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Pressure Wave Numerical Simulation of Passenger–Freight Train Passing on Steel Truss Bridges

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ABSTRACT: With the continuous expansion of rail transport capacity and the increasing speeds of freight trains, it has become increasingly common for passenger and freight trains to share the tracks on double-track or high-speed rail sections. To reveal the evolution of pressure wave characteristics during non-uniform-speed encounters between high-speed trains and freight trains on bridges, this study establishes a full-scale computational model of a steel truss flexible arch bridge and the conditions under which a train passes over it, with the bridge model serving solely as an aerodynamic boundary condition. The numerical simulation is based on the three-dimensional compressible unsteady Navier-Stokes equations and the $k-\epsilon$ two-equation turbulence model, combined with sliding mesh technology. The computational domain includes stationary and moving regions with interface data exchange, and the mesh is generated using Poly-Hexcore with a refined boundary layer to ensure y^+ values within acceptable ranges. A systematic grid sensitivity analysis is conducted, and the numerical method is validated against wind tunnel test results for stationary trains, showing good agreement. The results indicate that during the passing of a passenger train and a high-speed freight train, pressure fluctuations occur due to factors such as bogies and vehicle clearances; pressure waves on the passing side are significantly greater than those on the non-passing side, and pressure wave values gradually decrease near the roof measurement points; for freight train cars, the full-wave peak values at the mid-point measurement locations on the passing side exhibit a linear relationship with the square of the speed; for passenger trains, when the freight train's speed exceeds 160 km/h, the full-wave peak values at the central measurement points on the passing side of each car exhibit an approximate exponential increase; during the passing of freight trains, the full-wave peak values at the measurement points on the passing side of the freight train are 49.9%–52.9% higher than those during the passing of passenger-freight trains; when passenger trains pass each other, passenger-freight full-wave peaks are 6.3%–9.9% higher than passenger-passenger peaks. These research findings provide a theoretical basis and data support for the aerodynamic safety of trains passing on mixed-traffic lines, as well as for vehicle body selection and optimized design.

KEYWORDS: High-speed trains; freight trains; steel truss flexible arch bridges; trains passing on the bridge; pressure wave

1 Introduction

With the rapid development of society, trains have become an indispensable means of transportation in people's daily lives. Passenger-freight trains refer to a formation that operates on the same railway line, carrying both passengers and freight. This type of train formation plays a significant role in railway transportation, as it not only improves the utilization rate of railway lines but also meets the transportation

needs of various types of cargo and passengers. However, passenger-freight trains face numerous challenges during operation, one of which is the impact of aerodynamic characteristics. As freight trains accelerate and the composition of passenger-freight trains becomes more complex, different types of rolling stock generate varying aerodynamic effects during operation. For passenger trains, the increased speed of freight trains may lead to intensified lateral vibrations of the car body, which in severe cases could result in damage to the car walls or side windows; For freight trains, the aerodynamic effects increase dramatically due to the impact of passing pressure waves, posing risks to the smooth and safe operation of the train and, in severe cases, potentially leading to derailment. The passing of different trains is illustrated in Fig. 1. Therefore, studying the time-domain characteristics of pressure waves during the passing of passenger-freight trains is of great significance for improving train operational efficiency, reducing energy consumption, and enhancing train stability.



Figure 1: Diagram of different trains passing each other.

Current research on the aerodynamic characteristics of trains primarily involves three methods: track tests, wind tunnel tests, and numerical simulations. Existing studies have shown that when a train's operating speed reaches 200 km/h, and crosswind speeds exceed 30 m/s, there is a high probability of derailment or overturning. Baker et al. [1,2] conducted extensive research on wind tunnel and full-scale vehicle tests to investigate the steady-state and transient aerodynamic forces on various types of trains under crosswind conditions. Suzuki et al. [3] studied the aerodynamic characteristics of typical trains operating on bridges and embankments through wind tunnel tests. Diedrichs et al. [4] used experimental and numerical simulation methods to study the flow field around the ICE2 locomotive while operating on a 6-m-high embankment. Guo et al. [5] used CFD and dynamic meshing techniques to analyse the aerodynamic interactions between high-speed trains and bridges under crosswind conditions, and further analysed the coupled response between the trains and the bridges. Yu et al. [6] investigated the crosswind aerodynamic loads acting on the train body under different wind direction angles, wind speeds, and train speeds. Li et al. [7] investigated the aerodynamic effects generated by high-speed trains passing through twin tunnels, based on the unsteady, viscous, compressible N-S equations and the RNG k-e turbulence model, and utilising a sliding mesh technique. Li et al. [8] studied the effect of the gap length between two-unit trains on aerodynamic drag, using a commercial long-formation high-speed train and a two-unit train as research subjects. Niu et al. [9]

used numerical simulations and field tests to investigate the aerodynamic performance of a multi-unit train pair during open-air operation and when passing each other. Wang et al. [10] through aerodynamic studies of trains passing through windbreaks with different gaps under crosswind conditions, determined the effect of windbreaks with different gaps on the aerodynamic characteristics of trains. Li et al. [11] conducted a comparative analysis of different leading-edge lengths for maglev trains, determining the impact of varying leading-edge lengths on the aerodynamic performance of maglev trains. Ming et al. [12] investigated the aerodynamic behaviour of lorries and trains encountering each other on a bridge under crosswind conditions, based on the unsteady, incompressible N-S equations and the RNG k- ϵ turbulence model. Relevant studies [13–15] indicate that steel truss bridges possess good airflow permeability; however, different truss spacing and arrangement configurations significantly alter the surrounding flow field, potentially inducing severe aerodynamic disturbance effects. Trains passing over steel truss bridges are subjected to asymmetric aerodynamic loads, increasing the risk of derailment. Koç et al. [16,17] proposed a computational method for trains and bridges that significantly reduces computation time compared to the finite element method.

In summary, most research on the aerodynamic pressure wave characteristics of train encounters has focused on high-speed and maglev trains. A small number of studies have examined the pressure waves generated by encounters between conventional passenger trains and express freight trains, while research on the pressure wave characteristics of encounters between high-speed trains and express freight trains is even scarcer. However, due to the significant differences in aerodynamic profiles between high-speed trains and freight trains, sudden changes in pressure waves occur at the moment of passing, posing safety risks to train operations. Therefore, investigating the characteristics of pressure waves during the passing of high-speed trains and freight trains is crucial for developing speed-up strategies for freight trains. Therefore, this study employs numerical simulation methods to investigate the characteristics of pressure waves and the surrounding flow field distribution during the passing of freight trains on bridges with passenger trains at different operating speeds. The aim is to analyze the relationship between pressure waves and speed at different vehicle positions during the passing of passenger-freight trains on bridges at various freight train speeds, thereby providing a reference for improving the operational efficiency and safety of mixed-traffic train operations when increasing the speed of freight trains on bridges.

2 Methodological Framework and Computational Model

2.1 Methodological Framework

To avoid limiting the analysis to a single engineering case, the numerical procedure adopted in this study is formulated as a transferable framework for evaluating transient pressure waves during mixed passenger-freight train passing on bridge structures. The framework consists of seven steps: (1) defining representative mixed-operation scenarios and train-speed combinations; (2) simplifying the train formations according to aerodynamic standards and validated train models; (3) constructing a bridge-included computational domain that preserves the main train and bridge aerodynamic boundaries; (4) solving the three-dimensional compressible unsteady RANS (Reynolds-Averaged Navier-Stokes Equations) equations with an appropriate turbulence closure; (5) using sliding meshes and interface data exchange to reproduce the relative motion of the two trains; (6) conducting mesh sensitivity analysis and validation against available wind-tunnel data; and (7) extracting pressure-wave indicators, including positive peak, negative peak, full-wave peak, and speed-dependent fitting relationships. The required inputs are train geometry, bridge geometry, track spacing, operating speed, boundary conditions, mesh criteria, and validation data. The outputs are pressure time histories, spatial pressure distributions, peak statistics, and empirical speed-response relationships. Therefore, the same framework can be transferred to other passenger-freight combinations by replacing

the geometry and operating parameters while retaining the governing equations, verification procedure, sliding-interface strategy, and pressure-wave indicators.

2.2 Geometric Model

This study is based on China's CRH380A and CRH380B high-speed trains and freight trains. Following CEN (European Committee for Standardization) standards [18,19], the models were simplified to establish full-scale three-car models [20]. These three car sections are designated as Head, Mid, and Tail. In the numerical simulation, the train's bogies and windshield models are retained. The train height is taken as the characteristic height, where the CRH380A has a characteristic height $H = 3.7$ m, with the Head and Mid sections measuring 26.5 and 25 m, respectively, and a train width of 3.4 m, as shown in Fig. 2a. For the CRH380B, the characteristic height $H = 3.9$ m, with the Head and Mid cars measuring 26 and 25 m, respectively, and a train width of 3.3 m, as shown in Fig. 2b. Wen et al. [13] established a model consisting of one locomotive and two freight boxcars. By comparing wind tunnel tests with numerical simulations, the results can be used to analyze the aerodynamic characteristics of long-formation freight trains. Therefore, the freight trains considered in this paper consist of one locomotive and two boxcars, with the locomotive and flatcars measuring 21 and 23 m in length, respectively, and a coupler length of 1 m, consistent with the freight train model in Reference [21]. The distance between the CRH380B and the freight train on the track is 4 m. The bridge geometry model is consistent with Reference [22], with the exception of a simplification to the track, detailed dimensions are not discussed further in this paper.

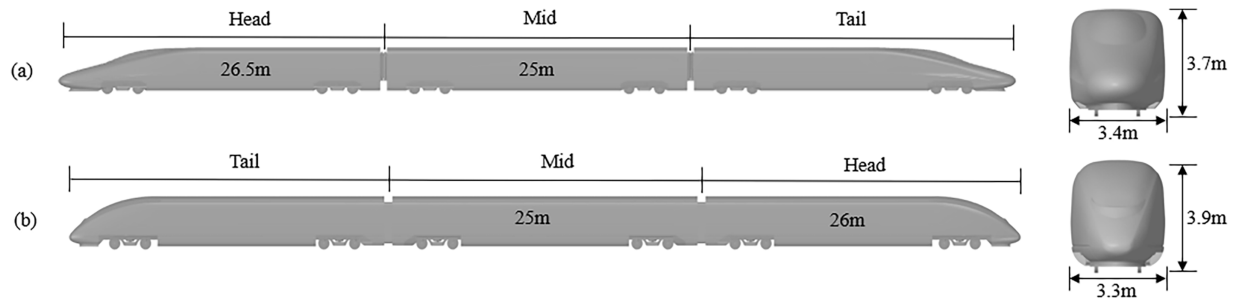


Figure 2: Train geometric models. (a) CRH380A. (b) CRH380B.

