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Safety of the express freight train running over a long-span bridge

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Abstract

Purpose – Express freight transportation is in rapid development currently. Owing to the higher speed of express freight train, the deformation of the bridge deck worsens the railway line condition under the action of wind and train moving load when the train runs over a long-span bridge. Besides, the blunt car body of vehicle has poor aerodynamic characteristics, bringing a greater challenge on the running stability in the crosswind.

Design/methodology/approach – In this study, the aerodynamic force coefficients of express freight vehicles on the bridge are measured by scale model wind tunnel test. The dynamic model of the train-long-span steel truss bridge coupling system is established, and the dynamic response as well as the running safety of vehicle are evaluated.

Findings – The results show that wind speed has a significant influence on running safety, which is mainly reflected in the over-limitation of wheel unloading rate. The wind speed limit decreases with train speed, and it reduces to 18.83 m/s when the train speed is 160 km/h.

Originality/value – This study deepens the theoretical understanding of the interaction between vehicles and bridges and proposes new methods for analyzing similar engineering problems. It also provides a new theoretical basis for the safety assessment of express freight trains.

Keywords Express freight train, Long-span bridge, Crosswind, Wind tunnel test, Running safety

Paper type Research paper

1. Introduction

The rapid development of the economy and society leads to the demand for safe and efficient railway freight services, which contribute to the research of express freight trains. Meanwhile, with the development of high-speed railway, the railway freight capacity has been released and strengthened, which provides favorable conditions for the development of express freight.

Express freight train has the characteristics of large cargo weight and high running speed. It mainly adopts box wagon with a blunt body and a high center of mass, which has a poor aerodynamic performance. The high running speed and poor aerodynamic performance may result in deteriorated running safety when the train runs in the complex environment especially on the bridge and in the crosswind (Huo, Liu, Chen, Li, & Gao, 2022; Soper & Baker, 2020). Besides, the wheel-rail dynamic response is more intense owing to the higher speed. Therefore, higher requirements are put forward for the smoothness and stability of the

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railway line, resulting in new railway lines with a high percentage of viaducts and bridges. In some Asian countries with highly developed high-speed railway (HSR) networks such as China and Japan, viaducts and bridges account for more than 75% of the railway lines (Montenegro *et al.*, 2021; Zhai, Han, Chen, Ling, & Zhu, 2019), and the ratio of bridges to the total length even reaches 80.5% in the Beijing–Shanghai HSR line. This reality increases the probability of risk subjected to strong crosswinds when the train runs over a bridge (Wang *et al.*, 2022). In particular, the long-span bridge with low stiffness may produce more significant deck deformation under the action of wind and train moving load, which will further deteriorate the line conditions and thus more notable impact on running safety (Li, He, Zhu, Zhai, & Yan, 2024; Han, Chen, Yang, & Liu, 2022). Therefore, the in-depth study on the safety of trains running over a bridge under crosswinds is of great implication.

