes overlooked in low-frequency vehicle dynamics analysis. If such components coincide with local structural modes, resonance-induced fatigue may occur [1].

The critical limitation of many fatigue assessments is that they still depend on simplified load spectra or deterministic design cases. Such approaches are useful for standard verification but may not represent the actual service environment, especially under wheel polygonization, rail corrugation, turnout impacts, degraded suspension, or heavy-haul operation. The real fatigue loads are influenced by evolving wheel-rail contact, operational speed, axle load, track condition, and sensor-observed degradation trends [13, 17]. Therefore, dynamic load characterization should be updated during service rather than treated as a fixed design-stage input.

Damage mechanisms in railway vehicle structures are diverse. High-cycle fatigue is common because components undergo a very large number of stress cycles during service. Variable-amplitude fatigue is also significant because real operating loads vary with speed, track quality, passenger or freight load, and environmental conditions. Crack initiation often occurs at weld toes, bolt holes, geometric transitions, axle seats, and bracket connections. Once a crack initiates, its growth depends on stress intensity, load sequence, residual stress, material properties, corrosion and inspection interval. Therefore, fatigue damage should be analyzed as a coupled process involving load generation, stress concentration, material resistance, and maintenance strategy.

4.2. Reliability of key vehicle components

Different railway vehicle components face different reliability challenges. The most safety-critical components are wheelsets and axles, among others, as their failure can have severe costs. Axles are subjected to rotating bending, torsion, press-fit effects, residual stress and surface damage. Small defects may grow under repeated cyclic loading, making crack detection and inspection planning essential.

Bogie frames are also highly fatigue-sensitive. They carry loads from the wheelsets, suspension systems, traction motors, braking devices and carbody. Welded joints in bogie frames are particularly vulnerable because welding introduces geometric discontinuities, residual stress and material property variation. Even when global stresses appear acceptable, local weld stress may exceed fatigue limits under dynamic loading. This explains why detailed local analysis and experimental validation are necessary for bogie reliability assessment [59].

Carbody structures also face a different set of problems. Modern carbodies are often designed to be lightweight. Improves energy efficiency but can reduce stiffness and increase vibration sensitivity. Elastic vibration, equipment loading, door openings, window cutouts, and joint regions may generate local fatigue problems. Although carbody failure is usually less sudden than axle or wheelset failure. The fatigue cracks can compromise structural integrity, sealing performance, noise insulation and long-term durability.

Suspension components, bearings, dampers, brackets and bolted connections also play important roles. Their degradation can alter vehicle dynamics, increasing loads on other components. For example, damper performance loss may increase carbody vibration or bogie instability, while suspension stiffness variation may produce uneven wheel loads. Thus, component reliability is not independent; deterioration in one subsystem can accelerate damage in another [41]. A bracket crack, bearing defect, damper degradation, or wheel tread defect should therefore be interpreted not only as a local failure, but also as a possible source of changed vibration transmission and redistributed dynamic loads.

Across components, the common reliability pathway is that vibration-induced loads create local stress cycles, which interact with geometry, material condition, wear, and inspection history to determine fatigue damage and maintenance demand.

4.3. Fatigue assessment under vibration-induced loading

Fatigue assessment of railway vehicle structures usually involves load identification, stress calculation, cycle counting, damage accumulation, and life prediction. Dynamic loads can be obtained from field measurements, multibody simulations, vehicle-track coupled models or standardized load spectra. Stress responses are then calculated using finite element models, strain measurements or transfer functions. Rainflow counting and cumulative damage rules are commonly used to estimate fatigue damage under variable-amplitude loading [60].

However, traditional fatigue analysis has several limitations. The load spectra are often simplified, while actual service loads are non-stationary and route-dependent. The linear damage accumulation may not accurately represent load sequence effects, crack closure, residual stress or corrosion-fatigue interaction. The local weld geometry and manufacturing variability are difficult to capture accurately. The vibration-induced fatigue may be underestimated when high-frequency stress components are filtered out or ignored [61,62].

A more reliable approach is to combine vehicle-track dynamic simulation, finite element stress analysis, field strain measurement, and probabilistic crack-growth modeling. In this sequence, multibody and coupled dynamic models estimate service loads, finite element models convert loads into local stress histories, and monitoring data update the assumed load spectrum and damage state. Although this approach is more demanding than conventional design verification, it better represents the actual service route from excitation to stress, damage, and reliability loss.

A vehicle may experience fatigue damage even though its static strength requirements are achieved. This is particularly relevant for lightweight structures and high-speed vehicles. Local resonance in a bracket, weld, or equipment support can produce high stress amplitudes even when global vehicle vibration appears moderate. Therefore, fatigue assessment should include both global dynamic loads and local structural modal behavior. Ignoring either side can lead to unsafe life prediction or overly conservative maintenance.

4.4. Probabilistic reliability assessment methods

Because railway vehicle structures operate under uncertainty, probabilistic reliability methods are increasingly important. Material properties, weld quality, geometric tolerances, track irregularities, wheel profiles, load spectra, operating speeds, and environmental conditions all vary in practice. A deterministic fatigue life may therefore give a misleading sense of precision. Probabilistic methods provide a more realistic description by estimating failure probability, reliability index, or risk level.

First- and second-order reliability methods are useful for efficient reliability approximation. Especially when limit-state functions can be formulated clearly. Monte Carlo simulation is more general and can handle complex nonlinear problems, but it may be computationally expensive. Response surface methods, surrogate models, stochastic finite element analysis and Bayesian approaches can reduce computational burden while incorporating uncertainty. Bayesian updating is especially valuable because it allows reliability predictions to be revised when new monitoring or inspection data become available [63, 64].

