A Review of Research on Design Theory and Engineering Practice of High-speed Railway Turnout

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Abstract

This paper systematically reviews the research progress, problems, specific countermeasures and development trends of the dynamic design theory as applied to high-speed railway turnouts. This includes wheel-rail contact solving, high-speed vehicle -turnout dynamic interaction simulation, analysis of long-term turnout performance deterioration, safety assessment of train passing through the turnout, and the maintenance and management of turnout serviceability. High-speed turnouts still face severe technical challenges with regard to their acclimation to the future development of rail transit technology. Some of these challenges include the suitability of next-generation higher-speed turnouts to a complex environment, life-cycle design, optimization of wheel-rail matching and vehicle-turnout dynamic performance, real-time status capture and performance assessment, health management and damage prediction. It is now necessary to deepen the basic theoretical study of high-speed railway turnouts, and integrate cutting-edge techniques, such as advanced materials and manufacturing, intelligence and automation, big data and cloud computing, in an effort to enhance China’s capabilities for original innovation in high-speed railway turnout technology. By analysing the present situation in a problem-orientated manner, this paper aims to provide a new perspective, as well as some basic data for academic research into technological innovations for railway engineering.

Keywords: High-speed railway turnout, vehicle-turnout dynamic, real-time status capture, performance assessment, health management, damage prediction
1. Introduction

The turnout lies at the intersection of railway lines, and is a piece of rail equipment essential for shunting a high-speed train. Because of its complex structure, changeable condition, and various potential defects, the turnout is a vulnerable spot in high-speed railway lines and also a key but difficult point of maintenance. It is also a piece of critical infrastructure that affects both running stability and overall safety. In order to ensure the safety and long-term serviceability of a high-speed railway system, high-speed railway turnouts should always be kept stationary, stable and reliable, so that trains can run safely, steadily and without interruption under the combined action of multiple factors such as trainload, temperature variation, foundation deformation and the local environment [1]. However, there is also a wheel load transition zone and single-wheel/multi-rail contact behaviour in the turnout area. A significant change in contact parameters takes place during the rolling contact between wheels and turnout rails [2]. This is a type of distinct transient rolling contact, directly affecting the wheel-rail contact and its damage, and results in a much more complex and changeable wheel-rail relationship in the turnout area than in railway lines [3]. Moreover, it is more susceptible to changes in structural operating modes and the external load environment. With improper design or maintenance, the train-turnout dynamic interaction will inevitably be aggravated. That is the root cause for the shortened service life of turnouts and the reduced running quality of trains [4]. It is therefore particularly urgent to improve and develop a dynamic theory and corresponding method for simulating the serviceability of high-speed railway turnouts, and to conduct an in-depth study on the evolution of wheel-rail contact in the turnout area. In this way, it will be possible to reveal the interaction mechanism between wheel-rail contact behaviour evolution and serviceability evolution in the turnout zone, and discover the damage mechanism of turnout parts to resolve the conflict between service behaviour and service life of turnouts. Only in this way can integrated control be assured over the long-term serviceability of high-speed railway turnouts. To achieve this, however, certain challenges must be overcome.

Under the long-term combined action of multiple factors, the wheel-rail relationship in a high-speed railway turnout area becomes extremely complex. Since it is used to shunt trains, the high-speed railway turnout involves a complicated arrangement of rail lines. A switch-and-lock mechanism can be used to draw the turnout rails closer to each other, forming a combined profile so that the wheels can roll from one rail to another. However, the combined profile of high-speed railway turnout rails is characterized by a dynamic spatial-temporal evolution. Owing to the different supporting stiffnesses and constraint modes between the switch rail and the stock rail (or between the point rail and the wing rail), as well as their dynamic interaction, a change takes place in the geometric shape of the combined profile during dynamic wheel-rail interaction. Furthermore, in the long-term service of turnouts, the two rails in the combined profile inevitably suffer varying degrees of wear, damage and cumulative deformation, which are in turn accompanied by deterioration of the turnout structure. As a result, the combined profile of the turnout rails evolves dynamically over time. The dynamic evolution of the combined profile will cause the wheel-rail contact and its corresponding relationship to seriously deviate from the original design goal, reducing the running stability and comfort of high-speed trains in the turnout area. Meanwhile, the vulnerable parts, including the switch rail and point rail, will bear greater force and suffer even more severe damage. In addition, the wheel-rail contact status also changes as wheels suffering from varying degrees of wear pass through the turnout area. All this requires the establishment of a wheel-rail contact model and a numerical method that considers the basic characteristics of the high-speed railway turnout structure and the actual serviceability of the trains. In this way, a more advanced simulation theory can be developed, along with techniques for studying the wheel-rail rolling contact behavior in the high-speed railway turnout area.

