Effect of track irregularities on the dynamic behavior of a tram vehicle

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Abstract

This paper presents an investigation of the effects of track irregularities on the dynamic responses of a tramway vehicle. A three-dimensional vehicle-track model is applied to investigate the dynamic behaviors of a tram vehicle subjected to the excitations of four types of track geometry irregularities: longitudinal level, alignment, cross level, and twist. Numerical simulations are then carried out to study the influences of the wavelength and amplitude of track irregularities on the running safety and ride comfort of the tram vehicle. The sensitive wavelengths of the track irregularities resulting in resonance of the vehicle-track system are identified. The numerical results show that the wavelength characteristics of track defects have a significant influence on the dynamic performances of tram vehicles, which should be carefully taken into account in the vehicle design, the track maintenance, and the vehicle operating strategy.

Keywords: Tram vehicle; Track irregularities; Vehicle-track interaction; Running safety; Ride comfort

1. Introduction

Track irregularities have an important effect on the dynamic behavior of railway vehicles. Severe track geometry defects can result in poor ride comfort and in some cases derailment. To improve the ride comfort and running safety of trains, it is important to clearly understand the relationship between the track irregularities and the dynamics performances of railway vehicles.

The methods of describing and assessing track geometry irregularities and their effects on the running behavior of railway vehicles have been studied by many researchers [1–11]. However, the research on the effects of the wavelength characteristics of individual track defects on the dynamic behaviors of tram vehicles seems to be rare. The USA Federal Railroad Administration carried out a series of engineering studies to support the development of high speed track geometry standards [1]. These standards were intended to cover train operating speeds from 110 mph to 200 mph. Fujimoto et al. [2] investigated the influence of track gauge variations on rail vehicle dynamics. In their studies, the data from a test train running on a track with artificially included irregularities and data obtained in simulation studies were compared. Furukawa and Yoshimura [3] applied the work system identification theory to identify the dynamic characteristics of the vehicle and to predict how track geometry affects its vertical vibration and dynamic wheel load. The system identification is one of the stochastic signal-processing theories similar to spectral analysis, but is able to identify the vehicle dynamic characteristics with fewer observed signals. Cheli et al. [4] investigated the effect of track geometrical defects on derailment risk of tramcar vehicles. The results showed that the dynamic effects related to track irregularities excitation are of fundamental importance to the derailment phenomenon. Karis [5] investigated the correlation between track irregularities and vehicle responses based on field test results. He found that the correlation in the vertical direction between vertical forces and longitudinal levels is high. Berg et al. [6–7] presented a study of assessing track geometry quality by the use of dynamic track–vehicle simulations and wavelength spectra analysis. In their studies, a new approach using second-order derivatives of the track irregularities was proposed to analyze and present the track geometry quality. Gao et al. [8] examined the sensitive wavelength range of track irregularities on high-speed rails using the artificially generated cosine irregularities. Zhang et al. [9] established a vertical coupled vehicle-track dynamic model to identify the vertical track irregularity PSD. The PSD of the vertical track irregularities is identified using a combination of the inverse pseudo-excitation method and the symplectic mathematical method. Choi et al. [10] investigated the influences of the wavelength and amplitude of track irregularities on the running behavior of KTX trains. Their results indicated that track alignment has a significant impact on the running safety whereas longitudinal level does not have any significant impacts. Wu et al. [11] studied the dynamics performances of railway wagons subjected to the combination forces from in-train dynamics, wind, track curving, and track geometry irregularities and defects at the same time.

To support the rapid construction of modern tramways in
China and the development of track irregularity maintenance standards for the embedded rail track, we conducted this research to investigate the dynamics responses of tram vehicles due to track irregularities using a three-dimensional tramway vehicle-track coupling model. The influence of the longitudinal level, alignment, cross level and twist irregularities on the running safety and ride comfort of tram vehicles are reported. The presented results can help to create an understanding of the relationship between track irregularities and tram vehicle dynamics behaviors as well as supporting the development of irregularity control standards for tramway tracks.