2.3 Setting Boundary Conditions

Fig. 3 shows the size of the computational domain for the stationary train. To ensure the accuracy of the solution, a refinement region measuring $104 \text{ m} \times 6 \text{ m} \times 6 \text{ m}$ was established around the train model and designated as "Refinement region." According to standard EN 14067-6:2010, the computational domain is specified as follows: at least 8 characteristic heights upstream and at least 16 characteristic heights downstream. Based on this standard and relevant studies, the minimum distance between the train and the inlet boundary is set to at least 12 characteristic heights, and the minimum distance between the train and the outlet boundary is set to at least 24 characteristic heights. A computational domain that is significantly larger behind the train than in front of it facilitates the development of the train's wake. For cases without crosswind, the surface in front of the train within the computational domain is defined as a velocity inlet; the surface behind the train is defined as a pressure outlet, with a reference pressure of 0 Pa; the bottom surface is defined as a slip wall; and the top and side surfaces are defined as symmetric boundaries. For cases with crosswind, one side surface is defined as a velocity inlet, and the other side surface is defined as a pressure outlet, with a reference pressure of 0 Pa for both. The primary difference between cases with and without crosswind lies in the definition of the side surfaces of the computational domain.

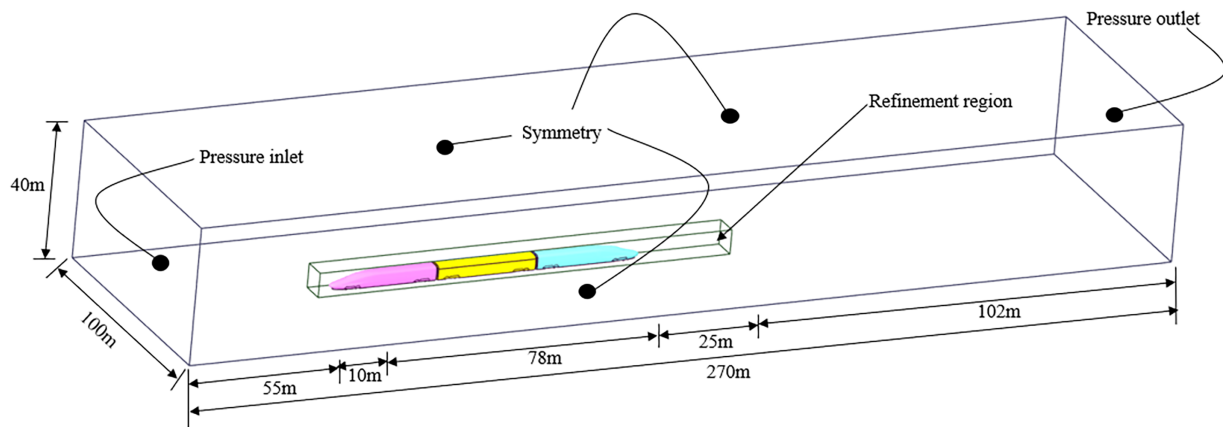


Figure 3: Boundary conditions for a stationary train and domain size.

The calculation domain for the passing of passenger-freight trains on a bridge is shown in Fig. 4. When a passenger train and a freight train pass each other on the bridge at 200 km/h, the Mach number is 0.33, which is greater than 0.3; therefore, the compressibility of air must be taken into account in the study of the pressure wave characteristics during train passing. The boundary conditions for the moving train are set as shown in Fig. 4, with a reference pressure of 0 Pa for the pressure outlet boundary. The steel truss flexible arch bridge is retained in the stationary region of the computational domain to represent the aerodynamic boundary encountered by trains running on the bridge. Because the bridge defines the local flow passage near the train bodies.

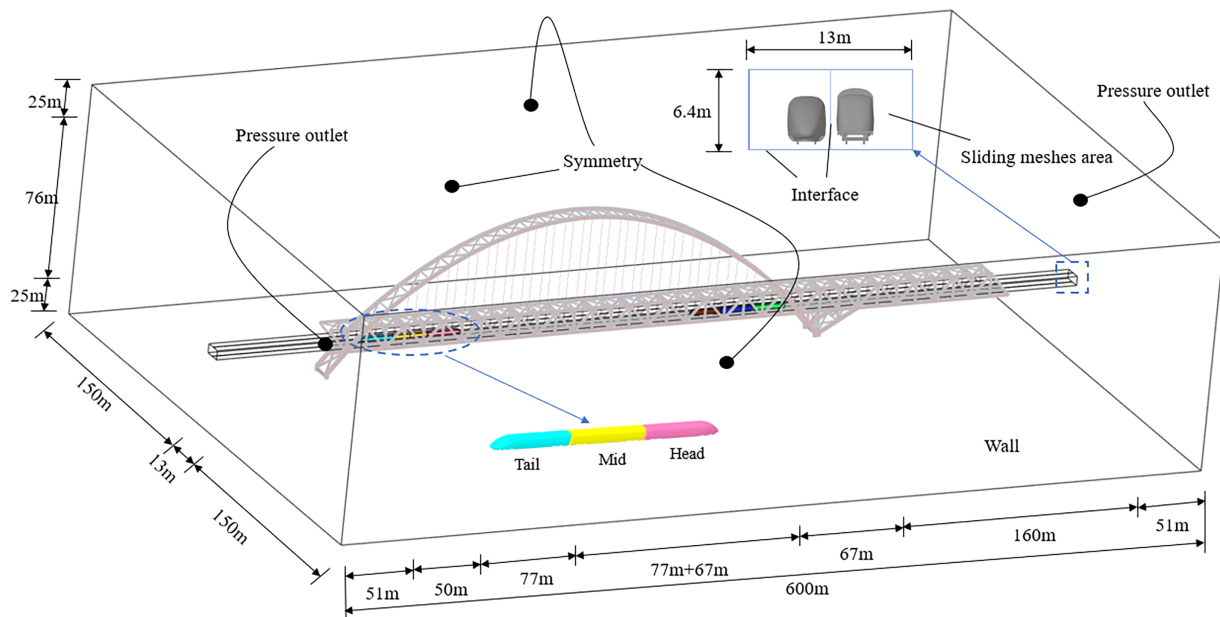


Figure 4: Boundary conditions for passenger-freight trains passing on the bridge and the size of the computational domain.

2.4 Mathematical Computational Model

In RANS methods, the $k-\epsilon$ (k-epsilon) turbulence model is widely used to simulate the aerodynamic characteristics of trains in operation. Although recent studies have indicated that the $k-\epsilon$ turbulence model

has limitations in simulating train aerodynamics, this model remains effective for simulating pressure waves generated during train overtaking in open-air or tunnel environments [11,22]. Therefore, this study employs the RANS k - ϵ turbulence model to simulate the aerodynamic characteristics of trains at rest and during bridge crossings of passenger-freight trains. The specific computational method is as follows:

Fluid control equations employ the concept of time-averaged values, which are expressed as the sum of the pulsating values and the average values of instantaneous flow parameters. Thus, for fluid velocity:

$$\mu_i = \bar{\mu}_i + \mu'_i \quad (1)$$

$\bar{\mu}_i$ is the average fluid velocity; μ'_i is the pulsating fluid velocity.

Similarly, fluid pressure and other parameters can be expressed as follows:

$$\phi_i = \bar{\phi}_i + \phi'_i \quad (2)$$

ϕ represents parameters such as energy, pressure, and material density.

Substituting variables such as fluid energy, velocity, pressure, and density into the continuity equation yields the continuity equation for time-averaged quantities. Similarly, substituting these variables into the momentum equation yields the momentum equation for time-averaged quantities:

$$\frac{\partial \bar{\mu}}{\partial x} + \frac{\partial \bar{v}}{\partial y} + \frac{\partial \bar{\omega}}{\partial z} = 0 \quad (3)$$

$$\frac{\partial (\rho \bar{\mu}_i)}{\partial t} + \frac{\partial (\rho \bar{\mu}_i \bar{\mu}_j)}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial \bar{\mu}_i}{\partial x_j} - \rho \overline{\mu'_i \mu'_j} \right) \quad (4)$$

By applying assumptions to the variable $-\rho \overline{\mu'_i \mu'_j}$ in the above equations, the number of unknowns is made equal to the number of equations, thereby enabling the system of equations to be solved using an iterative numerical method. This study employs the Boussinesq assumptions.

The turbulent kinetic energy k is the kinetic energy associated with the turbulent pulsating velocity, and its transport equation is:

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho u_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho \epsilon \quad (5)$$

$$P_k = \mu_t \left(\frac{\partial \mu_i}{\partial x_j} + \frac{\partial \mu_j}{\partial x_i} \right) \frac{\partial \mu_i}{\partial x_j} - \frac{2}{3} \rho k \frac{\partial \mu_k}{\partial x_k} \quad (6)$$

ρ is the density of air, taken as 1.225 kg/m^3 ; u_j represents the velocity component (where $j = 1, 2, 3$ corresponds to the x, y , and z directions); μ_t is the turbulent viscosity; σ_k is the turbulent Prandtl number for turbulent kinetic energy k , and is set to 1.0; P_k is the turbulent kinetic energy generation term, representing the contribution of the mean flow to the turbulent kinetic energy; ϵ is the turbulent dissipation rate.

The turbulent dissipation rate ϵ represents the rate at which turbulent energy is dissipated as heat; its transport equation is:

$$\frac{\partial (\rho \epsilon)}{\partial t} + \frac{\partial (\rho \mu_j \epsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{\epsilon 1} \frac{\epsilon}{k} P_k - C_{\epsilon 2} \rho \frac{\epsilon^2}{k} \quad (7)$$

σ_ε denotes the turbulent Prandtl number for the turbulent dissipation rate ε , and is set to 1.3; $C_{\varepsilon 1}$ is set to 1.44; $C_{\varepsilon 2}$ is set to 1.92.

The turbulent viscosity μ_t is calculated using k and ε :

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (8)$$

C_μ is set to 0.09.

Given the initial values of turbulent kinetic energy k and turbulent dissipation rate ε , these are typically calculated using the turbulent intensity I and the characteristic length scale L :

$$k = \frac{3}{2} (U_m I)^2, \quad \varepsilon = C_\mu^{3/4} \frac{k^{3/2}}{L} \quad (9)$$

The turbulence intensity I is 1%.

2.5 Generation and Validation of Grids for Stationary Trains

For the stationary train, this study employed Fluent meshing to generate a mesh primarily based on Poly-Hexcore for the full-scale CRH380A train model. This mesh type has been widely used in numerical simulations of train aerodynamics. The numerical simulation model used a full-scale model, while the wind tunnel test model used a 1/8 scale model. The numerical simulation employed the same boundary conditions as the wind tunnel tests, with an inflow velocity of 60 m/s. Based on the above simulation, three meshes were generated for the stationary train, named mesh 1, mesh 2, and mesh 3. The number of mesh elements was 30.79 million, 24.83 million, and 17.64 million, respectively. The train boundary layer was consistent across all three meshes, with the first layer height set at 3 mm, a total of 8 layers, and a growth ratio of 1.2. The boundary layer configuration ensured that the y^+ values on the train surface ranged from approximately 20 to 140. To meet the accuracy requirements of the numerical simulation, the mesh around the train was refined using Fluent's adaptive meshing technology based on preliminary calculation results. Detailed mesh information is shown in [Table 1](#).

