Theory and practice for assessing structural integrity and dynamical integrity of high-speed trains

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Abstract

Purpose – The safety and reliability of high-speed trains rely on the structural integrity of their components and the dynamic performance of the entire vehicle system. This paper aims to define and substantiate the assessment of the structural integrity and dynamical integrity of high-speed trains in both theory and practice. The key principles and approaches will be proposed, and their applications to high-speed trains in China will be presented.
Design/methodology/approach – First, the structural integrity and dynamical integrity of high-speed trains are defined, and their relationship is introduced. Then, the principles for assessing the structural integrity of structural and dynamical components are presented and practical examples of gearboxes and dampers are provided. Finally, the principles and approaches for assessing the dynamical integrity of high-speed trains are presented and a novel operational assessment method is further presented.
Findings – Vehicle system dynamics is the core of the proposed framework that provides the loads and vibrations on train components and the dynamic performance of the entire vehicle system. For assessing the structural integrity of structural components, an open-loop analysis considering both normal and abnormal vehicle conditions is needed. For assessing the structural integrity of dynamical components, a closed-loop analysis involving the influence of wear and degradation on vehicle system dynamics is needed. The analysis of vehicle system dynamics should follow the principles of complete objects, conditions and indices. Numerical, experimental and operational approaches should be combined to achieve effective assessments.
Originality/value – The practical applications demonstrate that assessing the structural integrity and dynamical integrity of high-speed trains can support better control of critical defects, better lifespan management of train components and better maintenance decision-making for high-speed trains.

Keywords Structural integrity, Dynamical integrity, Vehicle system dynamics, High-speed trains, Bogie, Integrity assessment, Fatigue

Paper type Conceptual paper

1. Introduction

By 2023, China has a vast high-speed (HS) rail network spanning over 45,000 km, with more than 4,200 HS trainsets operating at a maximum speed of 350 km/h. The safety and reliability of these HS trains are essential for such extensive operations (Zhang, Wu, Wu, & Zeng, 2006).

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Structural integrity is usually defined as a structure's ability to safely withstand operational loads and reliably fulfill intended functions throughout its expected service life (Sedmak, Radaković, Milović, & Svetel, 2012). It involves the analysis of various failure modes, such as crack, fracture, fatigue, creep, corrosion and lamination. Structural integrity assessment approaches have been studied in various fields for decades (Sedmak *et al.*, 2012), and several general procedures have been developed (Ajay Shah, 2014; Gutiérrez-Solana & Cicero, 2009; Webster & Bannister, 2000). The European structural integrity assessment procedure (SINTAP) unifies the fracture assessment criteria and offers methods of varying complexity for different data quality and user knowledge (SINTAP, 1999). In 2006, SINTAP was further integrated into the European fitness-for-service network, which formulated a unified European procedure covering the analysis of fracture, fatigue, creep and corrosion (Koçak, Webster, Janosch, Ainsworth, & Kores, 2006). Subsequently, British Standard 7910 was updated in 2019, encompassing fracture, fatigue, creep and corrosion assessment throughout the design, fabrication and operation phases of metallic structures (British Standard BS 7910, 2019). In recent years, probabilistic methods for structural integrity assessment considering uncertainties have received increasing attention (Chavoshi, Booker, Bradford, & Martin, 2021).

When applying the above general procedures to a structure, various inputs are typically required, including structural design, material properties, loading conditions, boundary conditions and environmental conditions. In the case of HS trains, these inputs vary significantly over time and space during thousands of kilometers of daily operation and decades of service. Variations also occur among different train components due to the dynamic effects of wheel–rail contact and suspensions. Moreover, operational conditions and maintenance activities also affect the degradation and failure of HS train components. Consequently, the combined effects of these factors induce significant complexities and challenges in assessing the structural integrity of HS trains.

Static strength and fatigue strength are two major concerns in assessing the structural integrity of train components. The structural integrity of a car body under static loads is assessed considering the effects of environmental conditions (Shin & Hahn, 2005). The stress distribution in a bogie frame is assessed, where rigid multibody simulations produce load cases for calculating the stress distribution in finite element analysis (Hwa Park, Po Kim, Seok Kim, & Yong Lee, 2006). The dynamic stress of a pantograph is assessed considering the interaction between the vehicle and the catenary (Zhang, Liu, & Mei, 2006; Song, Zhang, He, Jiang, & Zhou, 2013). In recent years, rigid-flexible coupled or flexible multibody simulations have been more often used in fatigue assessments of car bodies (Miao, Zhang, Zhang, & Jin, 2009; Miao, Luo, Peng, Qiu, Chen, & Yang, 2020; Sun, Gao, Wang, Xu, & Lin, 2021), bogie frames (Xiu, Spiryagin, Wu, Yang, & Liu, 2020) and axles (Guo, Li, & Liu, 2022). Meanwhile, laboratory fatigue tests are widely applied to assessing the structural integrity of bogie frames (Lu, Zheng, Zeng, Chen, & Wu, 2019; Xiu *et al.*, 2020), where the load cases are usually defined according to standard spectra or multibody simulations.