With continuously increasing train speeds, an increasing number of high-frequency vibrating components appear in various structures along the high-speed railway, exerting a more significant impact on dynamic behaviour and serviceability. However, it is now an international scientific problem on how to
accurately grasp the characteristics and evolution behaviour of the wheel-rail system under high-frequency loads. At present, domestic and foreign research into rail vehicle systems and basic structural dynamics is limited to low-frequency excitation. There is, however, an interaction between material degradation/component damage and high-speed wheel-rail high-frequency vibrations that should also be taken into account. The evolution mechanism is complex, too. Traditional multi-rigid-body wheel-rail system dynamics cannot accurately simulate the high-frequency vibration of a wheel-rail system, so it is necessary to develop rigid-flexible coupling dynamics that consider the high-frequency flexible deformation of the wheel-rail structure, or even multi-flexible or multi-elastic system dynamics. In a high-speed running environment, the vehicle and track structure suffer from flexible high-frequency deformation. On the one hand, the force-displacement relationship derived from the half-space hypothesis is no longer applicable, while on the other, the deformation of the wheel-rail structure has a great influence on the relative motion or sliding of the wheel-rail contact surface, directly affecting the stick-slip distribution of contact patches and the calculation results of wheel-rail creepage/force. Therefore, vehicle-turnout system dynamics should also be developed gradually, in order to include wheel-rail system dynamics for multi-rigid bodies and rigid-flexible coupling, multi-flexible bodies and multi-elastic body system dynamics.

Starting from the challenges confronting high-speed railway turnouts, this paper first introduces the dynamic design theory of such turnouts, including wheel-rail rolling contact algorithms and vehicle-turnout coupling dynamic analysis models. Then, the practical application of the dynamic design theory is discussed, which includes a study on the mechanism of turnout performance deterioration under long-term service conditions and an assessment of the safety of trains passing through turnouts. Further to this, the importance of health management and condition monitoring is explained with regards to the safe operation of high-speed railway turnouts. Finally, the future direction of high-speed turnout research is discussed, aiming to provide researchers and engineers with a theoretical basis and ideas for further study.

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Fig. 1 Technology roadmap

2. Dynamic design theory and evaluation method of a turnout

In the early days of high-speed railway construction, China either focused on independently developing, or on importing, digesting, absorbing and re-innovating various key techniques for CRH trains and high-speed railway turnouts. However, at the design stage, no consideration was given to the actual wheel-rail dynamic action generated when trains passed through turnouts. Neither were assessment of the safety, stability and comfort of trains passing through turnout. The wheel-rail dynamic interaction in the turnout area is the root cause of the shortened service life of turnouts and the reduced quality of train operation. Under the coupled action of inevitable structure irregularity and external excitation in the turnout area, medium and high-frequency large-amplitude wheel-rail vibrations may be caused, thus aggravating...
the damage to turnout parts, significantly affecting the performance of vehicles passing through turnouts, and shortening the maintenance cycle of wheels. Therefore, it is of great importance to study the dynamic design theory and evaluation method of high-speed railway turnouts.

2.1. Wheel-rail rolling contact theory of high-speed turnouts

In a railway system, wheel-rail rolling contact serves to support and shunt trains. Train traction and braking are achieved through the rolling friction force on the wheel-rail contact interface. Therefore, the wheel-rail relationship has always been one of the core issues of railway research. This is because it concerns the safety and quality of train operation, the generation of wheel-rail frictional noise, and the evolution of damage on the wheel-rail contact interface. The relationship between the wheel and turnout is more complex than that between the wheel and plain line. The wheel-rail contact model is the link that couples the vehicle system and the switch system. Researchers have carried out wheel-turnout studies based on wheel-rail interaction in the section line, combing the characteristics of turnout structures. Researches have undergone the following stages: analysis of wheel-rail contact geometry, 3D asymmetric wheel-rail rolling contact calculations, establishment of fast algorithms for rolling contact in the turnout area to satisfy vehicle/turnout dynamics simulation, and solution of complex rolling contact problems based on the finite element (FE) method.

Contact mechanics originated from Hertzian theory [5] in 1882 to solve the normal contact problem, and it, broke through the limitation of elastic support method proposed by Winkler, which could only obtain an approximate solution. The most widely accepted theory is the Kalker’s three-dimensional non-Hertzian rolling contact theory in 1979, also known as the exact theory, or Kalker’s variational approach [6]. Besides, Kalker proposed simplified theory FASTSIM [7] in 1973~1982 to deal with the tangential contact problem, which is still the most commonly used rolling contact model for vehicle-track dynamics analysis. Shen–Hedrick–Elkins model was established in 1983 which is also widely applied for vehicle-track dynamics to calculated creep forces [8]. In addition, a creepages/force table using CONTACT is also a highly efficient method [9]. All the above-mentioned creep models used in vehicle-track dynamics are based on Hertzian contact patches. In order to analyze wheel-rail damage more accurately, a non-Hertzian contact model that is more advanced than ones based on Hertzian contact theory has since been introduced into simulation analysis. At present, virtual penetration methods are widely used to rapidly solve non-Hertzian wheel-rail rolling contact problems. There are currently three most typically models, including Kik-Piotrowski model [10-11], Linder model [12-13] and Ayasse-Chollet model [14]. FASTSIM is used to solve tangential contact problems in all the above three non-Hertzian contact algorithms based on virtual penetration. Nonetheless, Sichani found that the calculation accuracy of FASTSIM failed to meet the requirements under certain non-Hertzian contact conditions. To solve this problem, the FaStrip algorithm was developed by Sichani [15].