However, probabilistic reliability assessment faces practical limitations. The quality of the result depends strongly on the quality of input distributions, which are often difficult to determine. Service load spectra may be incomplete, inspection data may be sparse, and failure events may be rare [65, 66]. Overly complex probabilistic models can also create a false impression of accuracy if uncertainty sources are poorly characterized. Therefore, probabilistic reliability should be combined with engineering judgment, sensitivity analysis, field data, and conservative validation. Predictive models may support defect detection and maintenance planning, but their reliability depends on data quality, transferability, interpretability and validation under real operating conditions [67–69]. Thus, uncertainty quantification should include material variability, load variability, monitoring uncertainty, model-form uncertainty, and decision uncertainty.

4.5. Vibration-based health monitoring and diagnosis

Health monitoring provides a pathway from design-stage reliability assessment to service-stage reliability management. Sensors installed on axle boxes, bogie frames, carbodies, bearings and suspension systems can collect acceleration, strain, temperature, acoustic emission and displacement data. These measurements can be used to detect wheel flats, bearing faults, suspension degradation, structural cracks, abnormal vibration, and track defects.

Vibration-based diagnosis is attractive because vibration signals contain information about both excitation sources and structural response. Axle-box acceleration can reveal wheel–rail impact and track defects, while bogie and carbody acceleration can indicate suspension or stability problems. Strain monitoring can provide direct information on fatigue-relevant stress histories. Acoustic emission may support early crack detection, although signal interpretation in noisy railway environments remains challenging.

Measurement availability should be distinguished from reliability knowledge.

Accelerometers, strain gauges, wireless sensor networks, fiber-optic sensors, distributed acoustic sensing and IoT platforms can produce large volumes of data, but data volume alone does not guarantee reliable diagnosis [17, 20]. Sensor placement, calibration drift, environmental variability, synchronization, signal noise, and data loss can all distort health indicators. In addition, similar vibration signatures may arise from different sources, such as wheel flats, track defects, suspension degradation, or structural resonance. Therefore, monitoring should be linked to physical models and maintenance records rather than used as a stand-alone black-box classifier.

Data-driven methods, such as machine learning and deep learning, have improved fault classification and anomaly detection.

However, their application must be critically evaluated. Many algorithms perform well under controlled datasets but may struggle with changing operating conditions, sensor noise, limited labeled failure data and differences among vehicle types. Purely data-driven diagnosis can also lack physical interpretability. A more robust approach is to combine physical models with monitoring data, allowing diagnosis to be guided by known vibration mechanisms and structural behavior. Explainable and physics-informed AI is particularly important in safety-critical railway applications, where maintenance actions must be justified, auditable, and robust under operating variability [22,68].

4.6. Reliability-centered maintenance and life prediction

The purpose of reliability-centered maintenance is to align inspection, repair and replacement decisions with actual risk and structural condition. Conventional scheduled maintenance is quite simple, but it may fail to detect unexpected degradation and can result in unnecessary maintenance issues. In the case of condition-based maintenance, monitoring data and inspection results to evaluate component health significantly improve efficiency. Additionally, remaining useful life prediction can further support maintenance planning by assessing the duration a component can securely operate [70, 71].

For railway vehicles, life prediction should account for cumulative fatigue damage, crack growth, operating history, load spectra, inspection reliability, and uncertainty. Transferring monitoring data into reliable damage estimates is a critical challenge. Acceleration signals alone may not directly indicate fatigue life unless they are linked to stress response or damage models. Therefore, the integration of dynamic simulation, finite element stress analysis, measured load data and probabilistic crack-growth models is essential.

Digital twin technology has potential for this integration. A reliability-oriented digital twin can combine vehicle models, sensor data, operating history, uncertainty updating, and maintenance rules to estimate current condition and future risk. However, significant hurdles remain in its realization. **Figure 2** illustrates one key limitation by distinguishing unidirectional digital representations from bidirectional digital twins that support feedback, updating, and maintenance-oriented decision-making. Therefore, a digital twin should not be presented as a solution by itself. Its effectiveness depends on model fidelity, sensor durability, data quality, interoperability, cybersecurity, computational efficiency, and validation against real service degradation.

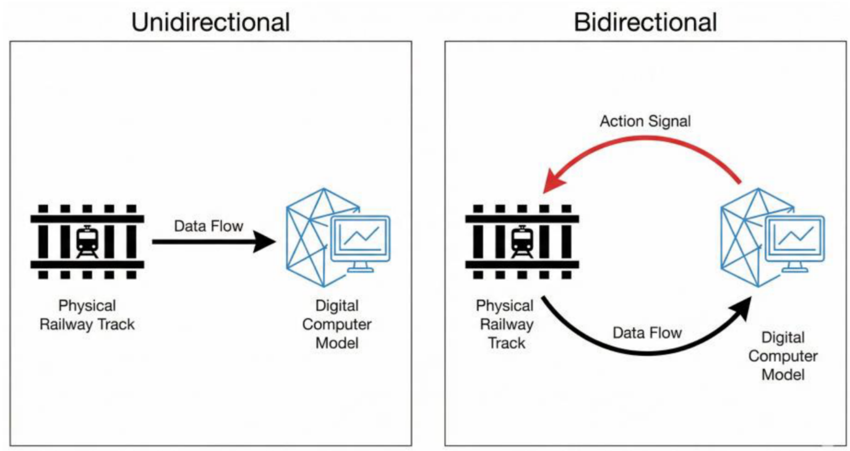

Figure 2. Difference between unidirectional digital representation and bidirectional digital twin feedback in railway predictive maintenance.
Source: Adapted from the literature [21].