There has been a significant amount of research on this issue over the past two decades. Li, Qiang, Liao, and Xu (2005) established an analytical model for dynamics of wind-vehicle-bridge systems, which was subsequently applied to study the safety of trains traveling over a long-span cable-stayed bridge (Zhang, Li, & Wang, 2016). Pedro *et al.* (2019) used the finite element method (FEM) to establish a vehicle-bridge coupled vibration analysis model, calculated the wheel-rail contact force and analyzed the safety and stability of the high-speed train when passing through a continuous beam bridge under the action of "Chinese Hat" gust. Xia, Guo, Zhang, and Sun (2008) proposed a dynamic model of wind-train-bridge system and applied it to obtain the dynamic response of the bridge and the running safety and stability indices of the train vehicles. Zhang, Xia, and Guo (2013) proposed an analysis framework for vehicle-bridge dynamic interaction system under turbulent wind and compared the dynamic response of the bridge and the running safety indices of the train while passing the bridge with wind barriers or without. Zhang, Ge, Xia, and Li (2015) conducted dynamic analysis of coupled wind-train-bridge system considering the shielding effect of the bridge tower with triangular wind barriers. He, Gai, and Wu (2017) proposed a rigid-flexible coupling method to simulate the train-bridge vibration under the actions of wind loads. The dynamic indices under various combinations of the train and wind speeds were used to evaluate the accuracy and efficiency of the proposed approach. Olmos and Astiz (2018) developed a nonlinear dynamic interaction train-bridge-wind model to assess the operational safety of high-speed trains over high-pier viaducts in Spain. Based on the aerodynamic performance of the train-bridge system, He, Fang, Li, and Shi (2019) conducted parameter optimizations of the louver-type wind barrier to improve the safety of trains running in an undesirable wind environment. Montenegro, Barbosa, Carvalho, and Calçada (2020), Montenegro, Barbosa, Carvalho, Calçada, and Baker (2020) developed a method for evaluating the possibility of derailment of trains running over bridges subjected to crosswinds and then compared and evaluated the influence of different wind models on the evaluation of running safety when moving over bridges. In order to investigate the effects of unsteady aerodynamic loads on the running safety of trains running on bridges, Han *et al.* (2020) established a three-dimensional and multi-body system model of train-track-bridge. They calculated the dynamic responses of the coupling system and compared the safety and comfort of a train running on a bridge under steady and unsteady aerodynamic loads at different crosswind speeds. To address the overturning risk assessment of high-speed trains over multi-span simply supported bridges under crosswind, Wang, Li, and Chen (2022) developed a train-bridge coupled system and estimate the wheel-rail contact forces, from which the overturning risk of train is assessed.

Fang, Li, Wei, Zhang, and Liang (2018) also investigated the running safety of the train running over sea-crossing railway bridge. They developed a wind-wave-vehicle-bridge dynamic analysis model for sea-crossing railway bridge under wind and wave loading. The dynamic response of bridge and vehicle was compared and the performance of bridge and vehicle were evaluated. The simulation results showed the dynamic response under correlated wind and wave was imperative for assessment of structural and vehicle safety and driving comfort of sea-crossing railway bridge. Liu, Cui, Guo, Cui, and Zhu (2020) also studied the train running performance on a sea-crossing bridge at different wind and train speeds.

In recent years, Lu's group has conducted a lot of research on the running safety of express freight trains over a bridge in crosswind environment. They performed the wind tunnel tests of the express freight train-bridge scale models to investigate the aerodynamic characteristics of the vehicles on simply supported girder bridge and steel truss bridge (Huang, Lu, & Wen, 2019; Wen, Li, Zhao, Huang, & Lu, 2022). And they also established the dynamic model of the express freight trains entering the bridge-subgrade transition in the crosswind environment and analyzed the influence rule of the crosswind speed, the running speed of the train, the variation of the stiffness of the subgrade-bridge transition and the bending deformation of the rail caused by the post-construction settlement of the road and bridge structure (Wen, Lu, & Huang, 2020). In addition, they conducted numerical simulations of stochastic wind speed, wind tunnel tests and computational fluid dynamics (CFD) simulation of vehicle-bridge scale model to calculate the wind load acting on the train and bridge. And they also evaluated dynamic responses of the bridge and train to present the diagrams of wind and train speed limits for safe operation (Wen, Li, & Lu, 2024).

So far there is no unified standard for safety of train running over the bridge. The assessment method on running stability in the crosswind is simplified, and the train-bridge interaction is also difficult to be considered. In this study, a dynamic model of wind-express freight train-long-span bridge coupling system is established. The dynamic responses of vehicle and bridge are analyzed, and the wind speed limit for safety is given. The results provide a reference for the operation of express freight train.