Table 1: Mesh sizes (mm) for different regions.

Mesh	Train Profile and Bogie Area	Other Parts of the Train	Refinement Region	Outer Surface
1	10.09~20.18	20.18~80.72	161.44	2000
2	12.11~24.22	24.22~96.88	193.76	2000
3	14.53~29.06	29.06~116.24	232.48	2000

According to the CEN standard [19], the aerodynamic coefficient and pressure coefficient are defined as follows:

$$C_d = \frac{F}{0.5 \rho U_m^2 A} \quad (10)$$

$$C_p = \frac{P}{0.5 \rho U_m^2} \quad (11)$$

F represents the average aerodynamic force of the train, P represents the average static pressure of the train; C_d is the average drag coefficient, C_p is the average pressure coefficient; U_m is the wind speed of 60 m/s; A is the reference area of the train in the direction of travel, which is 10.8 m^2 . These parameters are consistent with the findings in [8].

In this numerical simulation study, convergence is determined based on the aerodynamic convergence of the train, rather than the system's default residual criterion. According to previous research [10], setting the number of steps to approximately 3000 typically keeps the residual within the range of 10^{-3} to 10^{-4} . In this study, the number of steps was set to 4500, with each time step lasting 0.002 s and 30 iterations performed per time step. At the same time, the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm and a second-order discretization method were employed to obtain the train flow field and pressure. Given that the flow field around the train is in a turbulent state, to facilitate the comparison and analysis of the calculated train forces, pressures, and other parameters, this paper adopts the dimensionless time-averaged values of the periodic fluctuation parameters used in the references by Hemida and Krajnović [23], which are calculated using Eqs. (10) and (11).

Based on the above parameters, if the aerodynamic characteristics of the trains obtained from this numerical simulation study are similar to the results of wind tunnel tests, this indicates that the numerical simulation method used in this paper is accurate and can be applied to future studies on the aerodynamic characteristics of passenger-freight trains passing each other on the bridge.

A comparison of the numerical simulation results with wind tunnel test results is shown in Fig. 5 and Table 2. For the head car, the maximum error in the drag coefficient compared to the test results was 8.33%, occurring in Mesh 3; for the mid car, the maximum error was -10.11% , occurring in Mesh 3; and for the tail car, the maximum error was -5.45% , occurring in Mesh 3. This indicates that the mesh configuration and computational methods employed in this study can accurately obtain numerical simulation results. Based on the above analysis, the mesh configuration of Mesh 2 satisfies the requirements for subsequent numerical simulations; however, computational accuracy is positively correlated with the number of mesh elements, and an excessive number of elements significantly reduces computational efficiency. Therefore, the Mesh 2 configuration and computational methods will be adopted for subsequent studies on the aerodynamic characteristics of mixed passenger-freight trains passing on the bridge.

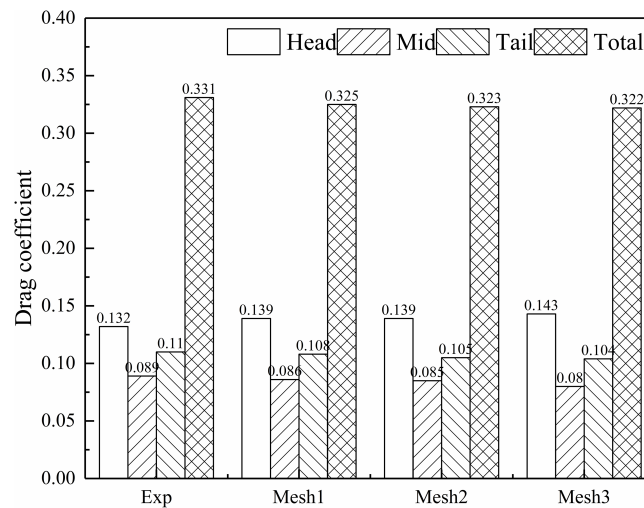


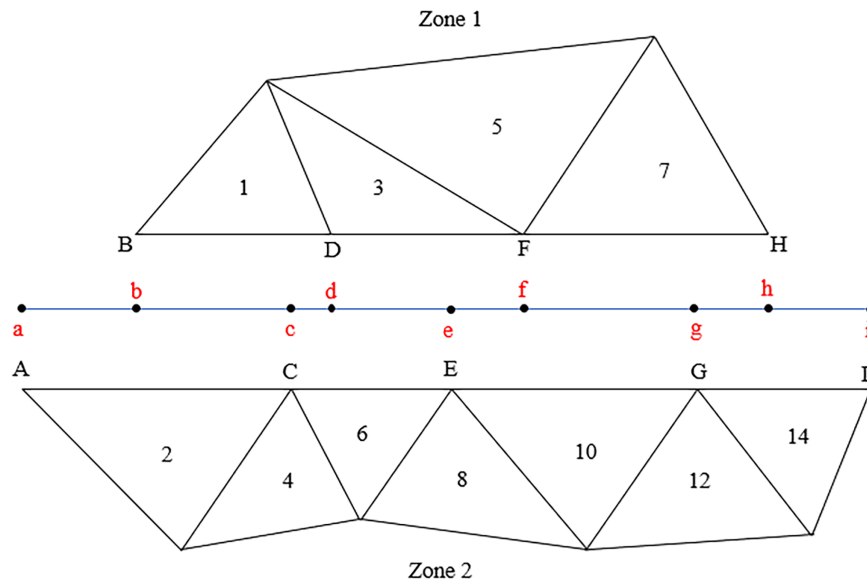
Figure 5: Comparison of drag coefficients for the CRH380A train.

Table 2: Average aerodynamic drag coefficients for trains.

	Head	Mid	Tail	Total
Exp	0.132	0.089	0.11	0.331
Mesh 1	0.139	0.086	0.108	0.325
Percentage	5.30%	-3.37%	-1.82%	-1.81%
Mesh 2	0.139	0.085	0.105	0.323
Percentage	5.30%	-4.49%	-4.55%	-2.42%
Mesh 3	0.143	0.08	0.104	0.322
Percentage	8.33%	-10.11%	-5.45%	-2.72%

2.6 Grid Generation and Solution Settings for Passenger-Freight Mixed-Traffic Train Passes on Bridges

To simulate the relative motion of passenger-freight trains on the bridge, the sliding mesh technique in Fluent was employed [24]. This technique enables the simulation of mixed-traffic train passing maneuvers without generating redundant mesh elements, thereby effectively improving computational efficiency. The entire calculation domain for mixed-traffic train passing on bridges was divided into two parts: a stationary region and a moving region. An “Interface” is established between the stationary and moving zones to facilitate data exchange. The specific process of node information exchange between sliding meshes is shown in Fig. 6, where Zone 1 and Zone 2 represent the two zones requiring data exchange, and B-D-F-H and A-C-E-G-I are the overlapping mesh sections between the two zones. Before iterating the calculation for each time step, an information exchange surface is generated between adjacent calculation zones, namely a-b-c-d-e-f-g-i in the figure. For example, to calculate the node information of element 3 in Zone 1, the node information of the intersection surfaces d, e, and f is required, and this information is provided by elements 6, 8, and 10 in Zone 2. Similarly, to compute the node information for cell 10 in Zone 2, the node information at the interface faces e, f, and g is required, and this information is provided by cells 3, 5, and 7 in Zone 1.

**Figure 6:** Schematic diagram of information exchange in a sliding mesh.

Separate moving mesh regions were established for passenger and freight trains, each with a height of 6.4 m and a width of 6.5 m. The moving meshes of the two trains are adjacent, and “Interface” data is set at the adjacent surfaces. Related literature [10,18,24] has studied the aerodynamic characteristics of high-speed train encounters using the same configuration, and the results indicate that this numerical simulation method shows a high degree of agreement with experimental results. In this study, a sliding mesh technique based on the concept of relative zone motion is employed. The computational domain is partitioned into stationary and moving sub-domains, which exchange data via a non-conformal internal sliding interface. As the train advances, all mesh elements in the moving sub-domain surrounding the train translate rigidly with the train, maintaining their topology and geometry unchanged, while the mesh in the outer stationary region remains fixed. Rather than using mesh deformation or re-meshing, the flow communication between the two sub-domains is accomplished by a flux-conservative interpolation at the sliding interface at every time step, which updates the nodal connectivity across the interface and thus achieves coupled spatio-temporal solution of the flow field under relative movement.

Previous studies have shown that the first layer of mesh near the wall surface significantly affects the accuracy of numerical simulations [21,25]. In this study, the thickness of the first mesh layer for the CRH380B train was set to 3 mm, the boundary layer growth rate has been set at 1.2 times the standard value, resulting in a total of eight layers of the wall boundary layer. The surface mesh and wall boundary layer settings for the CRH380B train were consistent with those of the stationary CRH380A train (Mesh 2). Test calculations using this mesh showed that the y^+ values for the CRH380B train ranged from 20 to 160, as shown in Fig. 7. The surface mesh for the freight train ranged from 13.34 to 40.02 mm. The thickness of the first wall layer is set to 4 mm, the boundary layer growth rate has been set at 1.2 times the standard value, resulting in a total of 8 wall boundary layers. Test calculations using this mesh indicate that the y^+ values for the freight train range from 50 to 220. The surface mesh for the steel truss flexible arch bridge ranges from 87.9 to 439.5 mm. The thickness of the first wall layer is set to 4 mm, the boundary layer growth rate has been set at 1.2 times the standard value, resulting in a total of 8 wall boundary layers. Test calculations using this mesh indicate that the y^+ values for the bridge range from 70 to 240, while the outer surface mesh for the flow field is 1000 mm. The surface meshes for the mixed passenger-freight train and the bridge are shown in Fig. 8. Fluent’s adaptive meshing technology was similarly used to adjust the meshes around the train and the bridge.

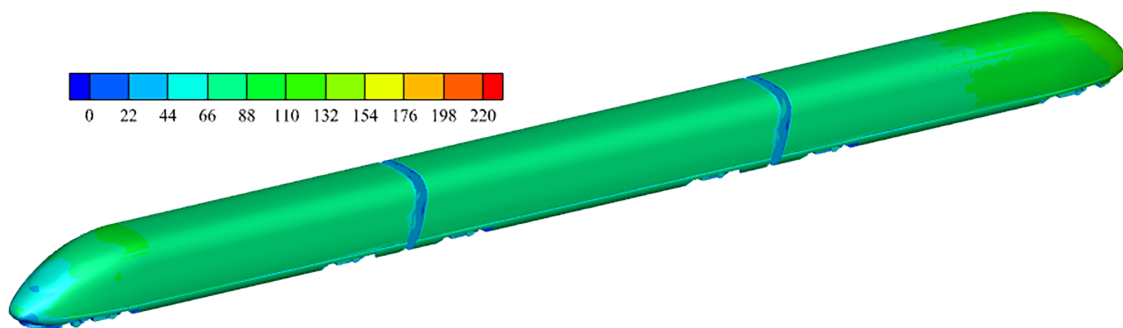


Figure 7: Y^+ values for the CRH380B train.