The reliability-oriented fatigue assessment process, from dynamic excitation to remaining useful life prediction and maintenance decision-making, is summarized in **Figure 3**. This workflow emphasizes that fatigue reliability is not a separate topic after vibration analysis; it is the mechanism through which vibration behavior becomes service risk. Structural reliability and fatigue performance of railway vehicles are therefore inseparable from vibration behavior and dynamic performance. Dynamic excitation determines load histories, load histories determine stress cycles, and stress cycles drive fatigue damage. The main challenge is to move from static and deterministic design verification toward dynamic, probabilistic, and service-informed reliability management. More sensors, larger models, and advanced algorithms do not automatically produce better reliability decisions unless they are physically interpretable and experimentally validated.

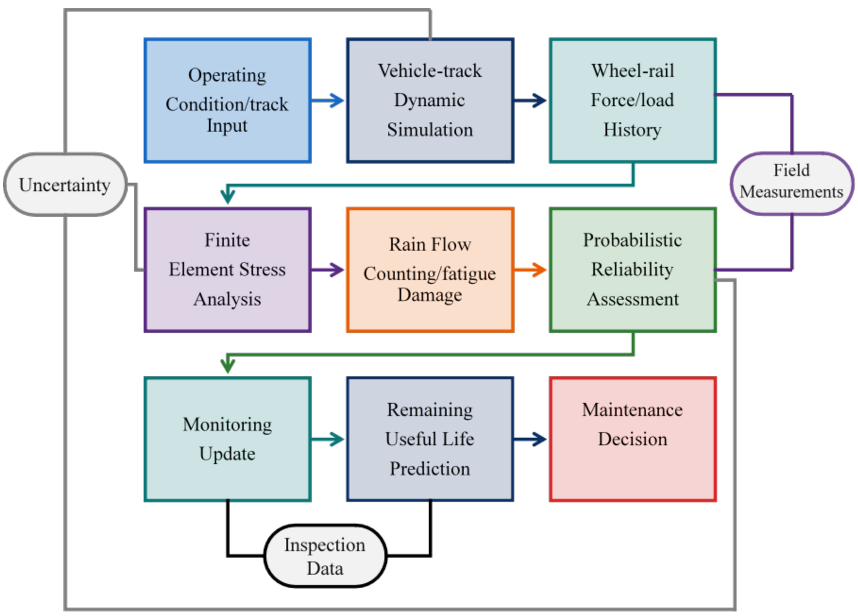

Figure 3. Reliability-oriented fatigue assessment workflow for railway vehicle components under vibration-induced dynamic loading.

5. Dynamic performance, stability, and vibration control

Dynamic performance depicts the operational outcome of railway automotive structural design and vibration behavior. It estimates if a vehicle can run comfortably, safely and reliably under various speeds, loading states, track conditions, and environmental disturbances. In contrast to isolated vibration indicators, dynamic performance is a system-level concept that involves ride comfort, safety, wheel-rail interaction, hunting stability, structural durability, and control efficacy. A rail car with low car-body vibration can still show poor wheel-rail force behavior, whereas a vehicle with high running stability may pass excessive vibration to travelers or structural parts. Hence, dynamic performance should be evaluated through multiple criteria instead of a single parameter [17].

The main problem in railway vehicle dynamic performance is the contradiction among performance objectives. A comfort ride normally requires soft suspension and effective vibration isolation, while running stability and curving performance may need enough hardness and damping. Lighter design may reduce energy utilization but it can improve cabody flexibility and vibration sensitivity. High-speed operation improves efficiency in transportation but increases the impact of track irregularities and wheel-rail contact nonlinearities. These contradictory needs make performance evaluation and optimization a multi-scale problem [72–74]. In this section, dynamic performance is regarded as the operational aspects of the vibration-reliability relationship: vehicle responses impact comfort and safety, repeated dynamic loads influence durability, and control or maintenance actions affect future system behavior.

5.1. Ride comfort evaluation

Comfort level of the ride is one of the most direct objectives of railway vehicle vibration because passengers feel vibration through car-body acceleration, interior noise, seat motion, and low-frequency back and forth movement. Vertical vibration, lateral vibration, roll motion, and car-body effects all contribute towards comfort, especially in high-speed rails and urban train systems where passenger expectations are high. Comfort level normally relies on acceleration-dependent indicators, like frequency-weighted vibration indices, and ride quality standards.

But still, the comfort of a ride cannot be determined only by acceleration magnitude. Human sensitivity changes with direction, exposure duration, vibration frequency, posture and the interaction between vibration and noise. Slow lateral vibration may cause discomfort even when acceleration levels are low to moderate, whereas high-frequency vibration can be taken more as noise and seat vibration. Carbody elastic modes may also complicate comfort feelings as different sitting positions inside the train may experience different vibration levels [75]. Hence, comfort level assessment should be based on vibration direction, frequency weighting, duration, seating conditions, structural transmission, and the combined effect of noise and vibration.

An important issue is that the evaluation of comfort level mostly focuses on the car-body response and may neglect the other causes of vibration. Decreasing car-body acceleration by changing suspension parameters may elevate comfort but enhance bogie vibration or wheel-rail force. Therefore, ride comfort should be measured along with running safety and structural reliability. A comfort-based design that transfers dynamic loads to other subsystems cannot be regarded as optimal from a life-cycle point of view. It is especially noteworthy for lighter car bodies, where flexible modes can decrease mass but may also enhance local vibration, equipment fatigue, and spatial variation of passenger comfort.