2. Methods

2.1 Wind load on the vehicle and bridge

According to the characteristics of atmospheric boundary layer (ABL) flow, the natural wind speed is mainly composed of mean wind speed $\overline{U}$ and fluctuating wind speed u, which can be expressed as

$$U = \overline{U} + u \tag{1}$$

In the wind field near the ground surface, the variation in mean wind speed $\overline{U}$ along the height h_r can be defined as

$$\frac{\overline{U}}{\overline{U}_r} = \left(\frac{h}{h_r}\right)^a \tag{2}$$

where $\overline{U}_r$ is the mean wind speed at the reference height h_r, which is considered as 20 m in this study. a is the vertical profile index of mean wind speed which equals 0.12 for the wind field above the river. u mainly reflects the fluctuation and stochasticity process of turbulence. The lateral speed u and vertical speed w are calculated by the harmony superposition method based on the power spectral density (PSD) functions, which are given as (MOT, 2018)

$$\begin{cases} S_u(n) = \dfrac{200f(z)u_*^2}{n[1+50f(z)]^{5/3}} \\ \\ S_w(n) = \dfrac{6f(z)u_*^2}{n[1+4f(z)]^2} \end{cases} \tag{3}$$

In the vehicle-bridge dynamic model, the spatial wind speed nodes are evenly set along the longitudinal direction of bridge to simulate the wind field. Owing to the small windward area, the wind load of the bridge tower is not considered. The lateral and vertical wind speed time history of mid-span of the bridge are shown as Figure 2(b) when the mean wind speed $\overline{U}_r$ equals 20 m/s.

Under the action of mean wind speed and fluctuating wind speed respectively, the wind load on the vehicle and bridge can be regarded as the sum of static wind load and buffeting wind load, which can be expressed as

$$\begin{cases} F_D = F_D^{st} + F_D^{bf} = \frac{1}{2}\rho\overline{U}^2 C_D HL + \rho BL\left(\overline{U}uC_D + \frac{1}{2}\overline{U}wC_D'\right) \\ F_L = F_L^{st} + F_L^{bf} = \frac{1}{2}\rho\overline{U}^2 C_L BL + \rho BL\left[\overline{U}uC_L + \frac{1}{2}\overline{U}w(C_L' + C_D)\right] \\ M_R = M_R^{st} + M_R^{bf} = \frac{1}{2}\rho\overline{U}^2 C_M B^2 L + \rho B^2 L\left(\overline{U}uC_M + \frac{1}{2}\overline{U}wC_M'\right) \end{cases} \tag{4}$$

where F_D, F_L and M_R denote the side force, lift and rolling moment of vehicle or bridge segment, respectively. H, B and L are the height, width and length of vehicle or bridge segment, respectively. C_D, C_L and C_M are the aerodynamic force coefficients, which are the function of yaw angle β (Figure 1(b)). C_D', C_L' and C_M' are the derivative of aerodynamic force coefficients with respect to the attack angle, which are obtained from the wind tunnel test and computational fluid dynamics (CFD) simulation in this study.

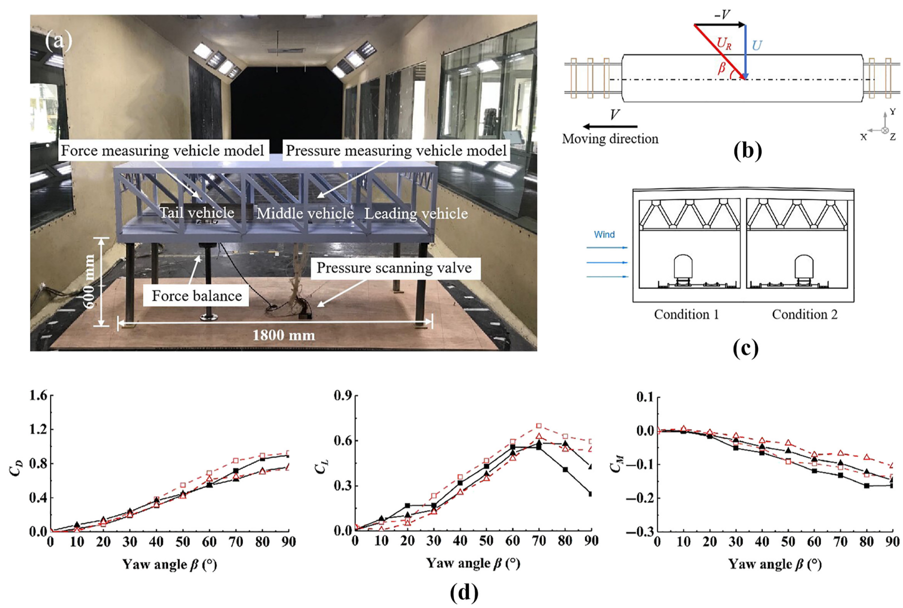

Figure 1.
(a) Vehicle-bridge scale model wind tunnel test (b) Yaw angle (c) Test conditions (d) Aerodynamic force coefficients of trailers