Based on the above grid information, the number of grid cells in the stationary area is 18.79 million, in the CRH380B train movement area is 9.41 million, and in the express freight train movement area is 7.82 million. The grid details are shown in Fig. 8. Additionally, for the study of the aerodynamic characteristics of passenger-freight trains passing on the bridge, each time step was set to 0.002 s, with 30 iterations per

time step. The SIMPLE algorithm and a second-order discretization method were used to obtain the train flow field and pressure.

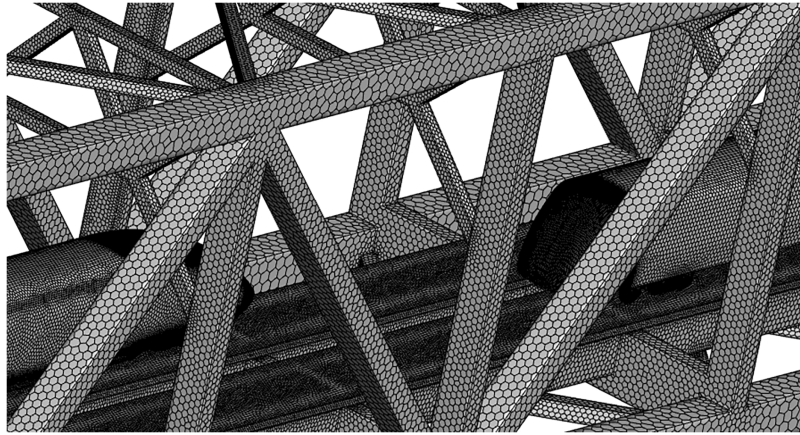


Figure 8: Passenger-freight combined train and bridge deck grid.

3 Flow Field Characteristics around Passenger-Freight Combined Trains during Passing Maneuvers

Based on the methodological framework outlined above, the specific results are as follows: As shown in Fig. 9, when a high-speed train and a freight train pass each other at a speed of 200 km/h, the pressure distribution on the passing side of the train is significantly greater than that on the non-passing side. Large areas of negative pressure exist at the top and bottom of the non-passing side of the train; in contrast to the non-passing side, there are virtually no areas of positive pressure on the passing side, and the pressure values at the midpoint of the passing side are higher than those at the top and bottom. Clearly, when trains pass each other, the car bodies will move closer together due to the influence of the negative pressure zones and the impact caused by the absence of positive pressure zones.

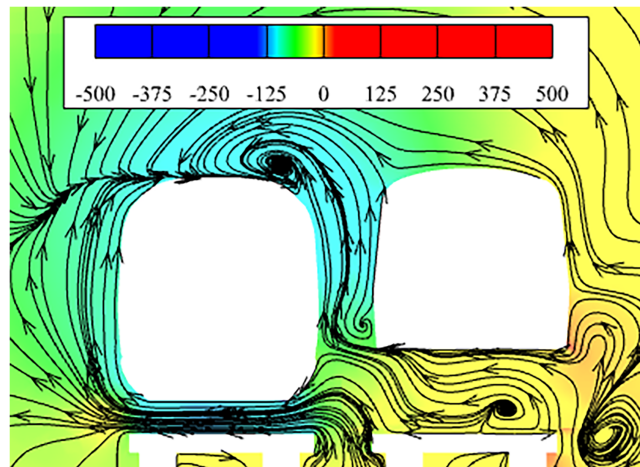


Figure 9: Pressure distribution diagram for passenger-freight mixed-traffic train passing (Pa).

4 Analysis of the Aerodynamic Characteristics of Passenger-Freight Trains during Bridge Passing Maneuvers

4.1 Layout of Pressure Monitoring Points on Passenger-Freight Shared Trains

During train passing maneuvers, the impact of instantaneous pressure waves can, in severe cases, cause damage to side windows and other components, resulting in injury to passengers and damage to the freight. Therefore, to study pressure fluctuations during the passing of passenger-freight trains and to determine the relationship between pressure waves and specific locations on the train body, pressure monitoring points were installed on the bodies of high-speed trains and freight trains. The monitoring points, aligned with the direction of travel, were positioned at the center of the bogies in each car. For high-speed trains, the monitoring points on the lead car are designated as H1–H8, where H1 is located at the mid-height of the passing side, H3 is at the center of the train roof, H5 is at the mid-height of the non-passing side, and H7 is at the center of the train bottom. Similarly, the monitoring points on intermediate cars and the trailing car are designated as M1–M8 and T1–T8, respectively, with the numbering corresponding to the positions on the lead car. For express freight trains, the measurement points on the locomotive are numbered J1–J8, those on the middle flatcars are numbered P1–P8, and those on the rear flatcars are numbered W1–W8, with the numbering indicating positions consistent with those of high-speed trains. The arrangement of lateral pressure measurement points for mixed passenger-freight trains is shown in Fig. 10.



Figure 10: Schematic diagram of surface pressure measurement points on passenger and freight trains.

4.2 Pressure Wave Characteristics of Train Passings on Bridges and off-Bridge Passings

To compare the interaction between trains on the bridge and when there is no bridge, this section uses a computational domain that aligns with the bridge boundary, with the ground replacing the bridge deck. Taking passenger trains traveling at 200 km/h and freight trains traveling at 160 km/h as examples, the time history of the pressure wave at point J1 is compared. The results are shown in Fig. 11.

As shown in Fig. 11, there is a significant difference in the pressure wave deviation between trains passing on the ground and those passing on the bridge. The primary reason is that ground train passing is affected by the proximity to the ground, which causes changes in the fluid flow around the train; this is also the main reason why the pressure wave of a ground train is larger than that of a train on the bridge. Based on this, the bridge discussed in this paper is a specific bridge selected as the boundary condition for train crossings on the bridge. The paper compares and analyzes the pressure wave characteristics of high-speed trains and freight trains crossing on the bridge at different freight train speeds.

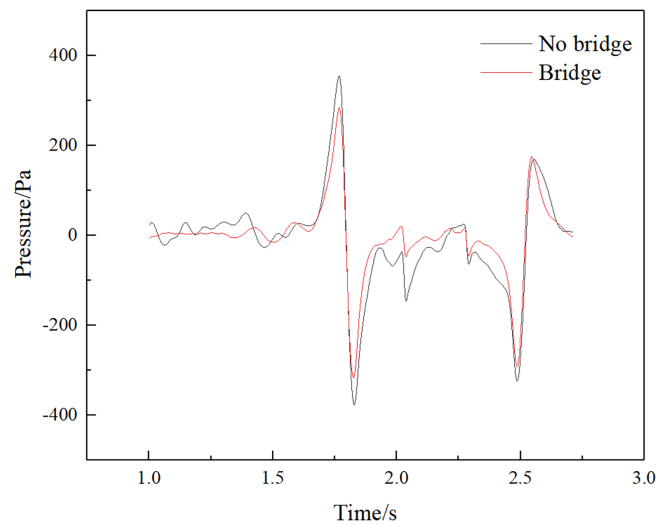


Figure 11: Pressure wave time histories at junction J1 for trains crossing the bridge and those without the bridge.

4.3 Surface Pressure Wave Characteristics of Passenger and Freight Trains during Passing Maneuvers

Freight trains in operation cause significant disturbances in the surrounding flow field; particularly during train passing maneuvers, air compression intensifies, resulting in alternating positive and negative pressure shock waves forming within an extremely short period of time—known as transient passing pressure waves. Fig. 12 shows the surface pressure distribution on the freight train at different passing times, with both the CRH380B high-speed train and the freight train traveling at a passing speed of 200 km/h, using the high-speed train as a reference.

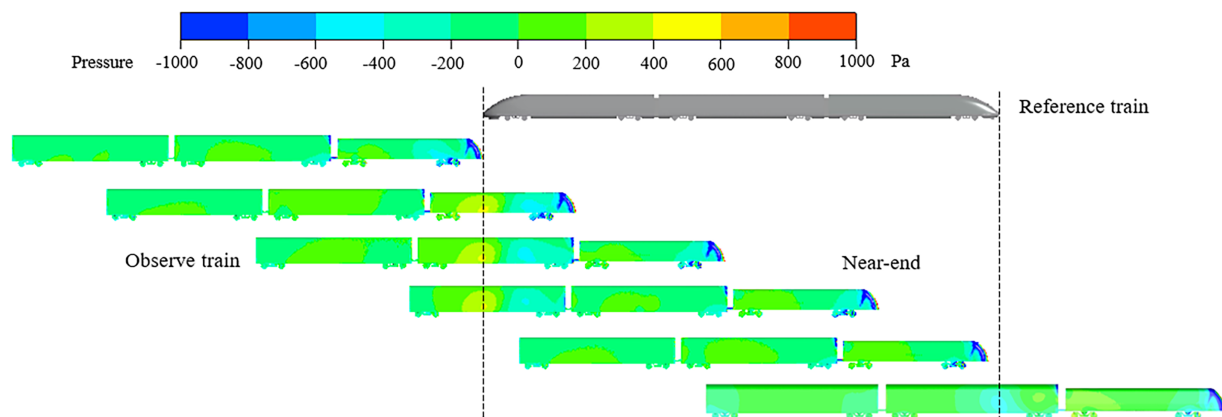


Figure 12: Surface pressure distribution during a 200 km/h passing maneuver between passenger and freight trains.

As shown in Fig. 12, before a high-speed train and a freight train pass each other, the front ends of both trains face the direction of the oncoming airflow. The train nose acts as a positive pressure zone, causing the fluid to move rapidly outward from the nose. As the flow reaches the side of the locomotive, the positive pressure gradually transitions to negative pressure. When the airflow passes over the locomotive body, the negative pressure gradually decreases on the side surface due to the blunt shape and curvature changes of the freight train. As the trains are about to pass each other, an initial pressure wave begins to form, and the

pressure at the locomotive's nose increases significantly. As the freight train moves forward, a large positive-pressure zone forms on the side of the observation train facing the passing train, as indicated by the dashed line in Fig. 12. When the reference train reaches this position, the positive pressure peaks. Influenced by the negative pressure zone created by the reference train's streamlined shape, the positive pressure rapidly transitions to negative pressure, reaching a negative-pressure peak. As the reference train moves forward, negative pressure stabilizes at all locations except for the gaps between cars, where pressure differentials persist. When the reference train reaches the rear of the observation train, the pressure wave on the passing side of the train body transitions from negative to positive, creating an alternation between negative and positive pressure. To further investigate the patterns of pressure wave changes at different locations on high-speed freight trains, the cross-section at the 1/2 bogie spacing of the locomotive and intermediate measurement points on each car were selected for analysis.