Another limitation is that comfort standards are normally tested under representative operating conditions, while real-time service comprises route-dependent irregularities, seasonal track stiffness variation, wheel wear, and variable passenger loads. Onboard vibration monitoring can increase comfort assessment by gathering route-specific acceleration data, but caution in sensor positioning, calibration drift, signal interpretation, and operational variability strongly influence the reliability of comfort-related indicators [11, 17]. Therefore, comfort should be improved not only as a compliance standard but also as a diagnostic indicator of track quality, vehicle condition, suspension degradation, and maintenance need.

5.2. Running safety evaluation

Running safety is important for the ability of the vehicle to keep a stable wheel-rail contact and avoid derailment, wheel unloading, overturning, or unsafe force levels. Common safety indicators include derailment coefficient, wheel unloading rate, horizontal wheel-rail force, and overturning-related criteria. These indicators are particularly important during curving, emergency braking, crosswind exposure, operation on degraded tracks and high-speed service.

The wheel-rail interface is central to running safety because it governs both support and guidance. Excessive lateral force can increase derailment risk, while reduced vertical wheel load can weaken wheel-rail contact and increase susceptibility to climbing or unloading. Track twist, cross-level irregularity, flange contact and suspension imbalance may intensify wheel unloading. In high-speed operation, small track defects can generate significant dynamic load amplification, making safety margins sensitive to infrastructure quality [76].

A limitation of conventional safety evaluation is that many indicators are calculated for specific operating cases and may not fully capture uncertainty. Real vehicles operate under variable track conditions, wheel wear, passenger load, suspension degradation, and environmental disturbances. A vehicle that satisfies safety criteria under nominal conditions may approach unsafe states under degraded or combined loading scenarios. Therefore, future safety evaluation should incorporate uncertainty analysis, probabilistic safety margins, and real-service monitoring data [77, 78]. Curved track, turnouts, longitudinal coupler forces, braking conditions, wheel-rail adhesion and loading state can also interact in ways that are not captured by a single nominal case [13,29].

Safety assessment should also be connected to reliability assessment. Wheel unloading, impact loads, and high lateral forces are not only immediate derailment-related indicators; they also accelerate wear, rolling contact fatigue, bogie-frame stress and suspension degradation. Therefore, an operating condition that remains below a derailment threshold may still be damaging from a life-cycle reliability perspective. Safety evaluation should therefore move from simple pass/fail assessment toward risk-informed evaluation, where degradation state, wheel-rail forces, uncertainty and maintenance history are considered together.

5.3. Running stability and hunting behavior

Running stability is one of the most important dynamic performance requirements, particularly for high-speed railway vehicles. Hunting motion is a self-excited lateral oscillation of wheel-sets, bogies or car-bodies caused by the interaction among wheel conicity, creep forces, suspension parameters and vehicle speed. When vehicle speed exceeds a critical limit, small lateral disturbances may grow into sustained or divergent oscillations, leading to poor ride comfort, increased wheel-rail forces, accelerated wear and safety concerns.

The critical hunting speed is influenced by wheel profile, equivalent conicity, primary suspension stiffness, yaw damping, wheel-rail friction, bogie design and track irregularity. Lower equivalent conicity can improve high-speed stability but may affect curving performance. Stronger yaw damping can suppress hunting but may also increase curving resistance and wheel-rail wear. These ifs and buts show that hunting control cannot be addressed by simply maximizing stiffness or damping.

Nonlinear hunting behavior deserves particular attention. Linear stability analysis is useful for identifying critical speed and parameter sensitivity but actual vehicle behavior is influenced by nonlinear creep saturation, flange contact, suspension clearance, friction and wheel-rail profile evolution. In practice, vehicles may exhibit limit-cycle oscillations rather than immediate divergence. Therefore, nonlinear time-domain simulations and field validation are necessary for realistic stability assessment [79]. Track flexibility, worn wheel profiles, curving, wagon loading state and nonlinear friction damping can further change hunting stability. In some cases, rigid-track assumptions may overestimate critical speed, meaning that simplified stability models may be non-conservative under real service conditions [13].

Hunting stability is also coupled with fatigue and maintenance. Sustained lateral oscillation increases wheel-rail force variation, promotes irregular wheel and rail wear, and may intensify bogie-frame vibration. Wear then changes equivalent conicity, feeding back into stability behavior. This explains why stability should not be evaluated only during design approval. It should also be monitored over the vehicle life cycle, especially for fleets exposed to high mileage, heavy loading, curves and turnouts. Stability indicators should therefore be connected to wheel profile management, suspension condition monitoring and maintenance planning.

5.4. Dynamic performance under special operating conditions

Railway vehicles rarely operate under ideal straight-track conditions only. Curves, turnouts, bridges, tunnels, degraded tracks, transition zones and crosswind environments impose additional dynamic challenges. Curving introduces lateral creep forces, flange contact, wheel unloading, and asymmetric suspension deformation. Tight curves in urban rail systems often intensify wheel-rail wear, squeal noise and vibration transmission. Turnouts and crossings generate discontinuities in wheel-rail contact, producing huge impact loads and transient vibration [80].

Bridge and vehicle interaction is another important issue, particularly for high-speed trains. Bridge flexibility can alter track support conditions and introduce resonance between vehicle and structure. Transition zones between embankments, bridges, tunnels and slab tracks can generate abrupt stiffness changes, leading to dynamic load amplification. Tunnels may influence aerodynamic pressure fluctuations and interior noise, but the crosswinds can increase lateral loads and overturning risk [68].

These special conditions reveal the limitation of evaluating dynamic performance under standard track irregularities alone. A vehicle optimized for straight high-speed lines may not perform well on curves or transition zones. Similarly, suspension settings suitable for comfort may be inadequate for strong crosswinds or degraded infrastructure. Therefore, dynamic performance assessment should include representative operating scenarios that reflect the complete service environment.