In the above research, the dynamics of a vehicle system provide operational loads and vibrations of vehicle components under nominal conditions. In reality, abnormal vehicle dynamics are common due to the wear and degradation of various vehicle components (Miao, Zhang, Wang, Yuan, Li, & Chen, 2023). It has been found that hunting motions (self-excited oscillation due to instability) significantly affect the vibration and stress of car bodies (Li, Wu, Liu, Wu, & Zeng, 2022) and bogie frames (Qu, Wang, Zhang, Li, & Wei, 2021) and further reduce their fatigue life. Meanwhile, wheel polygonization (periodic out-of-roundness) has been found to affect the vibration and stress of bogie frames (Sun, Wei, Liu, Dai, Qu, & Zhao, 2022), wheel axles (Zhang, Wang, Zhang, Zhu, & Yang, 2021) and bearings (Wang, Allen, Mei, Wang, Yin, & Zhang, 2019; Hou *et al.*, 2023) and further reduce their fatigue life.

The degradation of many train components not only depends on but also affects the dynamics of the vehicle system. For example, wheel–rail contact causes wear and polygonization and worn profiles further affect the wheel–rail contact, which in turn affects future wear and polygonization (Bevan, Molyneux-Berry, Eickhoff, & Burstow, 2013; Butini *et al.*, 2019; Peng, Iwnicki, Shackleton, & Song, 2021). Furthermore, the degradation processes of different components and failure modes can affect each other, such as the influence of wheel wear and polygonization on rolling contact fatigue (Bevan *et al.*, 2013; Butini *et al.*, 2019).

Existing research and practice have underlined the importance of vehicle system dynamics in assessing the structural integrity of train components. Additionally, the dynamics of HS trains affect not only the degradation and failure of train components but also the dynamic performance of the entire HS train (Iwnicki, 2006). For example, inadequate stability or curving performance of a HS train can increase the risk of train derailment, leading to sudden failure of the HS train and even the HS railway system. Therefore, a general framework for defining and assessing the structural integrity and dynamical integrity of HS trains is proposed, in which vehicle system dynamics play a central role (Zhang, Zeng, Song, & Wang, 2024). Within this framework, the safety and reliability of a HS train rely on both the structural integrity of its components and the dynamic performance of the entire vehicle system. As an extension of this framework, this paper aims to substantiate the assessment of the structural integrity and dynamical integrity of HS trains in both theory and practice. The key principles and approaches will be proposed, and their applications to HS trains in China will be presented. The novelty and contribution of our work are summarized as follows:

(1) This paper establishes a holistic framework that integrates the structural integrity analysis of train components and the dynamical assessment of entire vehicle systems.

(2) This paper presents the theory and practical applications for assessing the structural integrity of structural components and dynamical components of HS trains.

(3) This paper presents the theory and practical applications for assessing the dynamical integrity of HS trains, especially in the long-term operation stage.

The remainder of this paper is organized as follows: Section 2 will briefly introduce the definition and relationship between the structural integrity and dynamical integrity of HS trains. Section 3 will focus on the assessment of the structural integrity of HS train components, with gearboxes and dampers as examples to demonstrate the practical applications. Section 4 will focus on the dynamical integrity of the entire vehicle system and an operational assessment example is provided to showcase the applications. Finally, conclusions will be presented in Section 5.

2. Structural integrity and dynamical integrity of HS trains

A HS train is a sophisticated mechanical and electrical system. Bogies, also known as running gears, play a crucial role in the dynamics of a HS train. They are responsible for transmitting the train load to the track, steering the train along the track and reducing the vibration transmission from the wheels to the car body. A typical HS train bogie comprises numerous structural components for load bearing or transmission, such as the bogie frame, axle and axle box. Meanwhile, a HS train bogie also consists of many dynamical components that determine the dynamics of the vehicle system, such as wheels and suspensions (springs and dampers). The degradation of these dynamical components, such as wheel wear and reductions in stiffness or damping, can affect the loads and vibrations on other train components and also deteriorate the dynamic performance of the entire HS train.

The conventional definition of *structural integrity* is applicable to HS train components (both structural components and dynamical components) to describe their capability to withstand operational loads and fulfill their intended lifespan. By extending this concept to a holistic system of vehicle dynamics, the *dynamical integrity* of a HS train is defined to describe its capability to maintain acceptable dynamic characteristics and performance throughout its lifespan (Zhang *et al.*, 2024). The safety and reliability of a HS train rely on both its structural integrity and its dynamical integrity.