Fig. 13 shows the variation in surface pressure at monitoring points during the 200 km/h passing maneuver of a passenger and freight train. As shown in the figure, when the lead locomotive of the high-speed train passes through the monitoring section, a positive pressure peak is first generated, followed by a sharp drop in pressure that forms a negative pressure peak. When the rear car passes through the monitoring section, a negative pressure peak is first generated, followed by a sharp increase in pressure that forms a positive pressure peak. Fig. 13a indicates that there are significant differences in pressure wave amplitudes among different monitoring points at the same cross-section of the freight locomotive; the pressure wave amplitude on the side where the trains pass each other is much greater than that on the opposite side. Since freight locomotives have a greater ground clearance than high-speed trains, when a high-speed train passes a locomotive, the nose of the high-speed train is closer to the J8 monitoring point on the locomotive. Consequently, the J8 monitoring point exhibits the highest positive pressure amplitude, followed by the J1 monitoring point. Due to the dissipation of fluid kinetic energy caused by air viscosity, the pressure wave amplitude at the J7 monitoring point under the train is greater than that at J3. The data for each monitoring point are shown in Table 3. Fig. 13b further compares the pressure wave curves at the central monitoring point on the side where the freight locomotive and boxcar pass each other. The pressure wave trends for the locomotive and boxcar are largely consistent, both exhibiting two abrupt changes. During the passing of passenger and freight trains, the airflow is affected by the bogies and wind deflectors, causing significant fluctuations in the pressure waves. A comparison between the P train and the W train reveals that the amplitude of the pressure wave at the front of the P train is greater than that of the W train. However, as the high-speed train is about to pass the W train, the flow field changes due to the W train's blunt exterior, resulting in a greater negative pressure at the W train compared to the P train, while the positive pressure remains largely consistent.

As shown in Table 3, the full-wave peak pressures of the head wave are ranked from highest to lowest as J1, J8, J2, J7, J3, J6, J4, and J5. The full-wave peak pressures of the tail wave follow the same order as those of the head wave. The pressure amplitudes at the three measurement points on the train's passing side (J1, J8, and J2) are significantly higher than those at other locations, exhibiting characteristics of high pressure and strong fluctuations. The full-wave peak pressure at measurement point J1 is 648 Pa, the highest value among all measurement points, indicating the simultaneous presence of extremely strong positive pressure impact and negative pressure suction effects under the influence of the head wave on the passing side. At measurement point J7, the positive wave peak is 178 Pa and the full-wave peak is 270 Pa, far higher than the 59 and 146 Pa at J3, indicating that the intensity of the aerodynamic impact from the head wave on the bottom of the train is significantly higher than that on the top. During the tail wave phase, the negative wave peak values at measurement points J1 and J8 were -280 and -282 Pa, respectively, significantly higher than the positive wave peak values of 178 and 102 Pa. This indicates that the tail wave on the train's passing

side is dominated by a negative pressure suction effect, with full-wave peak values reaching 458 and 384 Pa, respectively, remaining at a relatively high pressure level. At measurement point J7, the full-wave peak was 141 Pa, 1.53 times that of J3; the positive wave peak of 109 Pa and the negative wave peak of -32 Pa were both significantly higher than the 26 and -66 Pa recorded at the top measurement points. The three monitoring points on the non-passing side of the train (J4, J5, J6) exhibited weaker fluctuation amplitudes during both the head and tail wave phases, indicating that the non-passing side monitoring points were subject to weaker aerodynamic disturbances from the train passing. Combined with Table 3, it can be seen that monitoring point J1 has the highest full-wave peak value; therefore, the central observation points on the passing side of each car were selected for subsequent research.

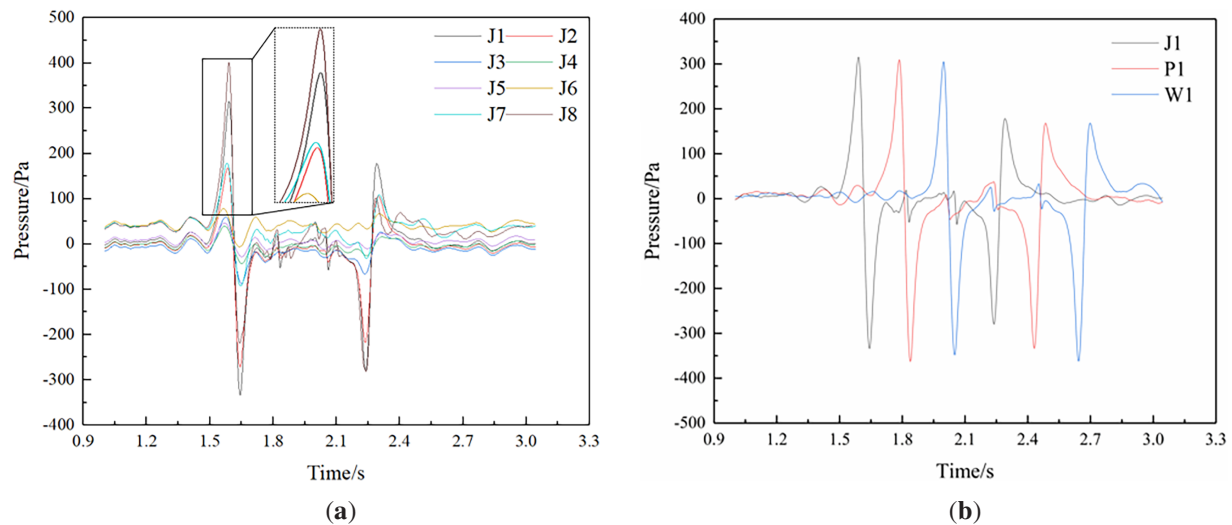


Figure 13: Variation in surface pressure measurement points on a freight train during a 200 km/h passing maneuver with a passenger-freight train. (a) Pressure distribution map for car J. (b) Pressure map of mid-section measurement points.

Table 3: Pressure wave amplitude at measurement points on the same cross-section of Car J.

Monitoring Station	Head Wave/Pa			Tail Wave/Pa		
	Positive Value	Negative Value	Full-Wave Peak	Positive Value	Negative Value	Full-Wave Peak
J1	315	-333	648	178	-280	458
J2	168	-271	439	106	-217	323
J3	59	-87	146	26	-66	92
J4	39	-43	82	16	-26	42
J5	46	-28	74	24	-10	34
J6	78	-6	84	67	-2	69
J7	178	-92	270	109	-32	141
J8	401	-219	620	102	-282	384

Due to factors such as track speed and train safety, priority is given to ensuring the safe operation of high-speed trains, while there is room for increasing the speed of express freight trains. Therefore, high-speed trains operate at the speed of 200 km/h. This study analyzes the aerodynamic effects of freight trains operating at speeds of 120, 140, 160, 180, and 200 km/h when passing high-speed trains.

Fig. 14 shows the pressure changes at the central monitoring points on the side of the freight train (J1, P1, W1) when it passes a high-speed train traveling at 200 km/h and the freight train at various speeds (120, 140, 160, 180, and 200 km/h). As shown in the figure, the pressure fluctuation patterns on the high-speed train's body surface are consistent when the freight train passes at different speeds. As the freight train's speed increases, the amplitude of pressure waves at the body monitoring points increases significantly. The pressure amplitude values at each monitoring point are shown in Tables 4–6.

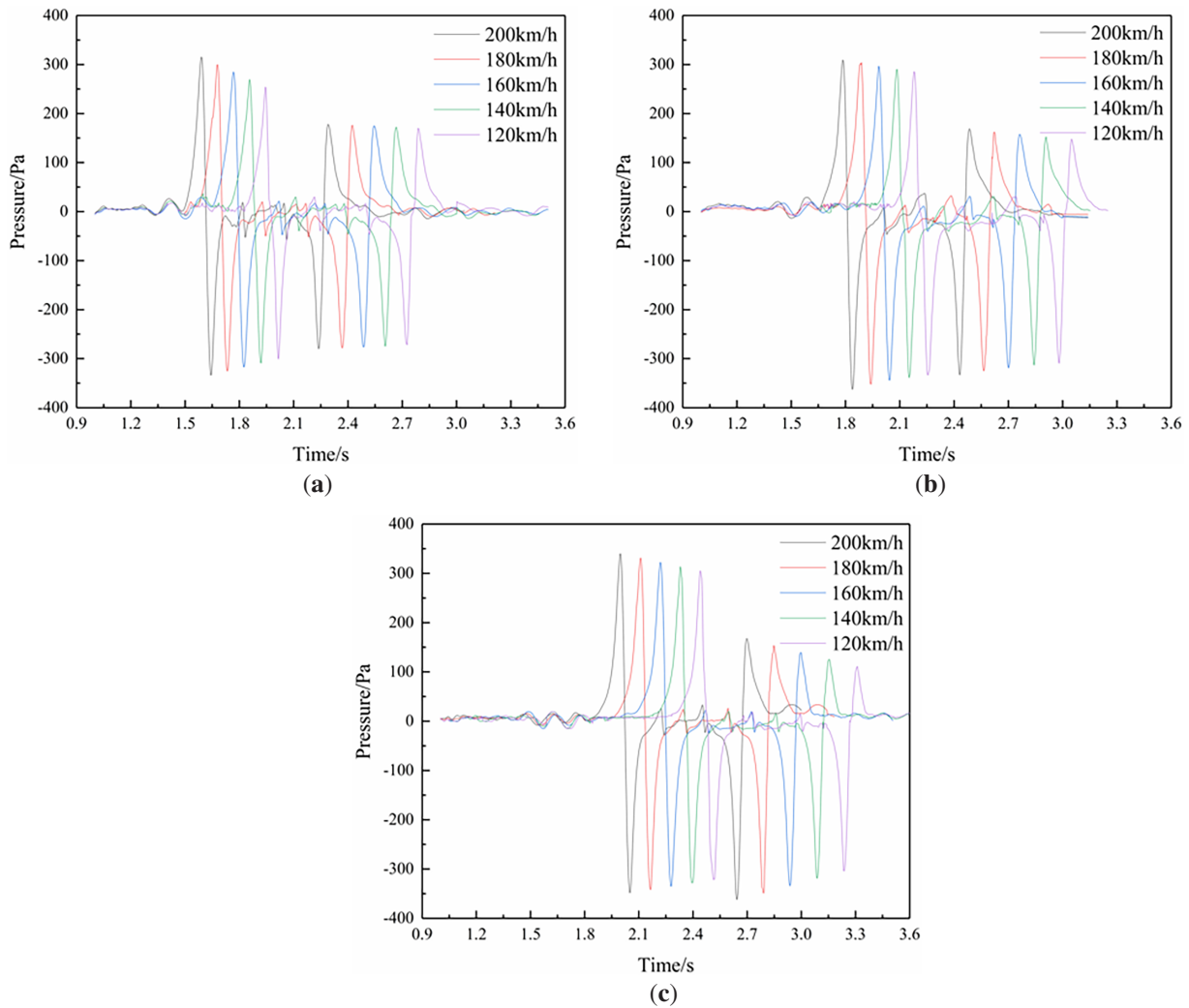


Figure 14: Pressure variation patterns at surface measurement points for freight trains at different passing speeds. (a) Pressure variation at measurement point J1. (b) Pressure variation at measurement point P1. (c) Pressure variation at measurement point W1.