Special operating conditions also show why monitoring and diagnosis must distinguish between vehicle-related and infrastructure-related causes of poor performance. Similar increases in acceleration or wheel-rail force may arise from worn wheels, degraded suspension, local track settlement, turnout impact or bridge-vehicle interaction. Correct source attribution prevents inappropriate corrective actions, such as retuning suspension when the dominant problem is local track degradation [17].

5.5. Passive, semi-active, and active vibration control

Vibration control is a key strategy for improving ride comfort, running stability, and structural durability. Passive control methods, including optimized springs, dampers, air springs, anti-roll bars, yaw dampers and tuned mass dampers, are widely used because of their simplicity, reliability and low maintenance requirements. Passive systems are effective within their design range but their performance is limited by fixed parameters. A damper optimized for comfort may not be ideal for stability and a suspension tuned for high-speed operation may perform poorly under low-speed curving or degraded track conditions.

Semi-active control offers a compromise between passive reliability and active adaptability. The two types of dampers, such as magnetorheological or controllable hydraulic, can modify their damping properties depending on operational conditions and environmental factors. Semi-active systems can also improve comfort and stability without requiring large external power input. However, their effectiveness depends on control algorithms, actuator response, sensor accuracy and fail-safe design. Poorly designed (or structured) control logic may introduce time-delay effects or unintended force transmission [81].

Active suspension systems provide greater control authority by applying external forces to suppress vibration or stabilize vehicle motion. They can potentially improve carbody vibration, reduce lateral motion, and enhance running stability over a wide operating range. Nevertheless, active systems face challenges related to energy consumption, reliability, cost, robustness, safety certification, and maintenance. In railway applications, any active control failure must not compromise safety. Therefore, active vibration control should be evaluated not only by performance improvement but also by reliability, fault tolerance, and life-cycle feasibility [82].

A reliability-aware view is important because vibration control can shift rather than eliminate dynamic energy. A control system that reduces car-body acceleration may increase wheel-rail forces, actuator loads, or structural stress elsewhere. Likewise, a system that improves stability may produce higher curving forces and wear if it is not coordinated with wheel-rail contact behavior. Modern vibration-control strategies should therefore follow source-path-receiver logic. Reducing excitation at the wheel-rail interface, interrupting transmission through the suspension or structure and protecting receivers such as passengers, equipment, and fatigue-sensitive components. Conventional mitigation methods can be effective but they may be limited for narrow frequency bands, low-frequency vibration, scalability and long-term durability; metamaterial and optimized damping concepts offer promising but still developing alternatives for targeted vibration attenuation [83].

Condition-aware control is a particularly important direction. Instead of using fixed parameters, future semi-active and active systems should respond to track condition, speed, vehicle load, wheel-rail state, and component degradation. The vibration data, multi-body dynamics, finite element models and AI-assisted forecasting could support real-time or near-real-time adjustment of vehicle parameters. However, these systems must be validated under full-scale conditions and designed with fail-safe logic, because inaccurate sensor data, delayed control action, or model mismatch could reduce safety margins.

5.6. Multi-objective performance optimization

Dynamic performance optimization must address multiple and often conflicting objectives. Ride comfort, running safety, hunting stability, curving performance, vibration reduction, structural reliability, noise control, energy efficiency and maintenance cost cannot be optimized independently. For example, reducing suspension stiffness may improve comfort but increase car-body displacement and reduce stability. Increasing damping may suppress vibration but increase force transmission and fatigue loading. Lighter structural design may reduce energy use but amplify elastic vibration and local stress [84].

Multi-objective optimization provides a systematic way to balance these competing requirements. Optimization variables may include suspension stiffness and damping, wheel profile, carbody stiffness, bogie parameters, vibration absorber characteristics and control parameters. Objective functions may include comfort indices, safety factors, wheel-rail forces, fatigue damage, stability margins, and life-cycle cost. However, optimization results are only meaningful if the underlying models are validated and the constraints reflect real operating conditions.

A key weakness in many optimization studies is overdependence on idealized simulations. Parameters optimized for one track condition, speed, or loading state may not remain optimal in service. Robust optimization is therefore more appropriate than deterministic single-condition optimization. It considers uncertainty in track irregularities, wheel wear, suspension degradation, vehicle load and environmental conditions. Reliability-based optimization is also important because it connects dynamic performance with structural failure probability and maintenance planning.

Machine learning can support rapid prediction, anomaly detection and parameter tuning, but its use in optimization remains limited by training-data quality, transferability, and interpretability [85]. Reinforcement learning and digital twins may eventually support adaptive maintenance scheduling and control-policy optimization but these approaches should be treated as engineering decision tools rather than purely mathematical searches for the best parameter set. Their outputs must remain constrained by uncertainty, monitoring reliability, safety certification, maintainability, and life-cycle cost.

Dynamic performance, stability and vibration control should therefore be viewed as interconnected parts of railway vehicle system design. Ride comfort cannot be separated from wheel-rail force behavior and stability cannot be separated from suspension design, wheel–rail contact and structural flexibility. Similarly, vibration control cannot be judged solely by acceleration reduction; it must also consider safety, fatigue, robustness, energy consumption and maintenance. **Table 2** demonstrates that dynamic performance objectives are mutually dependent and cannot be optimized in isolation. The dynamic performance should be judged by life-cycle balance. A design or control strategy is effective only if it improves comfort, safety, stability, durability, maintainability, and energy efficiency together, rather than optimizing one metric at the expense of another. The scientific, technical, and system-level challenges are discussed in Section 6.

Table 2. Dynamic performance objectives, interdependencies, and control strategies for railway vehicles.