When the vehicle passes through a small-radius curve or turnout, the wheel flange may come into contact with the gauge corner or switch rail. The contact surface is curved, forming “conformal” contact. Kalker’s 3D non-Hertzian rolling contact theory applies only to planar contact patches. When the wheel flange touches a rail corner, this theory can therefore only help to obtain an approximate solution. The authors created CURVE for surface contact using Kalker’s variational approach, expanding the application of CONTACT [16-17]. At the same time, owing to influencing factors such as the sideslip and yawing of wheelset, and asymmetric track arrangement in the turnout area, there is a very complex contact relationship between the wheels and the stock and switch rails (or wing and point rails), and two-point or even multi-point contact occurs in many cases. The Hertzian rolling contact theory based on many assumptions, cannot accurately reflect the complex wheel-rail contact relationship. Furthermore, the damage prediction of the wheel and rail, such as wear and rolling contact fatigue, needs accurate determination of the wheel-rail contact patch and calculation of normal and tangential stress distribution.
Therefore, it is necessary to adopt a non-Hertzian rolling contact method with higher calculation accuracy and efficiency. A rolling contact model based on the relevant influencing factors, as well as its algorithm (INFCON) are proposed by authors, with both calculational accuracy and efficiency taken into consideration [18].

![Comparison of stick-slip distribution](image1)

**Fig. 2** Comparison of stick-slip distribution

![Contact patch and pressure distribution calculated by INFCON](image2)

**Fig. 3** Contact patch and pressure distribution calculated by INFCON

2.2 Theoretical models for vehicle-turnout dynamic interaction

2.2.1 Dynamic model of wheel-rail transient rolling contact in a high-speed railway turnout area

Classical contact mechanics theory has great difficulty meeting the needs of high-speed railway development, mainly because it cannot be used to solve certain specific problems arising from the wheel-rail rolling contact process. This includes such issues as two-point contact, conformal contact and elastic-plastic contact, residual deformation accumulation, contact surface fatigue, rail corrugation, polygonal wheel wear, scratching, weld irregularity, excessive wheel load in the turnout area, and impact from a "third medium" or inertial force. As a result, the FE method has become the main approach for solving this type of complex wheel-rail relationship problems. Such problems usually appear as rolling contact behaviour in vibrating conditions, i.e., transient rolling contact, which is a focus of concern in contact dynamics and beyond the scope of application of Kalker’s steady-state rolling contact theories.
With on-going improvements in computer performance and the development of finite element algorithms in recent years, the FE method is now increasingly used to solve complex wheel-rail rolling contact problems. For the introduction of rolling behaviour into the FE model, there are currently two ways being adopted by researchers: ALE (Lagrangian Eulerian) modelling and transient modelling. This works under the idea that wheel rolling is divided into rigid body motion and deformation, which can be described using Eulerian and Lagrangian methods, respectively, meaning that rolling and sliding problems can be considered, but it remains suitable only for solving steady-state rolling behaviour.

At present, for transient rolling contact problems, the most common solution is to make use of the central difference method to explicitly solve the FE model described by the Lagrangian method. For the 3D wheel-rail transient rolling contact model built using the FE method, it can deal with the strain rate-related constitutive relationship of materials, as well as with the complex variable friction model and geometric irregularities in any status of 3D contact. The real geometric structural deformation of wheels and rails can be considered in a solid model. After interfacial rolling contact is coupled with structural vibrations, high-speed wheel-rail transient rolling contact behaviour can also be reconstructed numerically. In 2005, Zefeng Wen and Xuesong Jin took the lead in building a dynamic impact model for the insulated joint between rail and wheelset using ANSYS/LS-DYNA. They then used the implicit-explicit sequential method to reveal the effects of axle load and rolling velocity on the wheel-rail impact force and the dynamic stress on the rail [19]. After that, researchers all over the world developed a variety of transient rolling contact models, using them to solve different transient rolling contact problems [20-22]. The most famous one is a transient model built in ANSYS/LS-DYNA by Zili Li’s team at the Delft University of Technology. This model is similar to Wen’s, but considers the wheel-rail rolling contact status under traction conditions by applying torque. The research team then continued to explore ways of verifying the effectiveness of the model and extending it to engineering applications [23].