Figure 1 further illustrates the relationship between the structural integrity and dynamical integrity of a HS train. Assessing the structural integrity of a HS train includes the analysis of fatigue and failure of various structural components and the analysis of wear, degradation and failure of various dynamical components. Assessing the dynamical integrity of a HS train includes the analysis of loads and vibrations on various components as well as the dynamic performance of the entire vehicle system. Vehicle system dynamics play an important role in this process, which is performed based on structural parameters (masses, moments of inertia and dimensions), suspension parameters (stiffness of springs and damping of dampers) and geometric parameters (wheel profile and out-of-roundness). Certain track, operational and environmental conditions are also needed for the analysis of vehicle system dynamics. It is noteworthy that the wear, degradation and failure of dynamical components can in turn affect the suspension and geometric parameters, thus affecting the vehicle system dynamics.

Safety, stability and ride quality are the major merits of vehicle dynamic performance. Figure 2 presents how poor dynamic performance affects the load and furthers the structural integrity of a HS train. The rest of this paper will present the theory and practice of how to assess the structural integrity and dynamical integrity of HS trains.

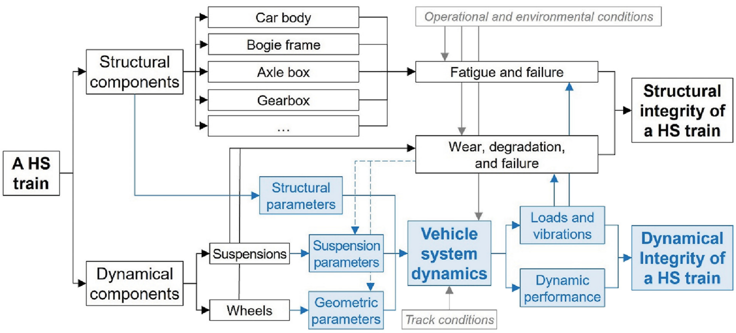

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Figure 1.
Structural integrity and dynamical integrity of a HS train

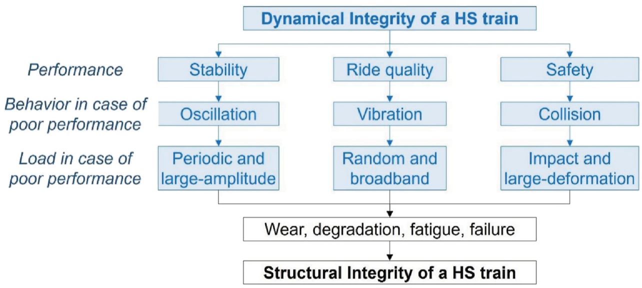

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Figure 2.
Influence of dynamical integrity on structural integrity of a HS train

3. Assessing the structural integrity of HS trains

3.1 Principles for assessing the structural integrity of HS trains

As introduced in Section 1, several general procedures are available and applicable for assessing the structural integrity of train components, and substantial research has been conducted on practical applications. In these procedures, the loads and vibrations on train components are crucial for assessing their structural integrity. For different train components, different principles should be applied to determine the loads and vibrations on them from the analysis of vehicle system dynamics.

For structural components, an open-loop analysis can be employed, as shown in Figure 3(a). The loads and vibrations can be obtained from the vehicle system dynamics and then applied to fatigue and failure analysis. Both normal and abnormal vehicle conditions should be considered in the analysis of vehicle system dynamics. Normal conditions represent nominal or well-maintained vehicle conditions, while abnormal conditions consider the influence of wear, degradation and failure of dynamical components, such as hunting and deteriorated wheel–rail contact, which can significantly increase the loads and vibrations on structural components.

For dynamical components, their wear, degradation and failure not only depend on but also affect the vehicle system dynamics. Therefore, assessing their structural integrity usually requires a closed-loop analysis, as shown in Figure 3(b). Such analysis is especially necessary for characterizing wheel wear and defects, including tread wear, flange wear and polygonization, since worn profile and out-of-roundness can have significant effects on the wheel–rail contact and further on future wear and polygonization.

When the wear, degradation and failure of multiple train components or multiple failure modes are highly correlated, they should be considered simultaneously. For example, wheel wear and rolling contact fatigue are usually analyzed together since wear can affect wheel–rail contact and also remove fatigue cracks. The increased complexity of such interactive relationships highlights the importance of considering a comprehensive system of vehicle dynamics for assessing the structural integrity of train components. More discussion will be given in Section 4.

To showcase how the above theory can be adapted and applied in practice, we will then present two examples that assess the structural integrity of a structural component (gearboxes) and a dynamical component (hydraulic dampers) in China's HS trains.