2. Numerical Model

The three-dimensional (3D) dynamic model of a tram vehicle-track system developed in Ref. [12] is adopted in this investigation. The multiaxle tram is composed of two power vehicles and one trailing vehicle, as shown in Fig. 1. Each vehicle consists of two car bodies connected by an intermediate articulated section and three bogies. The two end body sections are coupled to the center section by spherical joints and therefore the center bogie supports the end mass of these two sections, together with the center section. The two powered bogies are normal bogies with solid conventional axles, and the middle bogie is the trailer bogie equipped with independently rotating wheels. Both the motor bogies and trailer bogie are equipped with double suspension systems. The primary suspensions use the rubber springs arrangement acting on the axle-boxes, which connect the bogie frames to the axle-boxes. The secondary suspensions of the motor bogies, including coil springs and lateral and vertical hydraulic dampers, connect the car bodies to the bogie frame via bolsters, whilst the trailer bogie is not equipped with the bolster.

The tram vehicle model is set up by using the multi-body dynamics approach. The tram composing of three vehicles is modelled as a 96 degree-of-freedom (DOF) nonlinear multi-body system with nonlinear suspensions. The main components of the tram vehicle, including the carbody, the bogie frame, the bolster, the wheelsets, and the independently rotating wheels, are modeled as rigid bodies. These bodies are assumed to undergo small displacements relative to the moving reference, thus the kinematic relationships can be linearized. 3D spring-damper elements are used to represent the primary and the secondary suspensions, and the nonlinear dynamic characteristics of the suspension systems are considered, including the nonlinear lateral and vertical dampers, and the nonlinear bump-stops installed on the secondary suspension.

The track was modeled as a two layer system consisting of two rails, filling material, slabs, and adjustment layer beneath slabs. The rails were treated as Timoshenko beams with continuous elastic supports, in which the modal superposition method was used to reduce the order of the partial differential equations of beams. Continuous viscoelastic elements were used to represent the filling material and rail pad that connecting the rails and the slabs. The concrete slabs were modeled using the 3D finite element method, while the modal superposition method was adopted to improve the computational efficiency [12-13]. Uniformly viscoelastic elements were introduced to model the elastic layer beneath the concrete slabs.

The wheel–rail contact model includes two basic issues: the geometric relationship and the contact forces between the wheel and the rail. A spatial wheel–rail contact model [14-15] was hired in this study to characterize the geometry of the wheel–rail rolling contact. Two point contact behavior was considered when the flange root of the wheel contact with grooved head of the rail. The calculation of wheel–rail contact forces includes a normal mode and a tangent one. The normal model, which characterizes the relationship law of the normal load and deformation between the wheel and rail, is described by a Hertzian nonlinear contact spring with a unilateral restraint. The nonlinear model by Shen et al. [16-17] is used as the tangent model determining the relationship between the creepages and the total creep forces of the wheel/rail.

![Figure 1. Schematic of the tram vehicle-track model](image-url)
3. Numerical Results and Discussions

The track geometry in practice will deviate from its initial designed profile due to the effects of repeated vehicle loads, rail defects, track settlement, and etc. These deviations in the track geometry are defined as track irregularities and include alignment, track gauge, longitudinal level (vertical profile), cross level, and twist, as illustrated in Fig. 2. Alignment is the deviation in the lateral direction of consecutive positions, expressed as an excursion from the mean lateral position (track center line). Track gauge is the smallest distance between lines perpendicular to the running surface intersecting each railhead profile. Longitudinal level is the deviation in the vertical direction of consecutive running table levels, expressed as an excursion from the mean vertical position (track center line). Cross level is the difference in height (elevation) between the left and right rails. And twist is the algebraic difference between two cross levels taken at a defined distance apart, usually expressed as a gradient between the two points of measurement [10, 18].

The 3D tram vehicle-track model shown in Section 2 was used to investigate the dynamic interactions between the tram vehicle and the embedded rail tracks due to track irregularities with various wavelengths and amplitudes. A generic tram vehicle used in China is considered in this study, which is composed of two power vehicles and one trailing vehicle. The length of the tramcar is 29.5 m. The static axle loads for the power vehicles and the trailing vehicle are approximately 115 and 98 kN, respectively. The maximum speed of the tramcar is 70 km/h and this speed was assumed in the simulations. Tangent tracks are considered in this paper since attention is focused on the effects of track irregularities on tramway vehicle–track interactions.