Table 4: Pressure wave amplitude at measuring point J1 for freight trains passing at different speeds.

Passing Speed of Freight Trains (km/h)	Head Wave/Pa			Tail Wave/Pa		
	Positive Value	Negative Value	Full-Wave Peak	Positive Value	Negative Value	Full-Wave Peak
120	254	−300	554	170	−272	442
140	269	−309	578	173	−275	448
160	285	−317	602	175	−276	451
180	300	−325	625	176	−277	453
200	315	−333	648	178	−280	458

Table 5: Pressure wave amplitude at measuring point P1 for freight trains passing at different speeds.

Passing Speed of Freight Trains (km/h)	Head Wave/Pa			Tail Wave/Pa		
	Positive Value	Negative Value	Full-Wave Peak	Positive Value	Negative Value	Full-Wave Peak
120	285	−333	618	148	−309	457
140	290	−338	628	152	−313	465
160	296	−344	640	158	−319	477
180	302	−352	654	162	−325	487
200	309	−363	672	169	−333	502

Table 6: Pressure wave amplitude at measuring point W1 for freight trains passing at different speeds.

Passing Speed of Freight Trains (km/h)	Head Wave/Pa			Tail Wave/Pa		
	Positive Value	Negative Value	Full-Wave Peak	Positive Value	Negative Value	Full-Wave Peak
120	305	−322	627	111	−304	415
140	314	−327	641	125	−319	444
160	322	−335	657	139	−334	473
180	331	−342	673	154	−349	503
200	340	−348	688	168	−362	530

Table 4 shows that the positive peak value of the head wave at monitoring point J1 increases linearly as the speed of oncoming trains rises. At 120 km/h, the positive wave peak value is 254 Pa; by 200 km/h, it increases to 315 Pa. Within the 80 km/h speed range, the increase reaches 61 Pa, with the positive wave peak value rising by 7.6 Pa for every 10 km/h increase in speed. This indicates that higher speeds significantly enhance the positive pressure effect at the front of the train; The negative peak value of the head wave also decreases continuously as speed increases (absolute value increases), reaching a negative peak of −300 Pa at 120 km/h and dropping to −333 Pa at 200 km/h—an increase of 33 Pa in absolute value. On average, the absolute value of the negative peak increases by 4.1 Pa for every 10 km/h increase in speed, reflecting that the

intensity of the negative pressure zone at the front of the train continues to strengthen as speed increases. The positive pressure peak of the wake shows a continuous increase with rising passing speed: it is 170 Pa at 120 km/h and rises to 178 Pa at 200 km/h, with an increase of 8 Pa over the 80 km/h range, averaging 1.0 Pa per 10 km/h. This indicates that the sensitivity of the positive pressure effect at the train's rear to speed is lower than that at the front; the peak value of the negative tail wave exhibits a slight and stable increase with speed, reaching -272 Pa at 120 km/h and -280 Pa at 200 km/h, with an absolute increase of only 8 Pa; with the absolute value of the negative peak increasing by 1.0 Pa for every 10 km/h, a change far smaller than that of the head wave, indicating that the intensity of the negative pressure zone at the train's rear is relatively less affected by speed. At the same speed, the positive peak value of the tail wave is significantly lower than that of the head wave, and the difference between the two continues to widen as speed increases (the difference is 84 Pa at 120 km/h and 137 Pa at 200 km/h). Overall, during a passing maneuver, the amplitude of positive pressure fluctuations at the train's tail wave is much smaller than that at the head wave, while the amplitude of negative pressure fluctuations at the head wave is slightly higher than that at the tail wave; increasing speed further exacerbates the differences in pressure characteristics between the head and tail wave. Fitting the full-wave peak data for the head and tail waves in Table 4 yields Eqs. (12) and (13), which show that the full-wave peak (y) of surface pressure waves for freight and high-speed trains at different speeds is linearly related to the square of the train speed (v^2 , m/s).

$$p_{head} = 0.0471v^2 + 505.36 \quad R^2 = 0.993 \quad (12)$$

$$p_{tail} = 0.0080v^2 + 433.64 \quad R^2 = 0.994 \quad (13)$$

Table 5 shows that the positive peak value, negative peak value, and full-wave peak value of the P1 monitoring point's wave all exhibit a monotonically increasing trend as the passing speed increases. Specifically, the positive peak value increased from 285 Pa at 120 km/h to 309 Pa at 200 km/h, a rise of 24 Pa; the negative peak value increased from -333 to -363 Pa, an absolute increase of 30 Pa; the full-wave peak value increased from 618 to 672 Pa, an increase of 54 Pa. Overall, the data exhibits an approximately linear growth pattern, indicating that increased passing speeds significantly intensify the aerodynamic impact effect at the head of the train. The pressure of the tail wave also shows a continuous increase with rising passing speeds, though the overall rate of increase is lower than that of the head wave. The positive wave peak value increased from 148 to 169 Pa, an increase of 21 Pa; the negative wave peak decreased from -309 to -333 Pa, with an absolute increase of 24 Pa; the full-wave peak increased from 457 to 502 Pa, an increase of 45 Pa, with the growth rate of the full-wave peak being slightly lower than that of the head wave, reflecting the lower sensitivity of the aerodynamic load at the train's tail wave to changes in speed; at the same passing speed, the positive peak value, absolute value of the negative peak, and full-wave peak value of the head wave were all higher than those of the tail wave. The full-wave peak value of the head wave was 161–170 Pa higher than that of the tail wave, indicating that the aerodynamic impact load on the head of the train during the passing maneuver was significantly greater than that on the tail; at the same time, the pressure difference between the head and tail tends to increase slightly as speed rises; the higher the speed, the more significant the difference in aerodynamic loads between the head and tail. By fitting the full-wave peak data for the head and tail waves in Table 5, Eqs. (14) and (15) are obtained, showing that the full-wave peak (y) of the surface pressure wave for freight and high-speed trains at different speeds is linearly related to the square of the train speed (v^2 , m/s).

$$p_{head} = 0.0271v^2 + 587.12 \quad R^2 = 0.998 \quad (14)$$

$$p_{tail} = 0.0228v^2 + 431.7 \quad R^2 = 0.997 \quad (15)$$

Table 6 shows that the positive peak, negative peak, and full-wave peak values of the head wave at the W1 monitoring point all exhibit an approximately linear, monotonically increasing trend as the passing speed increases. Specifically, the positive peak value increased from 305 Pa at 120 km/h to 340 Pa at 200 km/h, representing an increase of 35 Pa over the 80 km/h speed range, with the positive peak value rising by an average of 4.375 Pa for every 10 km/h increase in speed; the negative peak value increased from -322 to -348 Pa, representing an absolute increase of 26 Pa, with the absolute value of the negative peak increasing by an average of 3.25 Pa for every 10 km/h increase; the full-wave peak pressure rose from 627 to 688 Pa, an increase of 61 Pa, with an average increase of 7.625 Pa per 10 km/h, indicating that the increase in passing speed continuously intensified the positive and negative pressure effects at the head of the train, as well as the overall aerodynamic impact intensity; the sensitivity of the tail wave pressure to changes in passing speed was significantly higher than that of the head wave, with greater increases in all peak values as speed increased. The positive wave peak increased from 111 Pa to 168 Pa, a rise of 57 Pa, with an average increase of 7.125 Pa per 10 km/h, representing a growth rate approximately 1.63 times that of the positive wave at the head; the negative wave peak increased from -304 to -362 Pa, an absolute increase of 58 Pa; the absolute value of the negative wave peak increased by 7.25 Pa for every 10 km/h, a growth rate approximately 2.23 times that of the negative wave of the head wave; the full-wave peak value increased from 415 to 530 Pa, an increase of 115 Pa, with an average increase of 14.375 Pa per 10 km/h; the rate of increase is approximately 1.88 times that of the head wave's full-wave, reflecting a more pronounced response of the aerodynamic load at the tail of the train to changes in speed; at the same passing speed, the peak positive pressure and full-wave peak pressure of the head wave remain significantly higher than those of the tail wave; the full-wave peak pressure of the head wave is 158–212 Pa higher than that of the tail wave, and this difference tends to decrease as speed increases; conversely, the rate of increase in the absolute value of the negative peak pressure of the tail wave is far faster than that of the head wave; at 200 km/h, the negative peak pressure of the tail wave (-362 Pa) has already exceeded that of the head wave (-348 Pa), indicating that under high-speed passing conditions, the rate of increase in the negative pressure effect at the tail of the train has overtaken that at the head, and the structural characteristics of the aerodynamic loads at the head and tail undergo dynamic changes as speed increases. By fitting the full-wave peak data for the head and tail waves in Table 6, Eqs. (16) and (17) are obtained, showing that the full-wave peak (y) of the surface pressure waves for both high-speed and freight trains exhibits a linear relationship with the square of the train speed (v^2 , m/s) at different speeds.

$$p_{head} = 0.0309v^2 + 594.16 \quad R^2 = 0.995 \quad (16)$$

$$p_{head} = 0.0582v^2 + 350.33 \quad R^2 = 0.995 \quad (17)$$

4.4 Characteristics of Surface Pressure Waves on High-Speed Trains during Encounters with Passenger and Freight Trains

High-speed trains cause significant disturbances in the surrounding flow field during operation. This is particularly true when passing freight trains, where the blunt shape of the freight trains, gaps between carriages, and bogies cause even more intense air compression, resulting in alternating positive and negative pressure shock waves forming within a very short period of time.

Fig. 15a indicates that there are significant differences in pressure wave amplitudes among different monitoring points at the same cross-section of the head car of a high-speed train; the pressure wave amplitudes on the passing side are much greater than those on the non-passing side. The positive pressure peaks of the head wave, ranked from highest to lowest, are: H1, H8, H2, H7, H3, H4, H5, H6. Due to the enclosed geometry between the underside of the train and the bridge deck, this structure restricts airflow and amplifies pressure waves as the train passes, resulting in greater pressure waves at measurement point

H7 beneath the train than at point H3. Fig. 15b further presents a comparison of pressure wave curves at the central monitoring point on the passing side of the high-speed train. The pressure wave trends for the head car, mid car, and tail car are generally consistent, all exhibiting multiple abrupt changes. During the passing of passenger and freight trains, the airflow is influenced by bogies, wind deflectors, and the blunt exterior of the freight train, resulting in significant fluctuations in the pressure waves. A comparison of the head, mid, and tail cars reveals that the full-wave peak values of the positive pressure waves show little variation. Although the negative peak of the pressure wave at the tail of the train is greater than that at the head and mid of the train, when a freight train passes a high-speed train, the non-streamlined geometry of the freight train causes the full-wave peak of the pressure wave at the tail of the high-speed train to be significantly higher than the full-wave peaks of the pressure waves at the head and mid of the high-speed train.