3.2 Example: Assessing the structural integrity of gearboxes

Gearboxes are key structural components in motor vehicle bogies that house gears transmitting traction torque from motors to wheelsets. In a gearbox, the gear wheel is connected to the wheelset and the pinion is connected to the motor. As a result, gearboxes are subject to intensive loads and vibrations from both the wheel–rail interface and motors. Wheel and rail irregularities and defects can induce severe impacts on wheel–rail contact, especially at high running speeds, which can accelerate the fatigue of gearboxes. This can lead to a lifespan shorter than the design and cause cracks, leakage, and even breakage before

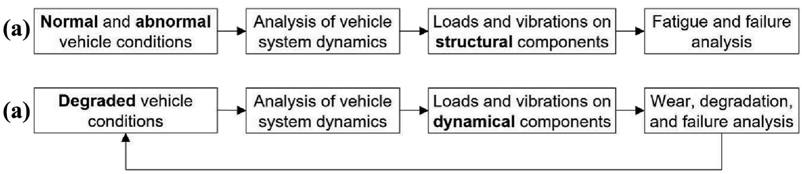

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Figure 3. Assessing structural integrity of HS train components

scheduled maintenance or renewal, thus being risky to the safe operation of HS trains. Such a risk becomes more pronounced as high-order wheel polygonization becomes a serious problem in China's HS trains. Therefore, it is important to assess the structural integrity of gearboxes, considering the dynamic loads and vibrations induced by polygonal wheels.

The dynamic response of a gearbox is significantly influenced by the coupled dynamics between the vehicle, the gearbox and the track. To assess the structural integrity of gearboxes, the methodology in Figure 4 is developed, which combines numerical simulations, laboratory tests and field tests. Wheel defects from real-field geometry measurements, specifically high-order wheel polygonization, are used as the source of excitations for the numerical simulations and laboratory tests.

A three-dimensional vehicle-transmission-track coupled model is developed. This model encompasses vehicle dynamics, gearbox mounting to wheelsets (through bearings) and bogies (through suspensions), gear meshing (with time-varying meshing stiffness and transmission errors), traction torque from motors, wheel–rail contact and slab track dynamics. More details of the model can be found in Wang, Allen, Mei, Yin, Cheng, and Zhang (2020). Polygonal wheels are considered in this model with periodic irregularities in the wheel radius. The dynamic behavior of the gearboxes can be simulated by solving the model numerically.

This simulation model is validated by comparing the simulated vibrations with those measured in laboratory and field tests. The laboratory tests are conducted on a full-scale roller rig for a single wheelset of a bogie (Wang *et al.*, 2018). The roller is manufactured with periodic out-of-roundness to resemble excitations due to wheel polygonization. During the tests, the bogie is loaded through the bolster and the wheelset is driven by the roller rotating at high speeds through wheel–roller contact. This allows the bogie to be tested with high-frequency excitations at the wheel–rail interface. Field tests are conducted by instrumenting a gearbox with accelerometers at different positions to measure the vibrations during train operations. It is noteworthy that the same type of HS train and gearbox is studied in the numerical simulations, laboratory tests and field tests.

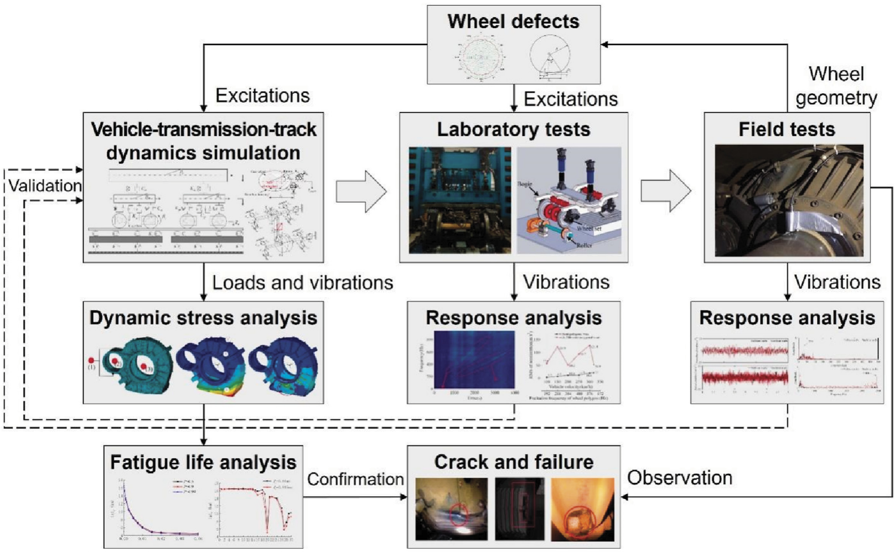

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Figure 4.
Methodology for assessing the structural integrity of gearboxes

The dynamic behavior of a gearbox is simulated with polygonal wheels of different orders and amplitudes. The result shows that polygonal wheels significantly increase the vibration of the pinion and the dynamic force on the gearbox from the pinion (Wang *et al.*, 2020). The simulated loads and vibrations on the gearbox are then applied to a detailed finite element model of the gearbox, and the dynamic stress of the gearbox is obtained. It is observed that the dynamic stress of the gearbox increases significantly when the excitation frequency of the polygonal wheel is close to the natural frequency of the gearbox. Meanwhile, the dynamic stress increases with the increase in the polygonization amplitude.