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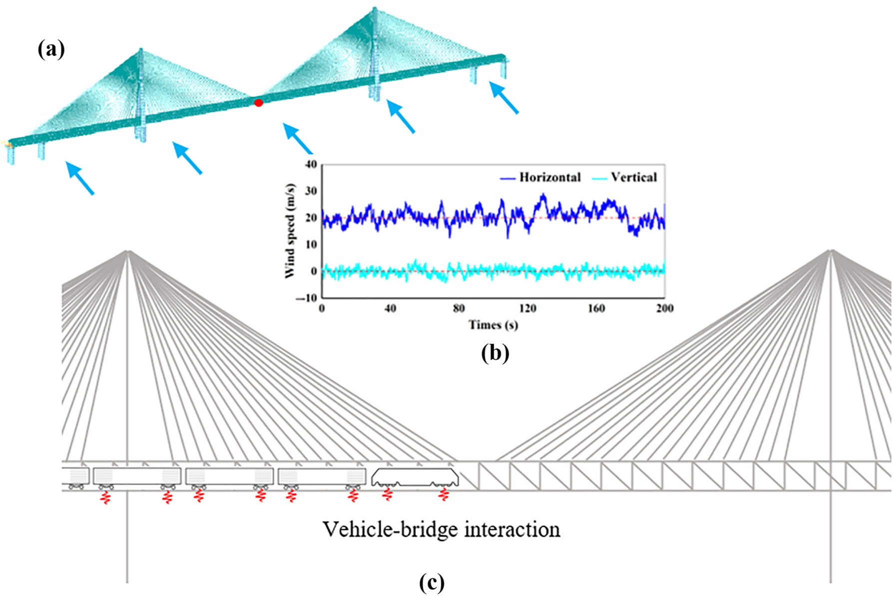

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Figure 2.
(a) FEM model of long-span bridge (b) Wind speed of mid-span node of bridge (c) Vehicle-bridge interaction

2.2 Wind tunnel test

To obtain the aerodynamic force coefficients of the express freight vehicle on the long-span bridge, the vehicle-bridge scale model wind tunnel test is conducted, as shown in Figure 1(a). The scale ratio of the model is 1:40, and the blockage ratio and the wind speed in the test are 8.2% and 20 m/s, respectively. The vehicle models include leading, middle and tail vehicles. The middle and tail vehicles are shaped based on express freight box wagon trailer, which are placed for measuring the aerodynamic force and the aerodynamic pressure on the surface of the vehicle, by a six-component force balance and an electronic pressure scanning valve, respectively. The positions of two models can be exchanged to measure the date of the vehicle at other positions.

During the test, the vehicle-bridge scale model rotates along with the turntable on the wind tunnel ground to measure the aerodynamic force coefficients of middle and tail trailers at yaw angles in the range of −90° - 90° (Figure 1(d)), including windward and leeward conditions (Figure 1(c)). The aerodynamic force coefficients of leading locomotive and bridge are calculated by CFD simulation, which are shown in Table 1.

2.3 Dynamic model of train and long-span bridge

The detailed train-bridge coupling dynamic model is established, in which the express freight train and the bridge are considered as two subsystems, as shown in Figure 2(a).

		C_D	C_L	C_M
Locomotive	Condition1	0.832	0.224	−0.258
	Condition2	0.715	0.284	−0.218
Bridge		0.572	−0.245	−0.116

Source(s): Authors' own work

Table 1.
Aerodynamic force coefficients of locomotive and bridge ($\beta = 90°$)

A long-span steel truss cable-stayed bridge is adopted, with a main span of 1092 m, which is established as a finite element model (FEM). The bridge tower, pier and main beam are modeled by beam element, and the bridge deck and stay cable are modeled by plate element and truss element, respectively. Degrees of freedom (DOF) of the track are not considered independently. The masses of rail, sleeper and ballast are modeled in the form of vibration mass of the bridge.