Objective	Common indicator	Interdependency	Control/Optimization strategy	Life-cycle concern
Ride comfort	Carbody acceleration, frequency-weighted comfort index, Sperling index	Softer suspension improves comfort but may reduce stability or increase displacement	Secondary suspension tuning, air springs, semi-active damping	Comfort should be balanced with wheel–rail force, fatigue, and equipment reliability
Running safety	Derailment coefficient, wheel unloading rate, lateral wheel–rail force	Higher guidance stiffness may improve safety but increase wear and curving resistance	Wheel profile optimization, suspension tuning, safety-margin control	Safety margins should account for degraded track, wear, and uncertainty
Hunting stability	Critical speed, lateral acceleration, wheelset yaw motion	Lower equivalent conicity improves high-speed stability but may worsen curving	Yaw damper optimization, wheel profile management, nonlinear stability analysis	Stability changes over time with wheel/rail wear and suspension degradation
Structural durability	Stress amplitude, fatigue damage index, reliability index	Lightweight design reduces mass but may increase flexibility and fatigue sensitivity	Reliability-based design, structural reinforcement, fatigue-aware optimization	Durability requires vibration-load histories and long-term monitoring
Vibration reduction	Acceleration RMS, transmissibility, dominant frequency amplitude	Reducing carbody vibration may increase bogie, actuator, or wheel–rail loads	Passive, semi-active, active, and hybrid vibration control	Control should be evaluated by comfort, safety, fatigue, energy use, and robustness
Noise and high-frequency vibration	Wheel–rail vibration spectrum, sound pressure level	Noise mitigation may be frequency-specific and may not reduce structural fatigue	Rail grinding, wheel/rail damping, absorbers, targeted vibration treatments	High-frequency vibration contributes to wear, fatigue, and environmental impact
Maintenance efficiency	RUL, failure probability, inspection interval, maintenance cost	Delayed maintenance improves asset use but increases risk; early maintenance wastes resources	Condition-based and reliability-centered maintenance	Maintenance decisions should integrate monitoring, reliability, cost, and service availability
Sustainability	Energy consumption, component life, replacement frequency, life-cycle cost	Lightweight and low-energy designs may increase vibration and fatigue sensitivity	Multi-objective robust optimization, sustainable material and design choices	Sustainability should include energy, durability, maintenance demand, and safety over the service life

6. Challenges and future perspectives

Despite substantial progress in railway vehicle dynamics, vibration control, fatigue assessment, and health monitoring, several scientific and engineering challenges remain unresolved. These challenges arise from the inherent complexity of railway vehicle-track interaction, the variability of real operating environments, and the increasing demand for safer, faster, lighter, and more sustainable railway systems. Future research should therefore move from isolated analysis toward validated life-cycle frameworks that connect vibration behavior, structural reliability, dynamic performance, monitoring, control, and maintenance decision-making.

The challenges and future perspectives are discussed at three connected levels. The first level concerns scientific challenges, including nonlinear vehicle-track interaction, uncertainty and validation. The second level concerns technical approaches, including intelligent monitoring, digital twins, AI-assisted diagnosis and adaptive control. The third level concerns system-level goals, including reliability-centered maintenance, sustainability and life-cycle railway vehicle design. This sequence reflects that better scientific understanding enables better technical tools, and better technical tools should ultimately support safer, more reliable, and more sustainable railway operation.

6.1. Scientific challenges: Nonlinearity, uncertainty, and validation

One of the most persistent challenges is the accurate modeling of nonlinear vehicle-track interaction. The wheel-rail contact interface is small, highly loaded, and continuously changing due to wear, profile evolution, creepage, adhesion variation and local defects. While simplified contact models are computationally efficient. They often fail to capture impact behavior, flange contact, creep force saturation, contact loss and high-frequency vibration. More detailed contact models can improve physical accuracy, but they require higher computational cost and more precise input parameters.

Track structures also introduce variable behavior, such as nonlinear and spatial behavior. Ballast settlement, rail pad aging, fastener degradation, slab track stiffness variation, bridge flexibility and transition zone discontinuities can significantly affect dynamic response. In many simulations, these factors are idealized or represented by constant parameters. This constrains the model's predictive capacity. A critical future direction is to develop adaptive vehicle-track models that update track and contact parameters based on measured service conditions. Such models would allow dynamic performance and reliability assessment to reflect the real operating state rather than idealized assumptions [86]. Efficient modeling therefore requires a balance among physical fidelity, computational cost, dynamic representation, and uncertainty treatment rather than simply increasing model complexity [22, 85].

Uncertainty cannot be avoided in railway vehicle operation. Vehicle mass changes with passenger or freight loading, wheel and rail profiles evolve with wear, suspension properties degrade over time and track irregularities vary along the route. Environmental factors such as temperature, humidity, wind, rain, and snow. Contamination also influences adhesion, material behavior, and dynamic loads. These uncertainties affect ride comfort, running safety, stability, fatigue damage, and reliability [39].

A major limitation of current assessment methods is their reliance on deterministic inputs. Many studies evaluate vehicle performance under selected speeds, track irregularity spectra or nominal suspension parameters. Although such analyses are useful for design comparison. They cannot fully describe the range of possible service responses. Future research should place greater emphasis on uncertainty quantification, probabilistic dynamic simulation, reliability-based design, and robust optimization. Instead of asking whether a vehicle performs well under one assumed condition. Future assessment should determine the probability that acceptable comfort, safety, and stability are maintained. Additionally, durability can be maintained across realistic operating conditions [87].