On the one hand, the movable rail component in the turnout area needs to be pulled so that trains can be shunted, ensuring that the switch rail and the stock rail (or the point rail and the wing rail), are kept close to each other in a certain range. Therefore, the high-speed turnout rail component with variable cross-section is very long, and the switch rail is not bound by the fastener within this range. The switch-and-lock mechanism has a weak restraining action at the traction point only. The switch rail is freely placed on the surface of the sliding bed platen, maintaining rigid contact, while the outer and inner flanges of the stock rail are buckled with an elastic bar and a resilient clip, respectively, coming into elastic contact with the sliding bed platen through the sub-rail rubber mats of the fastener system. As a result, there are different constraints and support conditions for the stock rail and the switch rail. What is more, owing to wheelset sideslip and yawing caused by structural irregularities, as well as the complicated rail line arrangement, there is an extremely complex relationship between the wheels, the switch rail and the stock rail in the turnout area. Significant dynamic displacement is thus generated, leading to dynamic reconstruction of the combined profile. The spatial location of the wheel-rail contact point changes abruptly in the wheel load transition zone within the turnout area, causing two-point or multi-point contact. Steady state hypothesis cannot accurately reflect the wheel-rail contact behaviour in a turnout switch, meaning an explicit FE method is required that considers both macro-dynamics and the coupling characteristics of wheel-rail mesoscopic contact behaviour. As a result of this, a wheel-rail elastoplastic transient contact dynamics model considering real geometrical and rolling-sliding characteristics was built, in order to make up for the deficiency of the traditional models, which fail to consider the effects of material and geometric nonlinearities [24-25]. This model therefore enables wheel-rail transient rolling contact behaviour in the turnout area to be more accurately described.
2.2.2 Rigid-flexible coupling dynamics model of a high-speed turnout

Wheel-rail system dynamics focus on issues of complex wheel-rail contact mechanics arising from train operation. From the perspective of system engineering, in order to solve specific problems, the wheel-rail system dynamics model and efficient numerical analysis methods were applied to simulate the vibration of the wheel-rail system under various excitation conditions. In this way, the various dynamic responses of the train system, track system, bridge and tunnel infrastructure in both the time and frequency domains can be revealed. Based on this, and according to relevant evaluation criteria and standards, the safety, stability and comfort of train operation can then be assessed, along with the bearing capacity, deformation characteristics and load transfer characteristics of the track structure, as well as the fatigue characteristics and reliability of all wheel-rail system components. This can be used to guide and optimize the structural design, material selection and parameter configuration with regard to the wheel-rail system, with an aim to devising optimal wheel-rail contact matching and controlling the wheel-rail excitation source. The ultimate goal is to provide theoretical support to ensure the safe, stable and uninterrupted operation of trains at specified speeds.

The main task of wheel-rail system dynamics is to study the derailment safety, capsizing stability, straight-route running stability, riding comfort and curve passage capacity of the train, along with the fatigue characteristics of wheel-rail components following excitation due to track irregularities. When the train runs at low speeds, the excitation wavelength of track irregularities is long, while the vehicle and track system vibrate within the medium and low-frequency range. The vibration frequency of the wheelset, bogie frame, car body and track system is generally less than 50Hz, 5Hz, 2Hz and 500Hz, respectively. Therefore,
the wheelset, bogie frame and car body can be regarded as rigid bodies, while components can be connected together through elastic and damping elements. The wheel and rail can be coupled together by means of the steady-state rolling contact theory. Therefore, the research of traditional wheel-rail system dynamics is primarily carried out on the basis of multi-rigid-body system dynamics, and so far, satisfactory research results have been achieved [26-27].

According to reference [28], a vibration frequency below 20Hz is enough to consider the curve passage capacity, riding comfort and running stability of the vehicle alone. Thus, the track model can be simplified. For higher vibration frequencies, the mass inertia of track components is very important. Below 250Hz, the vibration of ballast and subgrade is quite significant, while the rubber mat is of great importance for vibrations at frequencies of less than 700Hz; at frequencies above 700Hz, it is the rail itself that is most important. Schmid et al. built a bogie-turnout coupling dynamics model, and studied the wheel-rail dynamic interaction when the bogie passed through the switch panel of the turnout [29]. Kaiser et al. analysed the effects of rigid wheelsets and elastic wheelsets with different order modes on the bogie transfer function, and pointed out that in a medium-frequency band (50-500Hz), the fourth-order vertical bending mode would meet the accuracy requirements; for the vibration response at a higher frequency band (>500Hz), it would be necessary to select more vertical bending modes for the wheelsets [30]. Kassa and Nielsen established an FE model for a standard turnout, which could be used to study the dynamic vehicle-turnout interaction in a higher frequency domain. The effective calculated frequency can reach up to 300Hz when the first 500-order eigenmodes of the turnout are included in the model [31]. Alfi et al. built a mathematical model and studied the vibration characteristics of the vehicle-turnout system at low and medium frequencies [32]. This model, which fully considers the simultaneous contact between a single wheel and multiple rails, can accurately predict the dynamic performance when the wheel load transition occurs in the switch and crossing panels. Reference [33] provides a vertical model considering the torsional vibration of the rail section. In this model, the Timoshenko beam is used in place of the railhead, rail web and rail flange, while elastic elements are used to connect the middle. Not only can the model represent the flapping motion of the rail flange, but it can also consider vibrations up to 6, 500Hz.