Express freight trains adopt the formation of 1M + 20T, with the leading traction locomotive and box wagon trailers behind (Figure 2(c)). In this study, each vehicle consists of a car body, two bogies and four wheelsets, totally 35 DOFs are considered. The vehicle is established as a finite element model (FEM). Each part is modeled by beam element, and it is considered as a rigid body by assigning a large elastic modulus to the element.

Besides, the stiffness and the damping of the primary and secondary suspension systems are modeled as a linear spring-viscous damping.

The express freight vehicle adopts LM wheel profile, matching R60 rail profile. The nonlinear wheel-rail spatially dynamic coupling model (Zhai *et al.*, 2019) are used in the simulation of wheel-rail dynamic interaction. The wheel-rail normal forces are calculated according to the Hertz nonlinear contact theory, and the wheel-rail creep forces are calculated based on Kalker's linear theory and Shen-Hedrick-Elkins model. In addition, the US Level 6 track irregularity is applied, including vertical, lateral, roll and gauge irregularities. The wind loads in Section 2.1 are added as external excitation of train and bridge subsystems. The motion equation of the vehicle-bridge coupling system is established based on the modal superposition method, which can be expressed as

$$\begin{cases} [m_v]\{\ddot{\delta}_v\} + [c_v]\{\dot{\delta}_v\} + [k_v]\{\delta_v\} = \{f_{vn}\} + \{f_{vc}\} + \{f_{ve}\} \\ [m_b]\{\ddot{\delta}_b\} + [c_b]\{\dot{\delta}_b\} + [k_b]\{\delta_b\} = \{f_{bc}\} + \{f_{be}\} \end{cases} \tag{5}$$

where $[m_v]$, $[c_v]$ and $[k_v]$ are the mass, structural damping, and linear elastic stiffness matrices of the vehicle subsystem, respectively. $\{\delta_v\}$, $\{\dot{\delta}_v\}$ and $\{\ddot{\delta}_v\}$ are the displacement, velocity and acceleration vectors of the vehicle subsystem, respectively. Matrices with subscript b are the corresponding matrices of bridge subsystems. The dynamic responses of the system are calculated based on the separated iterative method and Newmark-β integral method.

3. Results

3.1 Dynamic responses of the bridge

To evaluate the dynamic responses of bridge under the action of wind and train moving load, two conditions are considered and the results are presented in Figures 3 and 4. It can be

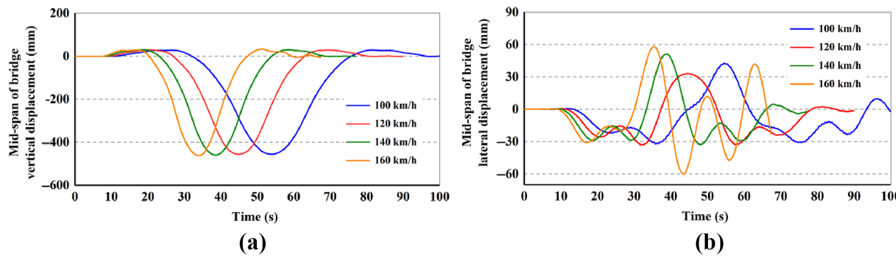

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Figure 3. Bridge responses under different train speeds (a) Vertical displacement (b) Lateral displacement of mid-span of bridge (Mean wind speed = 0 m/s)

observed that due to the low stiffness of the long-span bridge, the vertical and lateral deformations are sizable. It is found in Figure 3 that with the increase of vehicle speed, the extreme value of mid-span lateral displacement (Figure 3(b)) shows the trend of decreasing first and then increasing. While the difference of vertical displacement (Figure 3(a)) is not obvious.