In the case study, 20th-order polygonal wheels generate excitations at around 580 Hz when running at 300 km/h, which is close to the natural frequency of the gearbox (Wang *et al.*, 2018, 2020). This leads to high dynamic stress in the gearbox, especially near the oil level window. Such resonance responses can also be observed in both the laboratory and field tests. In the laboratory tests, a 13th-order polygonal roller is used, which is equivalent to the 20th-order wheel polygonization considering the radius ratio between the roller and the wheel. As the roller speed increases, the resonance of the gearbox can be observed at around 300 km/h (Wang *et al.*, 2018). Similarly, in the field tests, when one of the wheels exhibits 20th-order polygonization (with an amplitude of 0.05 mm), the amplitude of the measured gearbox vibration can exceed 200 g due to the resonance (Wang *et al.*, 2018).

Furthermore, fatigue analysis is performed by converting the simulated stress histories into a load spectrum and calculating the fatigue life using the cumulative damage theory. The result indicates a significant reduction in the gearbox lifespan when subjected to resonance due to the 20th-order wheel polygonization. This finding is verified by the fact that several gearboxes are cracked during train operations, which suggests the necessity of controlling the order and amplitude of wheel polygonization for HS trains. The effectiveness of the whole methodology demonstrates the importance of considering abnormal vehicle conditions for assessing the structural integrity of HS train components.

3.3 Example: Assessing the structural integrity of dampers

Hydraulic dampers are widely used in the primary and secondary suspensions of HS trains to reduce and absorb vibrations. They are typical dynamical components, as their damping characteristics influence the dynamic behavior and performance of HS trains. Due to dynamic loads and thermal effects, dampers degrade in long-term use and need to be renewed on a regular basis, usually every several overhaul cycles. In practice, their damping characteristics are measured only during overhauls, leaving the degradation of damping characteristics between overhauls and the remaining useful life after renewal unknown. Assessing the structural integrity of dampers is important for optimizing damper maintenance and renewal strategies to make better utilize of their lifespans.

Since damper degradation and vehicle system dynamics are coupled, the methodology in Figure 5 is developed to assess the structural integrity of dampers. Considering the

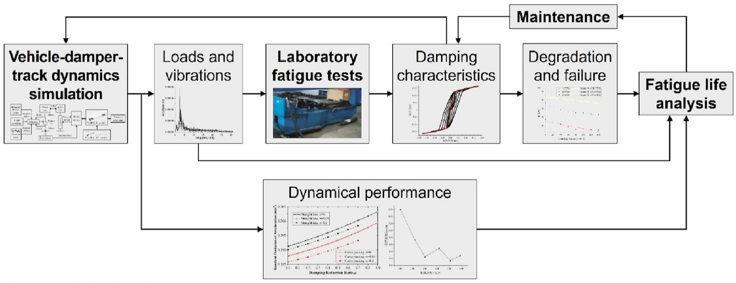

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Figure 5. Methodology for assessing the structural integrity of dampers

insufficient damping measurements, laboratory fatigue tests are conducted on a damper test bench with the damping characteristics measured regularly. The loads in such tests are obtained from vehicle dynamics simulations using measured damping characteristics. The degradation and failure of dampers can then be characterized by combining the damping characteristics measured during overhauls and the laboratory measurements. Subsequently, the remaining useful life of the tested dampers under equivalent operational conditions can be obtained. Some key methods are briefly outlined below, while more details can be found in Zeng, Song, Zhang, Hu, and Chang (2021) and Hu, Song, Zeng, and Zhang (2021).

(1) Nonlinear damping model in vehicle dynamics simulations: Dampers, especially yaw dampers, can exhibit significantly nonlinear damping characteristics. It is important to include such nonlinearity in the vehicle dynamics model, such as using piecewise linear damping (Zeng, Song, Zhang, Hu *et al.*, 2021; Zeng, Song, Zhang, Zhou, Xie, & Qi, 2021; Zeng, Song, Zhang, Zhou, Xie, & Tang, 2021). Typical operational conditions should be considered, such as running on straight and curved tracks with worn wheels (increased wheel conicity).

(2) Degradation model of damping characteristics: Modeling the degradation of damping characteristics requires the extraction of sensitive features. Such features can be nonparametric, such as directly from damping characteristics measurements (Hu *et al.*, 2021), parametric, such as from a damping model or probabilistic, such as from statistics (Zeng, Song, Zhang, Hu *et al.*, 2021; Zeng, Song, Zhang, Zhou, Xie, & Qi, 2021; Zeng, Song, Zhang, Zhou, Xie, & Tang, 2021).