A traditional multi-rigid-body vehicle system dynamics model is usually used to study dynamics problems in the low frequency domain. The increased train speed and the existence of wheel-rail wear intensify the wheel-rail interaction in the medium and high frequency domains. The inherent medium and high-frequency vibration characteristics of the vehicle-track system are also very likely to be excited, thus endangering the safety of vehicle operation, accelerating the development of wheel-rail wear and causing wheel-rail noise. In order to solve the above problems, a rigid-flexible coupling dynamic model of the vehicle-turnout system that considers the rotation effect of wheelsets was built by the authors [34-35]. It was then used to accurately simulate the dynamic characteristics and rolling contact behaviour of flexible wheelsets in the high-speed turnout area, revealing the effects of wheel-rail evolution in the turnout area on riding quality and dynamic damage of turnouts, providing technical support for the wheel-rail design of high-speed turnouts.
3. Applications of vehicle-turnout dynamic design theory

This section discusses the practical applications of the vehicle-turnout dynamic design theory, including turnout rail damage analysis and dynamic behaviour evolution in long-term service conditions, as well as an assessment of turnout-crossing safety.

3.1 Analysis of long-term dynamic behaviour of high-speed railway turnouts

Like the rails in railway lines, turnout rails are susceptible to cumulative plastic deformation such as wear, conquassation and plastic flow, as well as RCF such as shelling, spalling and head check. Depending on the service status of high-speed turnouts, certain types of rail damage can be clearly seen on the turnout rails due to the particularity of the turnout structure – these include side wear of curved switches, horizontal cracks on the non-working edge of straight switches, and head check on rails. Since it was opened to traffic, the Chinese high-speed railway system has been beset with emerging problems of how to understand the occurrence and development of special damage in turnout rails, its influencing factors and its impact on the safety of CRH trains passing through turnout and stability of CRH trains. This has led to the need for
finding suitable methods to improving the materials used and optimizing the profile, as well as scientifically devising criteria for maintenance and replacement of turnout rail components. At the early stages, focus has primarily been put on the short-term dynamic behaviour of high-speed turnouts in the process of high-speed railway turnout design and assessment. As for its long-term dynamic behaviour, such as profile evolution and behaviour deterioration, an in-depth study needs to be carried out referencing the theories of wheel-rail material wear and fracture mechanics.

A wheel-rail wear model, which is the most straightforward tool for the simulation of turnout rail wear, determines the distribution range of rail profile wear. Usually, the amount of wear is calculated according to the dynamic response of the wheel-rail system in a wheel-rail wear model. There are two types of wheel-rail wear models: the friction work model, or wear index model, which is based on wheel-rail frictional energy dissipation, and the wear model, which is based on sliding friction and wear. The above-mentioned wear models are derived on the basis of experimental studies in combination with theoretical research, and there are applicable conditions for each model. Typical wear models include Archard’s sliding friction and wear model, the wear work model and the wear index model [36-38]. With the development of vehicle-turnout system dynamics and wheel-rail rolling contact theory, it has become increasingly possible to simulate turnout rail wear. Because of the mutual restrictions between rail wear and the dynamic performance of the vehicle-turnout system, it is necessary to constantly update the rail profile in the simulation process to obtain the real-time dynamic response of the vehicle-turnout system as the input data for subsequent calculations.

Chudzikiewicz and Myslinski studied the thermo-mechanical coupling problems arising from wheel-rail contact, of which friction heat, thermal flow and material wear were all considered to be quasi-static problems [39]. T. Jendel developed a prediction model for wheel profile changes. This model consisted of a vehicle dynamics model, dynamic calculation time (by simulating actual operating conditions), a discrete line model (by simulating curve distribution), track irregularity and a wheel-rail friction coefficient. The dynamic calculation results, such as contact force and location, were imported into the wear model to reveal the distribution and amount of wear. Then, data smoothing and profile updating were performed for subsequent calculations. These steps were repeated in this way until the wheel reached its maximum allowable mileage [40-41]. A. Orvans performed a simulation in GENSYS and used Archard’s wear model to predict the wear of Stockholm’s light rails. A relatively rational wear profile was obtained by simulation, but there were differences observed between the simulation results and the test results [42]. I.Y. Shevtsov and V.L. Markine considered the effects of RCF and wheel-rail wear during wheel profile design, and determined the optimal equivalent conicity to ensure the running stability of wheelsets and reduce wear and contact stress [43]. B. Dirks et al. proposed a model for predicting both wheel-rail contact fatigue and wear. They expanded two contact fatigue prediction models, and analysed the effects of curve radius, wheel-rail profile, wheel-rail friction coefficient and track irregularity on wheel-rail service life [44]. B. A. Balsin and J.C.O. Nielsen used wear work to characterize the severity of damage to turnout rails, and studied the effects of wheel profile and wheel-rail friction coefficient on the damage of turnout rails [45]. E. Doulgerakis considered the effects of dynamic wheel-turnout response on wheel wear, and built a wheel wear prediction model to predict the uneven wear behaviour of wheels [46]. A simulation model was built in this paper for high-speed turnout rail wear, revealing the distribution of rail wear caused in the turnout area. This model was also used to predict the evolution law of a turnout rail profile under long-term service conditions and study the effects of rail wear on the dynamic wheel-rail performance in the turnout area. In addition, a simulation method was built to analyse high-speed turnout rail RCF, and the penalty function method was used to characterize the coupling competition relationship between rail wear and RCF, ascertaining the development law of turnout rail RCF under long-term service conditions [47-48]. A method was proposed to optimize the switch rail profile to reduce the dynamic wheel-rail interaction and
control rail damage, so as to offer guidance on the maintenance of high-speed turnouts currently in service [49].