Probabilistic analysis is useful, but it has limitations. Reliable probability distributions for track defects, wheel wear, suspension degradation, and load spectra are often unavailable. Reliable probability distributions for track defects, wheel wear, suspension degradation, and load spectra are often unavailable. Rare failure events provide limited statistical information. The monitoring data may be incomplete or noisy. Therefore, future uncertainty analysis should combine physical modeling, field measurement, expert knowledge, and interpretation of probability and statistical inference updates. This would make reliability evaluation more adaptive and less dependent on uncertain initial assumptions. Uncertainty should be treated not only as a modeling issue, but also as a sensing, diagnosis, prediction, and maintenance-decision issue.

Another important challenge is the shortage of full-scale validation data under real operating conditions. Laboratory experiments and roller-rig tests provide controlled environments. But they cannot fully replicate the complexity of actual railway service. Field measurements capture realistic behavior, yet they are often limited in duration, route coverage, sensor quantity, and accessibility. As a result, many models are validated only against selected response quantities, such as carbody acceleration or wheel-rail force, while local stress, fatigue damage, and long-term degradation remain insufficiently verified [88].

Long-term monitoring is especially important for reliability assessment. Fatigue damage accumulates gradually and the relationship between short-term vibration response and long-term structural degradation is not always direct. It is difficult to determine how dynamic loads evolve with wheel wear, track deterioration, suspension aging and maintenance interventions without continuous or repeated monitoring. This limits the accuracy of remaining useful life prediction and condition-based maintenance.

Future studies should establish standardized field datasets containing synchronized measurements of vehicle vibration, wheel–rail forces, track geometry, wheel profiles, structural strain, operating speed, loading condition, and environmental factors. Such datasets would support model validation, algorithm benchmarking, and reliability prediction. More importantly, they would help bridge the gap between theoretical modeling and engineering application [89]. Sensor placement, calibration drift, signal ambiguity, data volume, environmental variability, interoperability, and cybersecurity remain practical barriers to reliable deployment. Therefore, validation should move beyond short-term performance checks and include long-term degradation, route diversity, sensor robustness, and maintenance feedback.

6.2. Technical approaches: Intelligent monitoring, digital twins, AI, and adaptive control

Digital twin technology offers a promising route for integrating modeling, monitoring, diagnosis and maintenance decision-making. A railway vehicle digital twin can combine physics-based dynamic models, finite element structural models, sensor data, operating history, and updating algorithms to estimate current condition and predict future performance. In principle, it can support vibration assessment, fatigue damage tracking, fault diagnosis and maintenance optimization.

However, the practical implementation of digital twins remains challenging. A digital twin should not be only a digital copy of the vehicle or a visualization platform. It must receive reliable data, update model parameters, quantify uncertainty and provide actionable predictions. If the underlying model is inaccurate or the sensor data are unreliable. The digital twin may also produce misleading conclusions. Future digital twin development should therefore focus on hybrid frameworks that combine physical interpretability with data-driven adaptability. Physics-informed machine learning, reduced-order modeling and surrogate modeling. Bayesian updating can help balance computational efficiency, real-time applicability and physical reliability. The goal is to develop digital twins that are transparent, validated, and useful for safety-critical decision-making [21, 22, 90]. Smart monitoring technologies such as wireless sensor networks, fiber-optic sensing, distributed acoustic sensing, MEMS accelerometers, IoT platforms and smart composite materials can support this transition. But only if sensor durability, calibration, data quality, communication latency, and integration with legacy systems are addressed.

Machine learning and deep learning methods can process large amounts of monitoring data and identify patterns that may be difficult to detect through traditional signal analysis. These methods are particularly attractive for detecting wheel defects, bearing faults, suspension degradation, track abnormalities and abnormal carbody vibration [91]. Nevertheless, AI-based diagnosis faces major limitations in railway applications. Many algorithms require large labeled datasets. However, real failure data are rare because safety-critical components are inspected and replaced before failure. Models trained on one vehicle type, route, or operating condition may not generalize well to another. Changes in speed, load, track condition and sensor location can also alter vibration features and reduce diagnostic accuracy. Additionally, black-box AI models might exhibit a trust deficit in critical safety-related engineering decisions.

Future AI applications should therefore emphasize explainability, transferability and physical consistency. Hybrid physics-data models are likely to be more reliable than purely data-driven approaches. For example, vehicle-track dynamic models can identify physically meaningful features, while machine learning can improve pattern recognition and prediction under uncertain conditions. AI should be used not only to classify faults but also to support causal interpretation, reliability updating and maintenance planning [92]. Future systems should move beyond isolated fault classification toward degradation forecasting, remaining useful life estimation, prescriptive intervention planning, explainable AI, federated learning and reinforcement-learning-based maintenance scheduling [68,93].

Adaptive vibration control is another important direction that cannot be ignored. Passive systems are reliable but limited. Active and semi-active systems offer adaptability but introduce challenges about the cost, reliability, power demand and safety certification. Novel control systems should be condition-aware, fault-tolerant and integrated with monitoring data. Rather than controlling vibration only after it occurs. Furthermore, future systems may predict upcoming vi and vehicle state. They can then adjust suspension or control parameters in advance. However, adaptive control should not be evaluated only through acceleration reduction. It should also consider wheel-rail forces, fatigue damage, actuator reliability, fail-safe behavior, energy consumption and certification requirements. A control system that improves comfort but increases structural fatigue or wheel-rail wear would not satisfy life-cycle performance requirements.

6.3. System-level goals: Reliability-centered maintenance, sustainability, and life-cycle integration

Sustainable maintenance will also become increasingly important. Maintenance strategies should shift from fixed schedules toward risk-based and condition-based approaches. That is not possible without accurate health indicators, reliable damage models, and practical decision rules. The ultimate goal is to reduce unnecessary maintenance, prevent unexpected failures and extend component service life. Railway maintenance is moving from corrective and preventive strategies toward predictive and prescriptive approaches. Where it can monitor data, AI, digital twins, and optimization support intervention timing and resource allocation [21,22,93]. However, the transition from prediction to prescription remains difficult due to maintenance decisions, which must balance safety risk, service availability, cost, component life, inspection uncertainty and operational constraints.