(3) Equivalence between experimental loads and operational loads: Vehicle dynamics simulation is used for not only determining the loading conditions for the laboratory tests but also estimating the equivalent remaining useful life from the experimental loads. A novel method is proposed to build up such equivalence that takes into account both the dynamic loads in terms of total energy and the temperature effect in terms of a scaling coefficient (Hu *et al.*, 2021).

The above analysis provides insights into the degradation and failure of dampers between overhauls and after renewal. In the case study, the tested yaw dampers exhibit degraded but still permissible damping characteristics upon replacement (according to the maintenance regulation). The result shows that the replaced dampers still have a remaining useful life of more than one overhaul cycle, indicating the possibility of prolonging their use and the potential savings in maintenance costs.

The above two examples showcase how the structural integrity of structural components and dynamical components can be assessed and demonstrate its value for the safety of train operation and the optimization of train maintenance. It is noteworthy that the specific methodology may vary significantly for different components and failure modes. In other applications, the assessment procedures should be adapted for different purposes and conditions.

4. Assessing the dynamical integrity of HS trains

4.1 Principles for assessing the dynamical integrity of HS trains

According to Section 2, the analysis of vehicle system dynamics is the core of assessing the structural integrity and the dynamical integrity of a HS train. When assessing the dynamical integrity, more attention should be paid to the global behavior and performance of the vehicle system rather than individual components. The fundamental principles of such analysis are recommended as follows (Zhang *et al.*, 2024).

Complete objects: All dynamical components (e.g. wheels and suspensions), major structural components (with large inertia or flexibility) and critical interfaces (e.g. wheel–rail contact) should be incorporated into the analysis. It is essential to consider their characteristics and parameters as accurately as possible.

Complete conditions: Various conditions related to the vehicle (e.g. normal or defective), track (e.g. curve, rail profile and irregularities), operation (e.g. load, speed, and traction or braking torque) and environment (e.g. friction coefficient) need to be considered with reference to real-field scenarios.

Complete indices: A comprehensive set of indices needs to be considered in the assessment. On the one hand, the distribution, transmission, emission and amplification of loads and vibrations on and between different train components should be included. On the other hand, the dynamic performance of the entire vehicle system should also be included, such as safety, stability and ride quality. Specifically, to ensure sufficient dynamical integrity of a HS train, these indices are expected to meet the following requirements over the lifespan (Zhang *et al.*, 2024).

(1) *Within tolerance*: These indices should stay within permissible limits. For example, the maximum wheel–rail forces should be lower than certain limits and the critical speed should be sufficiently higher than the maximum operating speed.

(2) *Balanced*: Various indices should be balanced, especially when they conflict with each other. For example, the loads and vibrations through multiple suspension components should be well distributed, and the stability on straight tracks should be compromised to the dynamic performance on curved tracks.

(3) *Robust*: These indices should be robust to the variation of vehicle, track, operational and environmental conditions. For example, a vehicle should remain stable (without hunting) as the wheels wear and the suspensions degrade within permissible ranges.

4.2 Approaches for assessing the dynamical integrity of HS trains

Assessing the dynamical integrity of a HS train requires the accurate determination of loads and vibrations on various vehicle components and the effective analysis of the dynamic performance of the entire vehicle system. This section aims to present such approaches based on the work over the past decades. Figure 6 illustrates the NEO framework for assessing the dynamical integrity of HS trains, which exhibits the close collaboration between numerical, experimental and operational assessment approaches.

Numerical assessment refers to computer-based modeling and simulations of vehicle system dynamics, which are cost-effective in providing a wealth of information that is difficult or expensive to acquire in real-world fields. To simulate the dynamics of a HS train more accurately, the coupled dynamics theory is developed, which accounts for coupling relationships such as vehicle-track, pantograph-catenary and vehicle-vehicle interactions (Zhang, Shen, & Zeng, 2013; Zhang, 2019). The general idea is to first model key components using multibody dynamics or beam theory and then, model coupling interfaces using appropriate methods such as rolling or sliding contact. Several numerical methods have been developed to solve such a huge coupled model efficiently. For example, a cyclic variable method is proposed to solve a HS trainset vehicle by vehicle sequentially while propagating the coupling forces (Zhang *et al.*, 2013; Zhang, 2019). An adaptive sliding window method is proposed for simulating train-track-embankment-bridge coupling, which applies sliding windows of different sizes to different structures and components (Song, Zhang, Han, & Zou, 2018). The couple dynamics theory and the associated numerical methods enable more accurate and efficient assessments of the dynamical integrity of HS trains.