![Fig. 10 Longitudinal distribution of switch rail wear in the turnout area](image1)

![Fig. 11 Wear distribution on typical cross section and worn rail profile](image2)

(a) Standard profile  
(b) Measured profile

Fig. 12 Distribution of rolling contact fatigue damage on turnout rail

3.2 Research on the derailment mechanism and criteria in the turnout area

Because of the open constraints between the train and the track, vehicle derailment may occur objectively, and this is one of the main factors affecting the safety of train operation. Vehicle derailment can be divided into five types: climbing on rail, sliding from rail, jumping onto rail, dropping off rail, and derailing due to overturning. Upon the construction of the first railway, academic researchers all over the world began to study vehicle derailment. Their research focused mainly on three aspects: derailment evaluation indexes, derailment tests and derailment simulations. The derailment coefficient and wheel load reduction rate based on the Nadal criteria, two key safety indexes, are most widely used, and have always been important parameters for vehicle and track structure design. Along with the development of heavy-duty, high-speed railways and urban rail transit in China, the track structure and train operating performance have been continuously strengthened, while train control and transportation organization are constantly being optimized. This has led to an on-going decrease in the number of derailment accidents. However, such accidents do still occur from time to time in the turnout area, especially in No. 6 symmetrical turnouts in the marshalling yard and in small-sized common turnouts made of common steel on tram rails, accounting for a high proportion of vehicle derailments. This shows that the mechanism of derailment caused by the complex wheel-rail relationship in the turnout area has yet to be fully understood, and that derailment criteria based on interzonal rail lines are not necessarily applicable to the turnout area. Severe consequences will arise when a high-speed train derails in the turnout area, making it of critical importance to study the mechanism of such derailment by means of the wheel-rail rolling contact theory and dynamic simulation. In this way, it will be possible to put forward proper derailment criteria and corresponding measures for optimizing the wheel-rail relationship.
Research on derailment dates back to the late 19th century. In 1896, French scientists figured out the critical derailment condition based on the principle of static equilibrium, taking it as a criterion for a single wheel derailment. This became the famous Nadal formula [50]. Considering the complexity of derailment problems, and the difficulty of carrying out the required research, the problem has never been successfully solved, in spite of related studies being conducted without pause over the past more than 100 years. What is worse, there are many problems with the derailment criteria themselves. There is no unified, common criterion in the world for accurate judgment of derailment, let alone a derailment criterion suitable for turnout rails with a variable cross-section rail and a combined dynamic profile. Despite the wide application of the Nadal derailment coefficient, it has been found to be conservative in long-term operation and testing. Yokose argued that the limit of the Nadal derailment coefficient was related to the duration of lateral force [51]. By taking both steady-state derailment and derailment due to jumping into consideration, Japan Railway established derailment coefficient evaluation indexes based on the duration of lateral force. In the 1960s, to make the Nadal derailment theory less conservative in dealing with small and negative angles of attack, Yokose extended the Nadal derailment theory to 3D space in accordance with the nonlinear creep theory and the 3D force condition for equilibrium, conducting experimental research on 1:5 and 1:10 single wheelset models [52]. TTCI carried out extensive research into steady-state derailment by testing and simulation using NUCARS, the multi-body dynamics simulation software, and a track-loading vehicle. Elkins and Shust argued that wheels climbing on to a rail depend on the vehicle running distance related to the derailment coefficient, rather than on the duration [53]. Barbosa simulated the derailing process of a wheelset under lateral load using a 6-DoF single wheelset derailment model [54]. Jeong Seo Koo et al. built a single wheelset derailment simulation model considering wheel-rail collision according to the collision theory. It was found during the simulation process that different types of derailment, including derailment due to sliding, derailment due to climbing, derailment due to jumping, and derailment due to overturning, were closely related to the external load acting on the wheelset [55-56]. O’Shea et al. put forward a three-point wheel-rail contact method in place of the traditional two-point wheel-rail contact method based on multi-body dynamics theory to simulate wheelset derailment, achieving accurate simulation results [57-58]. Cheli et al. built a multi-compartment metro vehicle simulation model, and used this to study the effects of track irregularity on vehicle derailment [59].