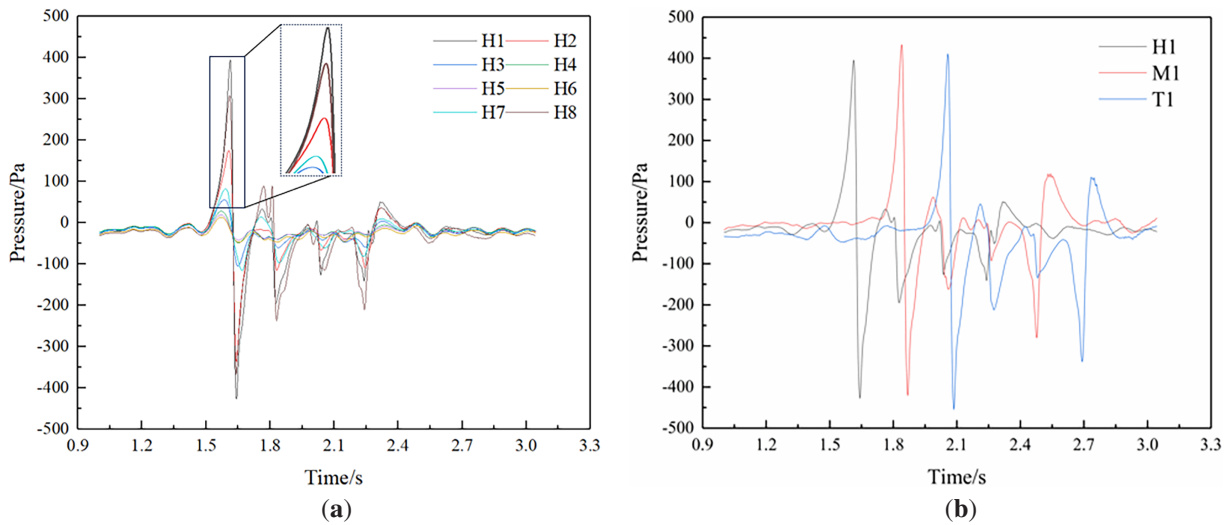


Figure 15: Variation in surface pressure measurement points on high-speed trains during a 200 km/h passing maneuver between passenger and freight trains. (a) Pressure distribution map for car H. (b) Pressure map of mid-section measurement points.

Due to factors such as track speed and train safety, priority is given to ensuring the safe operation of high-speed trains, while there is room for increasing the speed of express freight trains. Therefore, high-speed trains operate at the speed of 200 km/h. This study analyzes the aerodynamic impact of freight trains operating at speeds of 120, 140, 160, 180, and 200 km/h when passing high-speed trains.

Fig. 16 shows the pressure changes at the central monitoring points on the side of the high-speed train (H1, M1, T1) when the high-speed train is traveling at 200 km/h and the freight train is traveling at various speeds (120, 140, 160, 180, and 200 km/h). As shown in the figure, the pressure fluctuation patterns on the high-speed train's body surface remain consistent regardless of the speed at which the freight train passes. As the freight train's speed increases, the amplitude of pressure waves at the high-speed train's body monitoring points increases significantly. The pressure amplitude values at each monitoring point are shown in Tables 7–9. Since the pressure in the high-speed train's wake is significantly lower than that in the head wave, Tables 7–9 analyze only the pressure data from the head wave of the high-speed train.

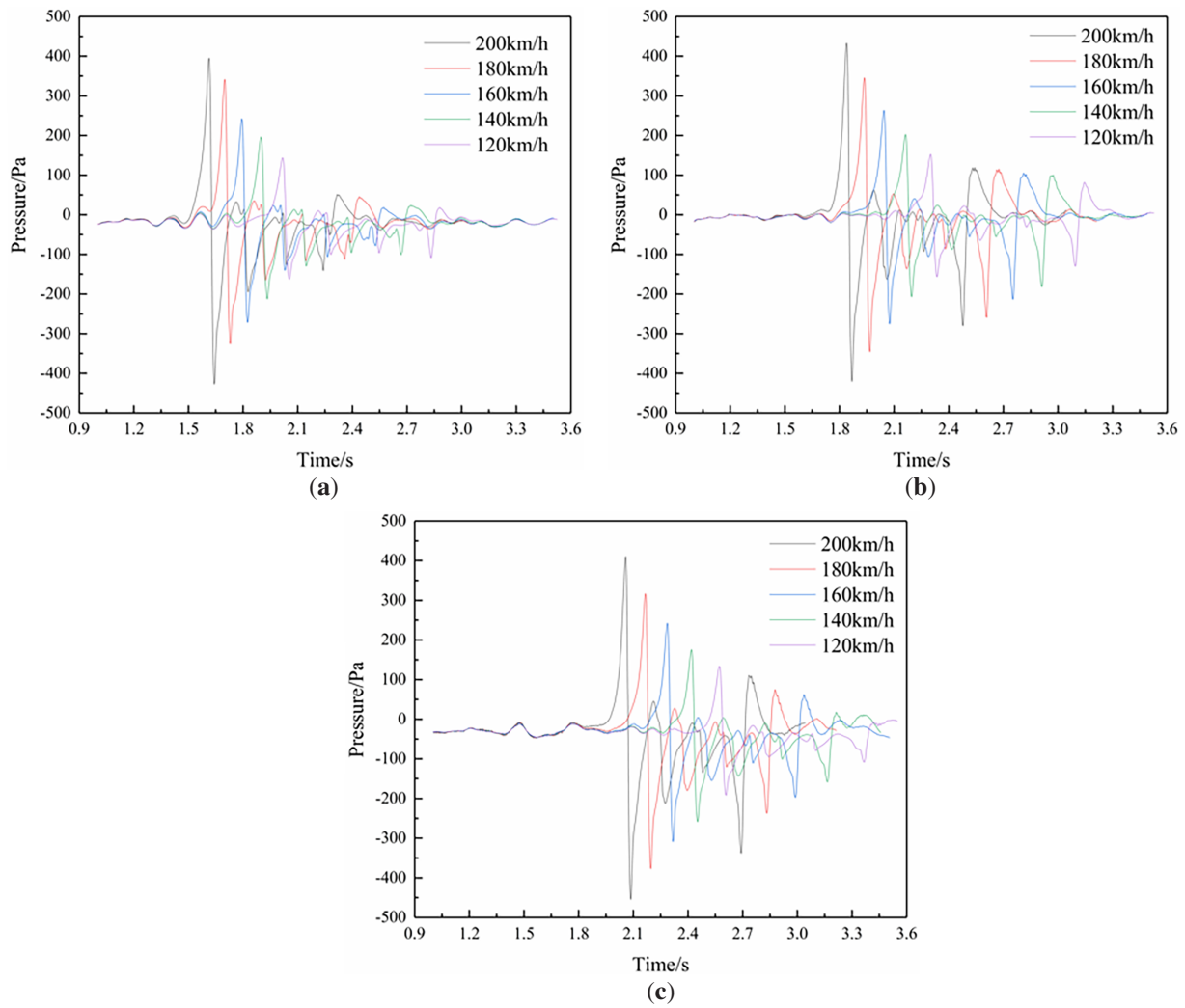


Figure 16: Variation in surface pressure at measurement points on a high-speed train at different passing speeds of freight trains. (a) Pressure variation at measurement point H1. (b) Pressure variation at measurement point M1. (c) Pressure variation at measurement point T1.

Table 7: Pressure wave amplitude at measuring point H1 for freight trains passing at different speeds.

Passing Speed of Freight Trains (km/h)	Head Wave/Pa		
	Positive Value	Negative Value	Full-Wave Peak
120	144	-163	307
140	196	-212	408
160	242	-272	514
180	341	-326	667
200	395	-428	823

Table 8: Pressure wave amplitude at measuring point M1 for freight trains passing at different speeds.

Passing Speed of Freight Trains (km/h)	Head Wave/Pa		
	Positive Value	Negative Value	Full-Wave Peak
120	152	−156	308
140	202	−207	409
160	264	−275	539
180	346	−346	692
200	433	−420	853

Table 9: Pressure wave amplitude at measuring point T1 for freight trains passing at different speeds.

Passing Speed of Freight Trains (km/h)	Head Wave/Pa		
	Positive Value	Negative Value	Full-Wave Peak
120	134	−192	326
140	176	−259	435
160	242	−309	551
180	317	−377	694
200	411	−455	866

Table 7 shows that the positive pressure wave at the head of a high-speed train exhibits a continuously accelerating growth trend as the speed of the passing trains increases. At 120 km/h, the peak value of the positive pressure wave is 144 Pa, increasing to 395 Pa at 200 km/h. Overall, the total increase in the positive wave peak value within the 120–200 km/h range reaches 251 Pa, with the rate of increase exhibiting a distinct nonlinear characteristic as speed rises. A significant growth discontinuity occurs in the 160–180 km/h range, indicating that the amplifying effect of the positive pressure generated at the head of the tail train is dramatically amplified under high-speed passing conditions; the absolute value of the negative peak pressure of the head wave also exhibits an accelerating growth trend as the passing speed increases. At 120 km/h, the negative peak pressure is −163 Pa, decreasing to −428 Pa at 200 km/h, with a total absolute increase of 265 Pa; The absolute value increases across the four speed ranges were 49, 60, 54, and 102 Pa, respectively, with a significant acceleration in the growth rate between 180 and 200 km/h, reflecting that the growth effect of the negative pressure zone at the front of the train under high-speed passing conditions is far greater than that in the medium and low speed ranges; the growth pattern of the full-wave peak value of the head wave is highly consistent with that of the positive and negative wave peak values, exhibiting a significant nonlinear accelerated growth. At 120 km/h, the full-wave peak value was 307 Pa; at 200 km/h, it increased to 823 Pa, which is 2.68 times the head value at 120 km/h; the increases in each speed range are 101, 106, 153, and 156 Pa, respectively. The rate of increase accelerates significantly after 160 km/h, indicating that when the speed during a passing maneuver exceeds 160 km/h, the overall aerodynamic impact loads on the train increase significantly. This is because the Mach number during the passing maneuver exceeds 0.3, at which point the effects of air compressibility become pronounced.

Table 8 shows that the positive value of the mid car pressure wave in high-speed trains increases from 152 Pa at 120 km/h to 433 Pa at 200 km/h, which is 2.85 times the head wave value; the increases across the four speed intervals were 50, 62, 82, and 87 Pa, respectively, with the rate of increase accelerating continuously as

speed rose; the growth effect became significantly amplified after the train reached 160 km/h; the negative wave peak value decreased from -156 to -420 Pa, which is 2.69 times the head wave value; the increases in each speed range were 51, 68, 71, and 74 Pa, respectively, also showing an accelerating growth trend; the full-wave peak value rose from 308 to 853 Pa, which is 2.77 times the head wave value; the increases in each speed range were 101, 130, 153, and 161 Pa, respectively, with a marked acceleration in the growth rate after 160 km/h, the absolute values of the positive and negative values of the head wave, as well as the full-wave peak value, all exhibit a nonlinear, accelerating growth trend as passing speed increases.