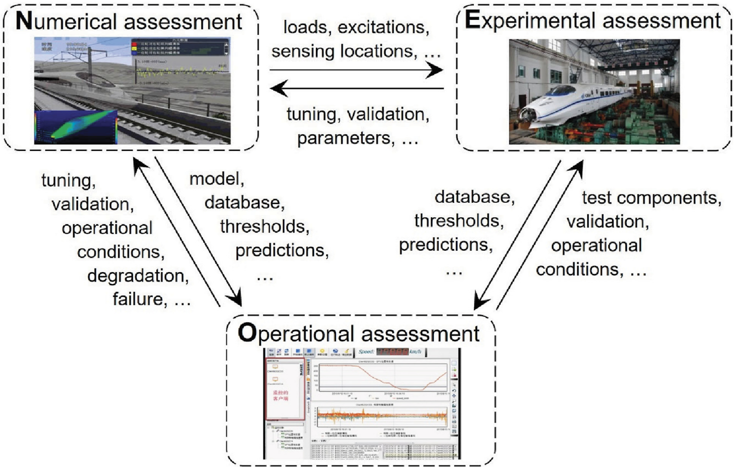

Figure 6.
NEO framework for assessing dynamical integrity of HS trains

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Experimental assessment refers to down-scale or full-scale testing of an entire bogie or vehicle on test benches or test railway lines. It enables dynamic characteristics to be tested under well-controlled loads and excitations as well as well-observed conditions. In such tests, sufficient speeds and different operational conditions should be tested. A typical example is the roller rig introduced in Iwnicki (2006), Ma, Zhang, Chen, and Zeng (1994), Zhang, Chen, Wu, and Jin (2002), as shown in Figure 6. Six pairs of rollers are used to drive the wheelsets of a full-scale vehicle to rotate, with a maximum equivalent speed of 700 km/h. Each roller can be controlled to move independently in vertical and lateral directions, resembling track irregularities. The two rollers in a pair can be controlled to rotate at different speeds, which resemble not only straight tracks but also curved tracks. Various tests can be performed, such as stability, curving and ride comfort. The roller rig has been used to test all major types of HS trains in China.

Operational assessment relies on onboard monitoring, trackside measurements and in-depot inspections. Such real-field operation and maintenance data are valuable since they cannot be fully replicated through simulations and experiments. Onboard and trackside technologies are usually used to monitor key components, such as wheels (Qi *et al.*, 2019) and key dynamic performance, such as hunting and stability (Zeng, Zhang, & Song, 2020). Regular in-depot inspections and measurements are performed to acquire more detailed and accurate information on vehicle conditions, such as wheel profile and out-of-roundness measurements. Additionally, planned or temporary maintenance, such as wheel reprofiling (Zeng, Song, Zhang, Zhou, Xie, & Tang, 2021), is conducted to keep the vehicle dynamics in good condition.

These three categories of approaches are inextricably linked, as shown in Figure 6 and they should support each other throughout the life cycle of HS trains as follows:

(1) Numerical assessment can provide simulated loads and excitations for experiments and suggest where measurements or attention are needed during experiments. Measurements in experimental assessment can be used to tune and validate numerical models and provide measured characteristics or parameters for use in simulations.

(2) Numerical assessment can provide physical models and large volumes of simulation data under various conditions for operational assessment. It can also recommend thresholds and predict future performance for operational assessment. Measurements or observations in operational assessment can be used to tune and validate numerical models and provide operational conditions for use in simulations.

(3) Experimental assessment can provide test data, recommend thresholds and predict future performance for operational assessment. Operational assessment can provide worn, degraded and defective components disassembled from trains and operational loads and conditions for experimental assessment.

In general, numerical and experimental assessment approaches have been widely applied for decades, whereas operational assessment approaches are still emerging. Advances in condition monitoring and machine learning provide more effective resources and tools for developing operational assessment approaches with high applicability. A novel operational assessment approach developed for China's HS trains will be presented below as an example.

4.3 Example: Operational assessment of the dynamical integrity of a HS train

Onboard monitoring techniques enable the dynamic response of HS trains to be monitored and their dynamic performance to be assessed in real time. However, this requires the installation of many sensors at different positions of each vehicle, such as the car body (for assessing ride quality), bogie frame (for assessing stability) and axle box (for assessing wheel–rail interaction). Most HS trains in China are not instrumented with sufficient sensors to allow such a comprehensive real-time assessment. Therefore, the assessment methodology in Figure 7 is developed for predicting the dynamic response and performance of HS trains using vehicle condition data available in daily operation and maintenance.

The major sources of data are trackside and in-depot measurements applied to dynamical components, especially train wheels. Parameters such as wheel diameter, flange thickness, conicity, polygonization order and amplitude have been regularly measured for years, allowing their degradation to be characterized based on historical data. The models of wheel wear and polygonization are developed, considering the effect of wheel position, wheel size and season (Zeng, Song, Zhang, Hu *et al.*, 2021; Zeng, Song, Zhang, Zhou, Xie, & Qi, 2021; Zeng, Song, Zhang, Zhou, Xie, & Tang, 2021; Zeng *et al.*, 2020). These models not only characterize the influence of various operational factors on wheel wear and degradation but also enable the prediction of the future condition of each individual wheel based on its latest condition.