Although vehicle derailment can be divided into many types, there is only one result: the wheels become separated from the rail, so that the wheelsets cannot continue to run normally. Therefore, in order to clarify the mechanism of vehicle derailment in the turnout area, it is necessary to simulate the dynamic process of wheelset derailment and then analyse the dynamic wheel-rail contact relationship on every typical cross section of the turnout where the vehicle is climbing on the rails [60-61]. A dynamic derailment simulation model was built in this paper to simulate the dynamic process of derailment in the turnout area. The calculation results were much the same as those obtained in field investigations. On this basis, the effects of different factors such as wheel-rail wear, vehicle speed, friction force and wheelset axle load on train derailment were investigated. In addition, a technique was proposed to enhance the safety of trains in the turnout area [62-64].
4 Health management and condition monitoring of high-speed railway turnouts

With a large number of high-speed railways built and opened to traffic in China, there is an increasingly obvious conflict between traffic safety and equipment condition management. After establishing an effective monitoring system, we can conduct long-term monitoring of fixed equipment to ensure the safe, reliable and efficient operation of high-speed trains. In particular, monitoring must be conducted over certain key vulnerable parts of fixed equipment, such as turnouts, important bridges, important tunnels, and weak subgrades. The turnout is one of the vulnerable parts affecting train operating safety, and more than 3000 groups of turnouts have been laid throughout the country. The high-speed railway turnout is a critical component for shunting trains, and consists of movable parts directly related to the wheel-rail relationship. Therefore, it is characterized by complex wheel-rail contact status, changeable rail sections, complex rail support and constraints, a large number of parts in the turnout area, assembly of many types of parts consisting of different materials, and worker and electricity linkage for shunting. All of these characteristics indicate that the turnout is a reasonably vulnerable piece of fixed high-speed railway equipment, and disastrous consequences can be caused by failure to solve turnout faults in time. Moreover, China's high-speed rail is under closed-off management, meaning the current management and detection means cannot help to quickly and comprehensively learn about the conditions of these key parts to ensure the safe operation of trains. At present, with turnouts in operation, the key to ensuring the safe and efficient operation of high-speed trains is ensuring turnout-crossing safety, enhancing the monitoring of turnout serviceability and improving the ability to deal with faults efficiently.

With the advancement of modern signal processing and sensor technology, non-destructive testing techniques based on acoustic emission technology are drawing increasing attention and being further developed. Acoustic emission (AE) is an elastic wave phenomenon that arises along with energy release in the process of material deformation or fracture. AE detection refers to collecting AE signals generated from
turnout rail damage using customized sensors. According to fracture mechanics, there are four influencing factors of AE signals, including the material itself, the material structure, load and forms of crack. For the monitoring object, the first three influencing factors are constant, so that a one-to-one mapping relation can be built between the forms of crack and AE signals. In other words, crack damage can be detected by monitoring AE signals. Big data-based AE signal processing is based on modern signal processing technology and big data mining technology. It works by re-characterizing massive data using modern signal processing techniques. The selected data tool is Wigner-Ville fourth-order spectrum, which can realize high-resolution time-frequency characterization of signals while suppressing noise. Based on high-resolution characterization of AE emission signals and noise suppression, a Wigner-Ville fourth-order spectrum can be used as the feature of AE emission signals required for big data mining and clustering. Then, existing massive data can be clustered together as a priori information to classify newly-collected AE signals, and subsequently, the turnout monitoring system will respond differently depending on the classification results.

Elastic wave detection, which has the advantages of long distance, large range, total cross-section and high convenience [65], has been a focal point for researchers throughout the world in recent years. Hayashi et al. [66] studied the propagation characteristics of elastic waves in rails, providing a basis for the potential application of elastic wave monitoring technology to rail breakage monitoring; Zhang et al. [67] studied the propagation characteristics of AE waves in turnout rails to identify and locate sub-rail defects, and investigated the Lamb wave dispersion characteristics of defect signals; Burger [68] used elastic waves to continuously monitor the integrity of a track, and elastic wave emission points were set up at an interval of 1 km along the track to confirm the integrity of the rail according to whether the receiving station received elastic wave signals; Loveday et al. [69] added a pulse echo operating mode to the broken rail detection system to locate railhead cracks and monitor their growth. Considering the effects of asymmetric cross-sections and longitudinal changes of cross-section on the propagation characteristics of guided waves, the researchers proposed a method for analysing the propagation characteristics of guided waves in the turnout rail, revealing the effects of cross-sectional changes on the propagation characteristics of guided waves in high-speed turnout rails [70]. Then, based on the principle of linear acoustics, they investigated the interaction mechanism between guided waves and typical crack injuries in high-speed turnout rails, and built an open turnout service status monitoring platform.
5 Conclusions and discussion on future research