Future railway vehicle development will increasingly require the simultaneous improvement of safety, stability, comfort, durability, energy efficiency and sustainability. Lightweight design will remain important for reducing energy consumption. But it must be balanced against structural flexibility, vibration amplification, and fatigue reliability. Sustainability should therefore not be treated only as a reduction in vehicle mass or energy use. It should include service life extension, reduced unnecessary maintenance, lower material consumption, improved reliability, reduced noise and vibration exposure, and better resilience under degraded operating conditions. Because some studies claim sustainability benefits without quantifying them through explicit environmental or life-cycle indicators, new research should include measurable indicators such as energy use, carbon impact, maintenance material demand, component replacement frequency, service disruption and life-cycle cost [21].

The future of railway vehicle research lies in integration. But this integration must be practical rather than merely theoretical. Nonlinear dynamics, structural reliability, vibration control, monitoring, AI and maintenance should not be treated as different disciplines. Dynamic behavior determines structural loads, structural degradation changes dynamic behavior, monitoring data reveal both and maintenance decisions influence future reliability [94]. Therefore, future research should not merely add more models, sensors or algorithms. It should connect them through a coherent life-cycle decision framework.

The most important challenge is not simply the development of more complex models or more advanced algorithms. Rather, it is the creation of reliable, validated and interpretable frameworks that can support real engineering decisions. Future investigation should prioritize physical insight, uncertainty awareness, full-scale validation, and life-cycle thinking. By doing so, railway vehicle engineering can progress from reactive vibration mitigation and scheduled maintenance toward predictive adaptive, and reliability-centered operation. This transition will be essential for next-generation railway vehicles that are safer, more stable, more comfortable and more sustainable [95]. The major research directions emerging from the challenges discussed in this section are illustrated in **Figure 4**, highlighting the transition toward an intelligent, adaptive and reliability-centered railway vehicle system.

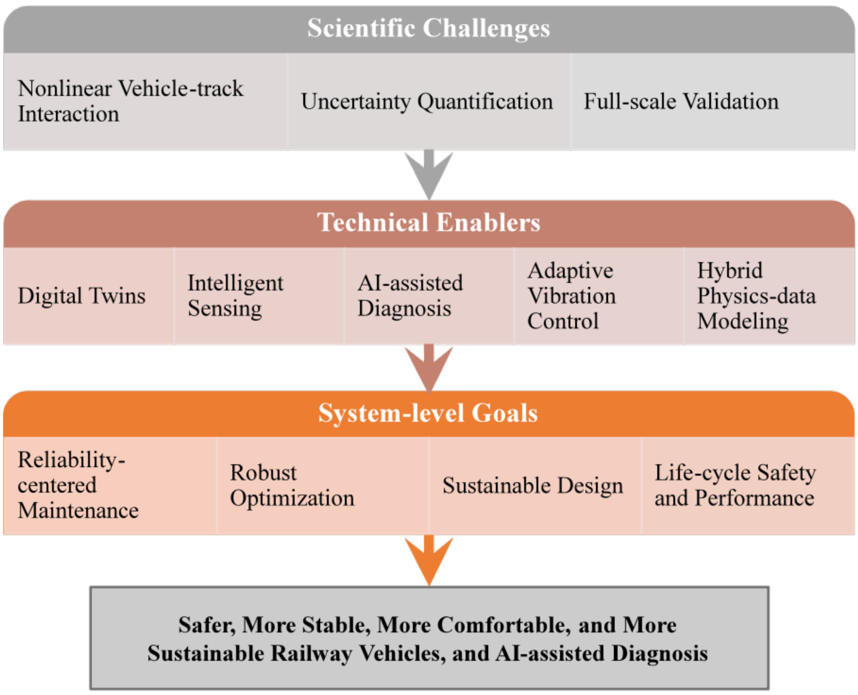

Figure 4. Future research roadmap for intelligent, adaptive, and reliability-centered railway vehicle systems.

7. Conclusion

This review examined railway vehicle vibration behavior, structural reliability and dynamic performance as interconnected parts of a coupled vehicle-track system. The synthesis shows that vibration in railway vehicles is not only a comfort-related response. It is a mechanism through which track irregularities, wheel-rail defects, braking forces and aerodynamic loads are transformed into structural stress, performance degradation, and maintenance demand.

A central finding is that vibration assessment must be linked with structural reliability. Dynamic loads generated at the wheel-rail interface are transmitted through wheelsets, bogies, suspension systems, car bodies, and local structural details. These factors may produce variable-amplitude stress histories and fatigue-critical responses. Therefore, deterministic strength checks or isolated vibration indices are insufficient for evaluating long-term service performance. A more reliable assessment requires validated multi-body dynamics, finite element analysis, vehicle-track coupled modeling, field measurement, probabilistic reliability analysis and uncertainty-aware updating.

The review also highlights that employing a single indicator to enhance dynamic performance has certain limitations. Ride comfort, running safety, hunting stability, wheel-rail force, vibration control, structural durability, energy efficiency, and maintenance cost are mutually dependent and may involve conflicting requirements. Future research should therefore focus on validated and interpretable integration rather than simply adding more complex models, sensors, or algorithms. Physics-informed modeling, and reliability-centered maintenance should be connected within decision-oriented frameworks. Such integration can support railway vehicles that remain safe, stable, comfortable, durable and sustainable under realistic operating uncertainty.

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