Vehicle dynamics responses are affected by both the amplitudes and wavelengths of the track irregularities. Track irregularities with long wavelengths usually affect the ride comfort, while track geometrical defects with short wavelengths threaten the running safety. Track irregularities with artificially generated single-cosine-wave shapes were assumed. Simulations were performed for the longitudinal levels, alignments, cross levels and twists. To examine the sensitive wavelength ranges of track irregularities on tram–track interactions and the effects of short wavelength defects, the simulations covered the range of wavelengths from 1 to 70 m [18]. The track irregularity amplitudes considered were in the range of 10–20 mm. To identify the influences of track irregularities on the running safety and ride comfort of the tram vehicles, dynamics responses such as the derailment coefficient, wheel unloading ratio, wheel–rail vertical force, lateral and vertical Sperling comfort indexes were analyzed. The wheel–rail vertical force is related to fatigue damage of the track parts: its limit value $Q_{lim}=90+Q_0$, where $Q_0$ is the static load on each wheel [19]. The allowable limit values of the derailment coefficient and the wheel unloading ratio are 0.8 and 0.6 in the evaluation of the operating safety of urban rail transit in China, while the allowable limit values of the lateral and vertical Sperling comfort indexes are 2.5 [20].

![Figure 2. Definition of track irregularities](image)

3.1. Longitudinal Level Defect

Longitudinal level defects can cause a car body to pitch and bounce, and cause fierce wheel–rail vertical force, which would affect the ride comfort and accelerate the fatigue damage of vehicle and track components. Two assessment criteria, the peak wheel–rail vertical force and the vertical Sperling comfort index, for the running safety and ride comfort are considered in examining the sensitive wavelength range and the effects of the wavelength and amplitude of the vertical profile defects on the vehicle–track interactions. Because the longitudinal level irregularities have little impact on the lateral vehicle–track interactions, the results of the derailment coefficient, wheel unloading ratio and lateral comfort index are omitted here.

Fig. 3 illustrates the effects of the wavelength and amplitude of vertical profile defects on the maximum values of the wheel–rail vertical force and vertical Sperling comfort index of the trailing vehicle. The legends in these graphs list the amplitudes of the track irregularities. The plotted wheel–rail
vertical forces are the maximum values extracted from all wheels of the power and trailing vehicles. The variations in the values of wheel–rail vertical force and vertical Sperling comfort index indicate that both the wavelength and amplitude of longitudinal level defects greatly influence the vehicle–track vertical interactions and the ride comfort of tram vehicles.

Fig. 3a shows the wheel–rail vertical forces increase dramatically as the defect wavelength decreases at wavelengths of less than 7 m. This means the wheel–rail vertical forces are very sensitive to the short wavelengths of track vertical defects. Fig. 3b shows the vertical Sperling comfort indexes increase rapidly as the defect wavelength decreases, and the amplitude increases at wavelengths of less than 20 m. When the longitudinal level defect amplitudes are greater than 10 mm, the maximum values of the vertical Sperling comfort indexes are greater than the limit value 2.5 in the wavelength bands of approximately 1–14 m for both power and trailing vehicles. From the results shown in Fig. 3, it could be tentatively concluded that the sensitive wavelengths of longitudinal level irregularities for the running safety and ride comfort are in the wavelength bands of approximately 1–10 m and 1–20 m.

Two main resonant wavelengths, approximately 5 m and 10 m, are observed in the responses of wheel–rail vertical forces and vertical Sperling comfort indexes, as shown in Fig. 3. The corresponding resonant frequencies are approximately 3.9 Hz and 1.9 Hz when the vehicle speed is 70 km/h. The first resonant frequency is related to the natural frequency of the power bogies, which corresponds to the mode shape of pitching motion of the end bogies when out of phase, as shown in Fig. 4. The second one is close to the natural frequency of the pitching motion of car bodies, corresponding to the U-Shaped pitching mode of the train (pitching motion of the end car bodies out of phase). The modal parameters of the tram vehicle selected were calculated using the commercial software SIMPACK®. This means the sensitive wavelengths of track irregularities are closely related to the natural frequencies of the vehicle system and the vehicle speed.

It is noted that the two sensitive wavelengths of longitudinal level defects are close to the length of the track slab (6 m) used in this investigation. In fact, the predominant wavelengths of the track geometry irregularities in slab track lines are greatly affected by the physical dimensions of the track components. Fig. 5 shows the PSDs of the measured vertical profile irregularities of a Chinese railway line with slab tracks. The longitudinal level defects form the predominant components with wavelengths around 100, 6.5 and 30 m, which are related to the distance between the neighboring rail welding points and the lengths of track slabs and bridges.