5.1 Conclusions

The high-speed turnout is one of the core devices in high-speed railway construction, operation and maintenance. During the continued design, development, operation and maintenance of high-speed turnouts, it is necessary to deepen and improve upon the dynamic analysis theory of turnouts in order to solve relevant dynamic problems such as wheel-rail relationships, component strength and vehicle-turnout coupled vibration. A theory needs to be established that can analyse the fatigue strength of components and reveal the occurrence mechanism for various types of damage and their influencing regularity on running stability and safety, in an attempt to solve the problem of turnout performance deterioration after long-term service. A high-speed turnout structure condition monitoring system also needs to be devised to solve the problem of durability—this involves issues such as frequent turnout failure, time-consuming overhaul, high maintenance loads, and similar. In this paper, the dynamic design theory and key techniques for high-speed railway turnouts were summarized in a systematic manner. In terms of wheel-rail contact behaviour in the turnout area, vehicle-turnout coupling dynamics, turnout serviceability and safety assessment, and turnout structure condition monitoring, this paper comprehensively discussed the practical application of dynamic design theory to high-speed turnouts, in order to provide researchers and engineers with a theoretical basis and ideas for further studies.

5.2 Future research directions

The theory and key techniques of high-speed railway turnout design are a promising and engaging topic of research, and one which abounds with interesting and challenging tasks. Future research directions can be considered from four aspects:

(1) Life cycle design of high-speed railway turnouts for LCC (life cycle cost) and RAMS
LCC and RAMS-related indexes are decomposed and put into the life cycle of high-speed railway turnouts to form corresponding demand constraints. These include DFC (design for cost), which involves high-speed turnout operating costs, maintenance costs, assembly and disassembly costs, process costs, design costs and scrap costs, and reliability design, which involves safety and reliability index distribution and constraints at each stage. Cost and reliability models are built at each stage to ensure reasonable cost allocation and a reliable stability margin for the required design parameters. After this, an LCC and a reliability model are built for design optimization and cost control, in order to achieve satisfactory life cycle design results.

(2) Adaptability improvement for high-speed railway turnouts in a complex operating environment

In response to a series of major national strategic needs, including the “Belt and Road” Initiative, maritime power construction, the western development and high-speed railway expansion, rail transit infrastructure worldwide is now starting to cover areas with a more complex natural environment at higher speeds. Owing to the complexity of the operating environment, the diversity of structural materials, the spatial effects of structural facets, the time required during the service process, and the coupled effect of other various factors, the high-speed railway turnout boasts a very complex spatio-temporal evolution mechanism and associated laws for its dynamic performance. This requires that high-precision, high-speed railway turnouts and substructures show excellent adaptability to the challenges presented by harsh natural environments and complex geological conditions such as severe cold, sandstorms, rain and snow, freezing and thawing, scouring and corrosion. Therefore, leading researchers are now studying the spatio-temporal evolution mechanism and associated laws for the dynamic performance of the high-speed turnout system in extreme climate or under adverse geological conditions.

(3) Research on basic scientific problems concerning higher-speed railway turnouts

When vehicles pass through a turnout at a speed of 400km/h or above, high-frequency dynamic or transient behaviour plays a very significant role in the process of high-speed wheel-rail interaction. Vibration wavelength is of almost the same order of magnitude as the diameter of the contact patch, making it easy to cause flutter or co-vibrations within the wheel-rail coupling system components, thus disrupting passenger comfort, accelerating the damage to vehicle-track system components, and seriously affecting the safety and reliability of high-speed train operation. Therefore, for the development of the next generation of high-speed railway turnouts, the key basic scientific problem demanding a prompt solution is the creation of a minimum time-step transient rolling contact model for three elastomers or elastoplastic bodies – one that considers the non-linearity and geometric non-linearity of system components. Contact irregularity and inter-facial thermal effects must be built in to investigate the rule of high-frequency interaction between high-speed rail turnouts and the vehicle system.

(4) Innovative design for next-generation high-speed railway turnout structures

The next generation of high-speed railways will put increasingly higher requirements on the safety, intelligence, durability and eco-friendliness of turnouts. With the development of structural dynamics, aerodynamics and acoustic theories, it has become necessary to press ahead with the innovation of materials, structures, technology and other aspects of high-speed turnouts. Key technologies are as follows: new supporting structures suitable for next-generation high-speed turnouts, reinforced advanced fibre composites, adaptive materials, and high-performance ferroconcrete. A high-speed railway turnout design system needs to be built on the basis of reliability theory, life cycle and sustainable engineering to enhance the industrialization, intelligence and automation of high-speed railway turnout manufacturing and laying. Another matter of great urgency is developing a high-speed railway turnout damage assessment method.
and an intelligent damage remediation technology based on the degree of structural damage. In this way, vibration attenuation and noise control techniques can be developed, creating a useful environmental evaluation system. In addition, a big data-based high-speed railway turnout risk management system can be created, along with other information management and maintenance decision-making technologies.

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References

The dynamic behaviour of derailed railway vehicles at large angle of attack [J].