Besides, the lateral deformation of the mid-span increases significantly under the wind load according to Figure 4. The maximum value exceeds 400 mm, and the buffeting force has an obvious effect on the response. The vertical (Figure 4(a)) and lateral deformation (Figure 4(b)) are both reduced with the number of trailers or the load. Especially for lateral deformation, when the number of trailers reduced from 20 to 10, the lateral moving wind load of train on the bridge is less, resulting in an obvious decrease in the lateral deformation. Compared with axle load, the influence of train moving wind load on lateral deformation is more significant.

3.2 Running safety of the express freight vehicle

The running safety indices of vehicles at different positions are shown in Figure 5. The results illustrate that the derailment coefficient and wheel unloading rate of the trailers are larger than those of the locomotive, and the safety of the empty trailer is relatively more sensitive to the wind load owing to the light axle load and larger windward area of car body according to Figure 5(a).

Besides, as shown in Figure 5(b), when the train runs on the windward side railway of the bridge (Figure 1(c)), the wind load has slight influence on the vehicle. Due to the shielding effect of the internal truss and the upper deck of the bridge, the impact of wind load is weakened. The values of safety indices of the leeward side condition are relatively smaller, but the difference is not sizeable, which cannot be distinguished in actual operation.

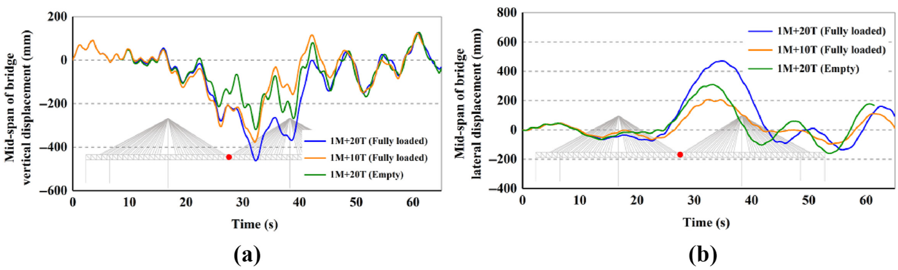

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Figure 4. Bridge responses under different formations (a) Vertical displacement (b) Lateral displacement of mid-span of bridge (Train speed = 160 km/h, Mean wind speed = 20 m/s)

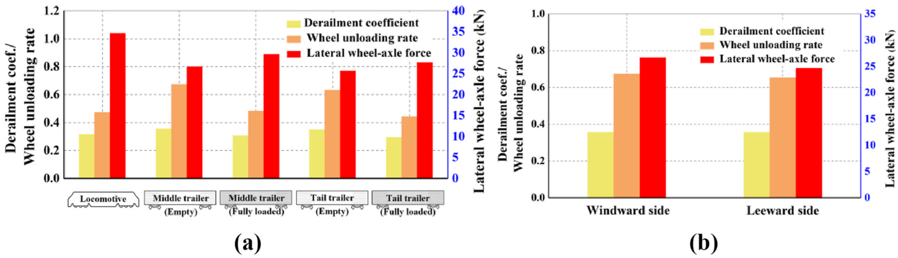

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Figure 5. Dynamic responses of express freight vehicles (a) Different running conditions (b) Positions on the bridge (Train speed = 160 km/h, Mean wind speed = 20 m/s)

Figure 6 presents the effect of train speed and wind speed on the safety indices. The impact between wheel and rail intensifies (Figure 6(c)), and the derailment coefficient (Figure 6(a)) and the wheel unloading rate (Figure 6(b)) increase with train speed. When the wind speed is higher than 10 m/s, with the increment of wind speed, the wheel unloading rate (limit value 0.65) increases significantly under the side force and rolling moment, which exceeds the limit prior to derailment coefficient (limit value 1.0). When the wind speed reaches 30 m/s, the wheel unloading rate is close to 1, which indicates that the situation of derailment occurs.