![Figure 3](image1.png)

**Figure 3.** Maximum wheel/rail vertical force and vertical Sperling comfort index as a function of wavelength and amplitude (trailing vehicle)

<table>
<thead>
<tr>
<th>Mode description</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitching motion of the A and B car bodies out of phase</td>
<td>1.8 Hz</td>
</tr>
<tr>
<td>Pitching motion of the A and B bogies out of phase</td>
<td>4.0 Hz</td>
</tr>
</tbody>
</table>

![Figure 4](image2.png)

**Figure 4.** Pitching modes of the car bodies and bogies
To avoid the vehicle system resonance caused by track irregularities as shown in Fig. 5, the tramcar suspension should be optimized to reduce sensitiveness to the specific line features and a resonant vehicle speed should be prohibited. The resonant vehicle speed $V_{res}$ related to the harmonic vertical defects caused by track components (rail, slab, bridge and etc.) can be estimated as follows:

$$V_{res} = 3.6 \times L_{tc} \times f_{vb} \text{ (km/h), } n = 1, 2, 3, \ldots$$  (1)

where $L_{tc}$ (m) is the length of the track components, $f_{vb}$ (Hz) is the nth vertical or pitching natural frequency of the vehicle system. For the tramcar considered in this paper, the length of the track slab is 6 m, the excited natural frequencies are 3.89 and 1.95 Hz. Thus, the resonant vehicle speeds calculated by Eq. 1 are 84 and 42 km/h. Because the maximum speed of the tramcar is 70 km/h, so 42 km/h is the only resonant vehicle speed that should be prohibited. In other words, this tram car cannot run on the embedded rail track with 6-m-length slabs at operating speeds of approximately 42 km/h. The above conclusion is validated by the simulation results shown in Fig. 6, where the wavelength of the vertical profile defects was 6 m and the amplitude was 10 mm. Fig. 6 indicates that the peak values of the vertical Sperling comfort indexes occur at approximately 42 km/h.

3.2. Alignment Defect

Track alignment variations can cause a vehicle to sway and yaw, causing large lateral wheel and axle forces, which would affect the ride comfort and have a negative impact on the running safety and fatigue damage of vehicle and track components. Fig. 7 and Fig. 8 illustrate the effects of the wavelength and amplitude of the alignment defects on the maximum values of the derailment coefficient and wheel unloading ratio. The variations in the values of derailment coefficient and wheel unloading ratio indicate that both the wavelength and amplitude of alignment defects greatly influence the operating safety of tram vehicles.

Fig. 7 indicates the derailment coefficients start to increase rapidly as the defect amplitude increases at wavelengths of less than 10 m for the power vehicles. For the trailing vehicles, an increase in the amplitude and a decrease in the wavelength of the track alignment irregularities lead to rapidly increased derailment coefficients at wavelengths of less than 18 m. When the track alignment amplitudes reach 14 mm, the maximum values of the derailment coefficient are greater than the limit value 0.8 at wavelengths of less than 5 m for both power and trailing vehicles. Fig. 8 shows the wheel unloading ratio is very sensitive to track alignment irregularities with short
wavelengths. The wheel unloading ratios decrease dramatically as the defect wavelength increases and the amplitude decreases at wavelengths of less than 5 m. At track alignment amplitudes greater than 20 mm and wavelengths less than 3 m, the maximum wheel unloading ratios exceed their limit 0.8 for both power and trailing vehicles.

The maximum lateral and vertical Sperling comfort indexes as a function of the wavelength and amplitude of alignment track irregularities are shown in Fig. 9 and Fig. 10. The variations in the values of lateral and vertical Sperling comfort indexes indicate that both the wavelength and amplitude of alignment defects greatly affect the ride comfort of tram vehicles. The lateral and vertical Sperling comfort indexes increase rapidly as the defect wavelength decreases and the amplitude increases at wavelengths of less than 40 and 30 m, respectively. When the alignment defect amplitudes are greater than 14 mm, the maximum values of the lateral Sperling comfort indexes are greater than the limit value 2.5 in the wavelength bands of approximately 1–7 m for both power and trailing vehicles. The maximum vertical Sperling comfort indexes for all of the cases considered in Fig. 10 are less than the allowable limit value.