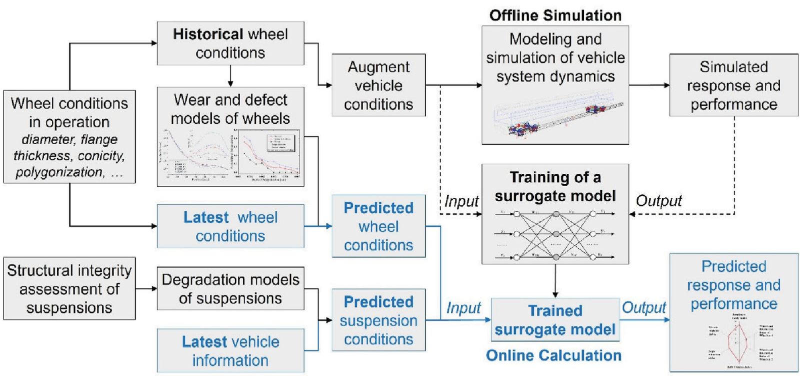

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Figure 7. Methodology for operational assessment of dynamical integrity

For dynamical components that are not yet monitored in practice, such as suspension components, it is difficult to obtain and update the conditions of each individual component. Alternatively, their long-term degradation is characterized using data from maintenance and laboratory tests, such as the damping degradation in Section 3.3. Such analysis describes statistically the degradation of suspension components with respect to running mileage, which can be used to predict their future conditions at an average level.

Information from condition monitoring and degradation analysis can be combined to assess the dynamical integrity of HS trains, as shown in Figure 7. First, based on the vehicle conditions from nominal and historical data, large-scale simulations can be performed to calculate the dynamic response and performance under different vehicle conditions. If the amount of vehicle condition data is insufficient, synthetic data can be generated to augment the dataset. Since these simulations are time-consuming, they are conducted offline, and the simulation results are stored. Meanwhile, historical records of dynamic response and performance can be included to further supplement the dataset. Then, a surrogate model is built and trained using the vehicle conditions as inputs and the corresponding dynamic response and performance as outputs. By utilizing the mapping capability and fast computation speed of a surrogate model, the dynamic response and performance of HS trains can be calculated online. The combination of simulated and historical data for training enables the surrogate model to learn from physical models and historical records.

Further, by feeding predicted vehicle conditions based on condition monitoring and degradation analysis into the trained surrogate model, the dynamic response and performance of in-service HS trains can be predicted online. In the case study (Zeng, Zhang, Song, Chang, & Zhang, 2019), a neural network is used as a surrogate model that produces a derailment safety index, a stability index, a ride quality index, a wheel–rail interaction index and a vibration intensity index for each bogie being assessed. These health indices predict, from different perspectives, the dynamic behavior and performance of a vehicle system in the near future. In contrast to traditional thresholds applicable to each individual parameter (e.g. permissible conicity or polygonization amplitude), the proposed framework focuses on the dynamics of a vehicle system under the coupled effects of various parameters from wheels at different positions. Such a multidimensional and coupled assessment of dynamical integrity can further support the predictive maintenance of HS trains. For example, HS trains with low health indices can be prioritized for maintenance, thereby reducing the risk of abnormal dynamic behavior during operations.

It is noteworthy that the specific methodology may vary significantly for different train types, data availability and operation and maintenance strategies. In other applications, the assessment methodology should be adapted accordingly.

5. Conclusions

This paper presents the theory and methodologies for assessing the structural integrity and dynamical integrity of HS trains and showcases their applications to HS trains in China. The conclusions are summarized below:

(1) Vehicle system dynamics is the core of the proposed framework, which provides the loads and vibrations on train components and the dynamic performance of the entire vehicle system.

(2) For assessing the structural integrity of structural components, an open-loop analysis considering both normal and abnormal vehicle conditions is needed. For assessing the structural integrity of dynamical components, a closed-loop analysis involving the influence of wear and degradation on vehicle system dynamics is needed.

(3) The analysis of vehicle system dynamics should follow the principles of complete objects, conditions and indices. Numerical, experimental and operational approaches should be combined to achieve effective assessments throughout the life cycle of HS trains.

(4) Assessing the structural integrity and dynamical integrity of HS trains can support better control of critical defects, better lifespan management of train components and better maintenance decision-making of HS trains.

We will endeavor to further increase the readiness, usability and practicality of the theory for broader applications. On the theoretical side, we will further substantiate the assessment theory of structural integrity and dynamical integrity by integrating standard procedures and relevant methods in more detail. On the practical side, we will apply the theory and methodology to many other train types and train components and we will develop software for train manufacturers and operators to implement such assessments for HS trains under design, verification, operation and maintenance.

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