Based on analysis above, it can be concluded that wind speed is the main influence factor on the running safety. The wind speed limits of different train speeds are calculated according to the wheel unloading rate, which are presented in Figure 7. When

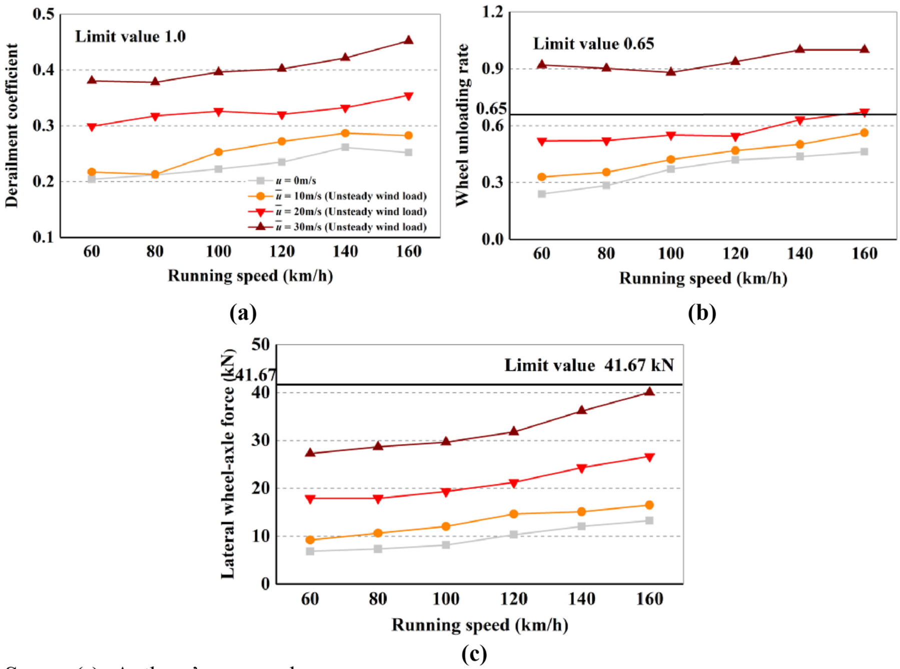

Figure 6.
Effect of wind and train speeds on the safety criteria (a) Derailment coefficient (b) Wheel unloading rate (c) Lateral wheel-axle force

Source(s): Authors' own work

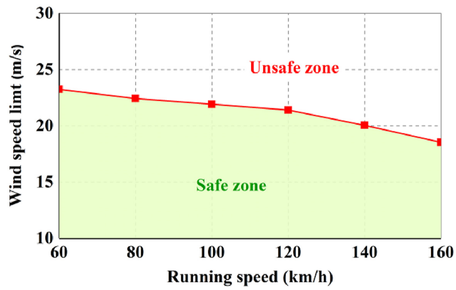

Figure 7.
Diagrams of wind speed limit

Source(s): Authors' own work

the train speed is 60 km/h, the wind speed limit should be 23.24 m/s. However, when the train speed is 160 km/h, the limit reduces to 18.83 m/s. The diagram can be used as a reference to speed limit for express freight trains when running over the long-span bridge.

4. Conclusions and contributions

In this comprehensive study, we delve into the crucial aspect of ensuring the safety of express freight trains traversing a long-span steel truss bridge. To accomplish this, we have formulated a sophisticated dynamic model that captures the intricate interactions between the train and the bridge. By analyzing this model, we have precisely calculated the dynamic responses of both the vehicle and the bridge, ultimately deriving a crucial wind speed limit that ensures safe operation.

The key findings of our research are noteworthy. Firstly, we observed that the empty trailer is particularly susceptible to wind loads compared to other vehicles, with its safety being the most sensitive. Interestingly, the specific location on the bridge where the train is positioned has a relatively minor influence. Secondly, we found in this study that, in comparison to train speed, the impact of wind speed on safety is far more significant. As wind speed intensifies, the wheel unloading rate is increasingly likely to exceed its permissible threshold. When the train runs at the full speed of 160 km/h, the wind speed limit of safe operation reduces to 18.83 m/s. Therefore, when traversing long-span bridges, it is imperative to set the speed of express freight trains at an appropriate level to safeguard operational safety.

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