From the results shown in Figs. 7–10, it could be tentatively concluded that the sensitive wavelengths of alignment irregularities for the running safety and ride comfort are in the wavelength bands of approximately 1–20 m and 1–40 m. Two peak values of derailment coefficients and wheel unloading ratios occur at approximately 3, and 10-13 m, respectively, which are mainly related to yawing motion of the bogies and rolling motion of the car bodies. This is because the excitation frequencies (approximately 6.4 and 1.4 Hz) associated with the defect wavelength and with the vehicle speed are close to the bogie yaw and car body roll natural frequencies (approximately 6.1 and 1.3 Hz). The resonant wavelengths, 3–6 m, observed in the responses of lateral and vertical Sperling comfort indexes are raised from the mode shapes of swaying and pitching motions of the bogies.

**Figure 7.** Maximum derailment coefficient as a function of wavelength and amplitude for the case of an alignment defect: (a) power vehicle and (b) trailing vehicle.

**Figure 8.** Maximum wheel unloading ratio as a function of wavelength and amplitude for the case of an alignment defect: (a) power vehicle and (b) trailing vehicle.
level defects have a significant influence on the wheel unloading or excessive accelerations, which would have negative effects on the running safety and ride comfort of railway vehicles. Figs. 11–14 show the influences of the wavelength and amplitude of cross level defects on the maximum values of derailment coefficient, wheel unloading ratio, and lateral and vertical Sperling comfort indexes.

Fig. 11 indicates the derailment coefficients are very sensitive to the short wavelengths of cross level irregularities. The derailment coefficients increase dramatically as the defect wavelength decreases at wavelengths of less than 5 m. The peak value occurring at approximately 7 m is induced by the resonance of rolling motions of the power bogies. This is because the excitation frequency (approximately 2.8 Hz) associated with the defect wavelength and with the vehicle speed is close to the bogie roll natural frequency (2.7 Hz). Fig. 11 shows both the wavelength and the amplitude of the cross level defects have a significant influence on the wheel unloading of the vehicles. The wheel unloading ratios increase dramatically as the defect wavelength decreases at wavelengths of less than 4 m. At a cross level defect wavelength of 1 m, the maximum wheel unloading ratios for all of the cases considered in Fig. 12 are greater than the limit value 0.6. The peak values occurring at 10-13 m are mainly related to the rolling motion of car bodies, as discussed in Section 3.2.

Fig. 13 and Fig. 14 illustrate the maximum lateral and vertical Sperling comfort indexes as a function of the wavelength and amplitude of cross level irregularities. The variations in the values of lateral and vertical Sperling comfort indexes indicate that both the wavelength and amplitude of cross level defects greatly affect the ride comfort of tram vehicles. Three main resonant wavelength ranges, 5-7 m, 10-13 m and around 25 m, are observed in the responses of lateral Sperling comfort indexes. The peak values occurring at 5-7 m are mainly pitching and rolling motions of the bogies and the peak values at 10-13 m and around 25 m are mainly caused by the rolling and yawing motions of the car bodies. The excitation frequency associated with the defect wavelength of around 25 m at a

![Figure 9](image9.png)

**Figure 9.** Maximum lateral Sperling comfort index as a function of wavelength and amplitude for the case of an alignment defect: (a) power vehicle and (b) trailing vehicle.

![Figure 10](image10.png)

**Figure 10.** Maximum vertical Sperling comfort index as a function of wavelength and amplitude for the case of an alignment defect: (a) power vehicle and (b) trailing vehicle.

### 3.3. Cross Level Defect

Cross level irregularities can cause a car body to roll and sway. Excessive car body motions would result in wheel unloading or excessive accelerations, which would have negative effects on the running safety and ride comfort of railway vehicles. Figs. 11–14 show the influences of the wavelength and amplitude of cross level defects on the maximum values of derailment coefficient, wheel unloading ratio, and lateral and vertical Sperling comfort indexes.
speed of 70 km/h is approximately 0.78 Hz, and the car body yaw natural frequency is 0.64 Hz. When the cross level defect amplitudes are greater than 14 mm, the maximum values of the lateral Sperling comfort indexes are greater than the limit value 2.5 at the resonant wavelengths.

The main maximum peak values of the vertical Sperling comfort indexes occur at 5 and 10 m, which are similar to the cases of the longitudinal level defects discussed in Section 3.1.

At cross level defect amplitudes greater than 10 mm, the maximum values of the vertical Sperling comfort indexes exceed the limit value 2.5 at the resonant wavelength 10 m. From the results shown in Figs. 11–14, it can be found that the sensitive wavelengths of cross level irregularities for the running safety and ride comfort are in the wavelength bands of approximately 1–20 m and 1–40 m.

Figure 11. Maximum derailment coefficient as a function of wavelength and amplitude for the case of a cross level defect: (a) power vehicle and (b) trailing vehicle

Figure 12. Maximum wheel load reduction as a function of wavelength and amplitude for the case of a cross level defect: (a) power vehicle and (b) trailing vehicle

Figure 13. Maximum lateral Sperling comfort index as a function of wavelength and amplitude for the case of cross level defect: (a) power vehicle and (b) trailing vehicle
3.4. Track Twist

Large track twist irregularities can cause a vehicle to roll, sway and result in wheel unloading, which threaten the running safety. Figs. 15–18 show the effects of the wavelength and amplitude of track twists on the maximum values of the derailment coefficient, wheel unloading ratio, and lateral and vertical Sperling comfort indexes.

Fig. 15 shows the derailment coefficients are very sensitive to track twist irregularities with short wavelengths of less than 10 m. The derailment coefficients increase dramatically as the defect amplitude increases and wavelength decreases, at wavelengths of less than 10 m. The peak value occurring at 4-7 m is induced by the resonance of rolling motions of the power bogies, which is similar to the cases of cross level defects discussed in Section 3.3. The maximum derailment coefficients for all of the cases considered in Fig. 15 are less than the allowable limit value. Fig. 16 indicates both the wavelength and amplitude of track twist defects greatly influence the wheel unloading of the vehicles. The wheel unloading ratios increase dramatically as the defect wavelength decreases at wavelengths of less than 4 m. At a cross level defect wavelength of 1 m, the maximum wheel unloading ratios for all of the cases considered in Fig. 16 are greater than the limit value 0.6. The peak values occurring at 5-7 m and 8-10 m are mainly caused by the rolling motion of the power bogies and the car bodies, as discussed in Section 3.2 and Section 3.3.

Figs. 17-18 show that both the wavelength and amplitude of track twists have significant effects on the ride comfort of tram vehicles. The lateral and vertical Sperling comfort indexes increase as the amplitude increases. Three main resonant wavelength ranges, around 5 m, 10-13 m and around 25 m, are observed in the responses of lateral Sperling comfort indexes. These resonant wavelengths are as almost identical to that found in Fig. 13 for the cases of cross level defects. The main maximum peak values of the vertical Sperling comfort indexes occur at 5 m and 13-15 m. The former is induced by the pitching motion of the end bogies, as discussed in Section 3.1. The peak values occurring at 13-15 m are induced by the resonance of rolling motions of the car bodies. The excitation frequencies (approximately 1.4 Hz) associated with the defect wavelengths and with the vehicle speed are close to the roll natural frequency of the car bodies (1.3 Hz). When the twist defect amplitudes reach 20 mm, the maximum values of the vertical Sperling comfort indexes are greater than the limit value 2.5 at the resonant wavelength of 10 m. From the results shown in Figs. 15–18, it can be found that the sensitive wavelengths of the twist irregularities for the running safety and ride comfort are in the wavelength bands of approximately 1–20 m and 1–40 m.
4. Conclusions

In the present paper, the influences of the wavelength and amplitude of the longitudinal level, alignment, cross level, and twist irregularities on the running safety and ride comfort of a tram vehicle were analyzed and reported. The sensitive wavelengths of the track irregularities resulting in resonance of the vehicle system were identified. The following conclusions can be drawn from the numerical results obtained:

** Both the wavelength and amplitude of track irregularities have significant effects on the running safety and ride comfort of tram vehicles. The safety indexes are very sensitive to track irregularities with short wavelengths below approximately 20 m, while the sensitive wavelengths of track defects for the ride comfort indexes are in a wider wavelength band.

** The sensitive wavelengths of track irregularities are closely related to the natural frequencies of the vehicle system and the vehicle speed. For the tram vehicle considered in this investigation, the sensitive wavelengths of the longitudinal level
defects are mainly determined by the pitching mode shapes of the bogies and car bodies, the resonant wavelengths of the alignment defects are mainly affected by the yawing motion of the bogies and the rolling motion of the car bodies, and the sensitive wavelengths of the cross level and twist defects are mainly influenced by the vehicle speed and the natural frequencies of the rolling and pitching motions of the bogies and rolling, yawing and pitching motions of the car bodies. **The wavelength characteristics of track defects have a substantial influence on the running safety and ride comfort of tram vehicles, which should be carefully taken into account in vehicle design, track maintenance, and vehicle operating strategy.**

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