Table 9 shows that the positive value of the head wave at the tail car of a high-speed train increases from 134 Pa at 120 km/h to 411 Pa at 200 km/h, which is 3.07 times the head value at 120 km/h. The growth rate exhibits a distinct nonlinear amplification characteristic as speed increases, with the growth rate accelerating significantly after 160 km/h, indicating a dramatic intensification of the positive pressure effect of freight trains under high-speed passing conditions; the absolute value of the negative peak pressure at the tail end also exhibits an accelerating growth trend as the passing speed increases. At 120 km/h, the negative peak pressure was -192 Pa, decreasing to -455 Pa at 200 km/h, which is 2.37 times the initial value; the absolute value increases for the four speed intervals were 67, 50, 68, and 78 Pa, respectively, with the growth rate peaking in the 180–200 km/h range, reflecting that the growth effect of the negative pressure zone at the head of the tail car of a high-speed train during high-speed passing maneuvers is far greater than that in the medium and low-speed ranges; the growth pattern of the full-wave peak of the head wave is highly consistent with that of the positive and negative wave peaks, exhibiting a significant nonlinear accelerating growth. At 120 km/h, the full-wave peak was 326 Pa; at 200 km/h, it increased to 866 Pa, which is 2.66 times the head value at 120 km/h; the increases in each speed range are 109, 116, 143, and 172 Pa, respectively. The growth rate rises sharply after 160 km/h, indicating that when the relative speed during a passing maneuver exceeds 160 km/h, the overall aerodynamic impact loads on the train increase significantly. This is because the Mach number during the passing maneuver exceeds 0.3, at which point the effects of air compressibility become pronounced.

4.5 Pressure Wave Characteristics at the Passing Points of Passenger, Freight, and Mixed Trains

High-speed trains feature a streamlined aerodynamic profile, while freight trains have a blunt profile. To investigate the relationship between pressure waves at mid-surface monitoring points on the side surfaces of passenger, freight, and passenger-freight trains during passing maneuvers, this study uses a passing speed of 200 km/h between a high-speed train and a freight train as an example to conduct a comparative analysis of the pressure wave characteristics at mid-surface monitoring points on the side surfaces of different train types.

Fig. 16 shows the variation in surface pressure at the monitoring point on a freight train when it passes a passenger-freight train at a speed of 200 km/h. During the passing of a passenger-freight train, the full-wave peak of the positive wave at the passenger-freight train's monitoring point is significantly smaller than that of the freight train's positive wave. When the passing trains pass through the bogie and car connection points, the fluctuations caused by passenger cars are smaller than those caused by freight trains, and the difference is significant. Fig. 17a shows that during the passing of a passenger-freight train and a freight train, the full-wave peak of the tail wave at the passenger-freight monitoring point J1 is greater than that of the freight train passing, primarily due to the aerodynamic profile of the locomotive. Fig. 17b,c respectively show that during the passing of a passenger-freight train and a freight train, the full-wave peak of the passenger-freight train's wake at measurement points P1 and W1 is slightly greater than that of the freight train's wake, though the difference is not significant. A comparison of trains J, P, and W reveals that the full-wave peak values of the

head wave are all greater than those of the tail wave, and the differences are significant. Based on this, the head wave data is used for comparative analysis.

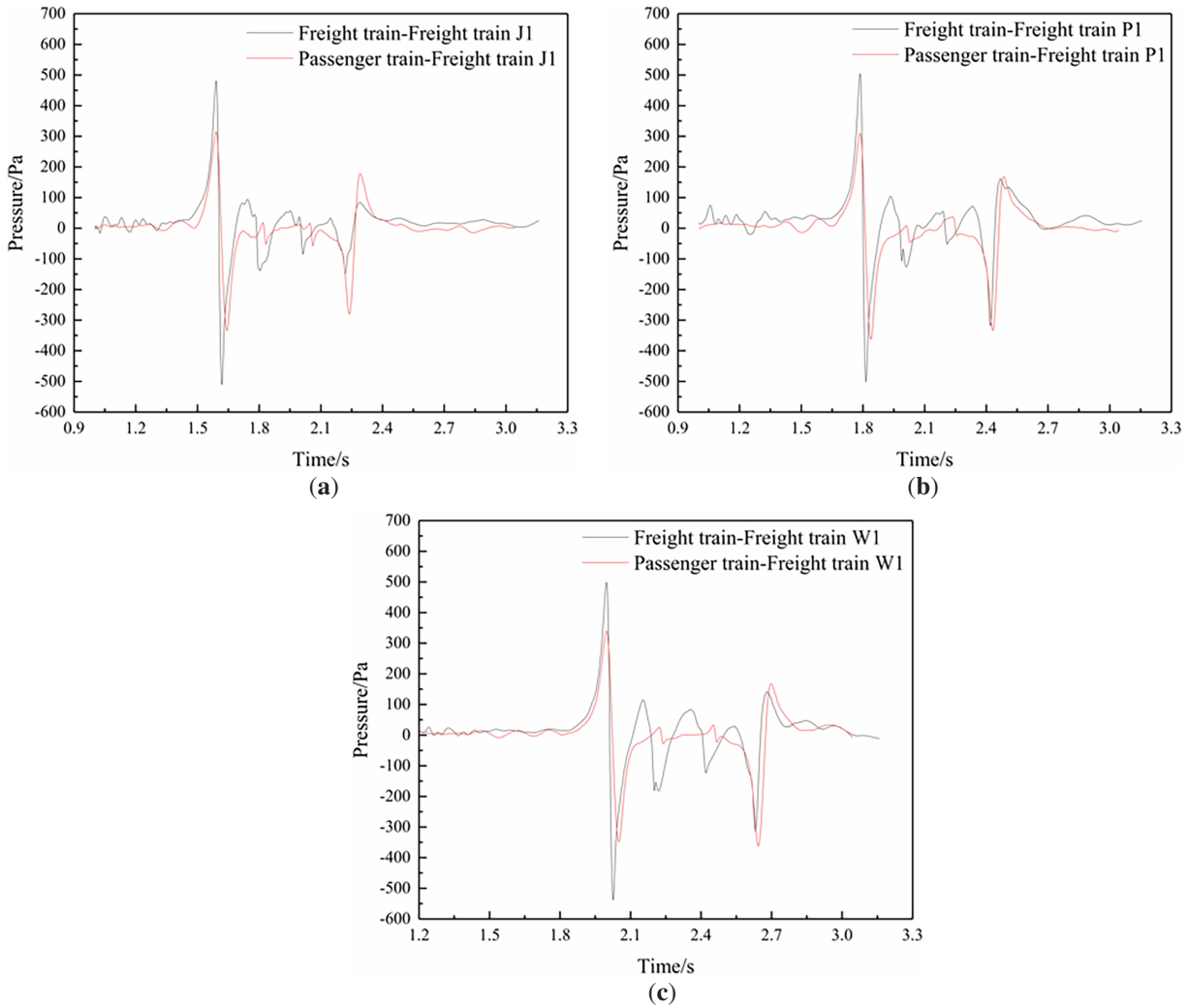


Figure 17: Pressure variations at measurement points on the surface of a freight train during a 200 km/h passing maneuver with a mixed passenger-freight train. (a) Pressure variation at measurement point J1. (b) Pressure variation at measurement point P1. (c) Pressure variation at measurement point W1.

Table 10 shows that under freight-freight passing conditions, the absolute values of the positive and negative wave peaks, as well as the full-wave peak values, at all measurement points on the freight train are significantly higher than those under passenger-freight passing conditions, indicating a marked difference in the intensity of the pneumatic shock loads. Under freight-to-freight conditions, the values at measurement points J1, P1, and W1 were 481, 505, and 499 Pa, respectively, while under passenger-to-freight conditions, the corresponding values were 315, 309, and 340 Pa. The positive wave peak values under freight-to-freight conditions were 52.7%, 63.4%, and 46.8% higher than those under passenger-to-freight conditions, respectively; under the freight-freight condition, the negative peak values at each measurement point were -510 , -502 , and -538 Pa, while under the passenger-freight condition, they were -333 , -363 , and -348 Pa. The absolute values of the negative peak values under the freight-freight condition were 53.2%, 38.3%, and 54.6% higher than those under the passenger-freight condition, respectively; under all-freight conditions, the full-wave

peak values were 991, 1007, and 1037 Pa, while under passenger-freight conditions, they were 648, 672, and 688 Pa. The full-wave peak values under all-freight conditions were 52.9%, 49.9%, and 50.7% higher than those under passenger-freight conditions, respectively, with the overall increase remaining stable at around 50%. Regardless of whether the encounter was freight-freight or passenger-freight, the full-wave peak value at measurement point W1 was the highest (freight-freight: 1037 Pa; passenger-freight: 688 Pa), indicating that this measurement point recorded the strongest overall aerodynamic impact load; measurement point P1 recorded the highest positive peak values (505 Pa for freight-freight), while measurement point J1 recorded the lowest positive peak values (481 Pa for freight-freight), reflecting relatively stable aerodynamic load distribution characteristics at different locations. Under the freight-freight configuration, the absolute value of the negative peak at measurement point W1 (538 Pa) is higher than that at J1 (510 Pa) and P1 (502 Pa), indicating that the negative pressure effect is more pronounced in the W car; under the passenger-freight configuration, the absolute value of the negative peak at measurement point P1 (363 Pa) was higher than that at J1 (333 Pa) and W1 (348 Pa), indicating that the negative pressure effect was more pronounced in car P.

Table 10: Pressure wave amplitude at measurement points during passing of passenger-freight and freight-freight trains at 200 km/h.

Types of Passing Trains and Measurement Points	Head Wave/Pa		
	Positive Value	Negative Value	Full-Wave Peak
Freight Train-Freight Train J1	481	-510	991
Passenger Train-Freight Train J1	315	-333	648
Freight Train-Freight Train P1	505	-502	1007
Passenger Train-Freight Train P1	309	-363	672
Freight Train-Freight Train W1	499	-538	1037
Passenger Train-Freight Train W1	340	-348	688

Fig. 18 shows the variation in surface pressure at monitoring points on a high-speed train when it passes a passenger or freight train at a relative speed of 200 km/h. During the passing of passenger and freight trains, the full-wave peak of the high-speed train's head wave is significantly greater than that of the high-speed train's head wave during the passing of high-speed trains. When the passing trains pass through the bogie and car connection points, the fluctuations caused by passenger trains are smaller than those caused by freight trains, and the difference is significant. Fig. 18a shows that during passenger-freight train passing and high-speed train passing scenarios, the full-wave peak of the trailing wave at measurement point H1 is smaller for passenger-freight train passing than for high-speed train passing. The primary reason for this is related to the streamlined appearance of high-speed trains and their long noses. Fig. 18b,c show, respectively, that during passenger-freight train passing and high-speed train passing, the full-wave peak values of the wake at measurement points M1 and T1 are both smaller than those of the high-speed train passing, though the difference is not as pronounced as that observed for the head wave. A comparison of trains H, M, and T reveals that the full-wave peak values of the head waves are all greater than those of the tail waves, and the difference is significant. Based on this, head wave data are used for comparative analysis.

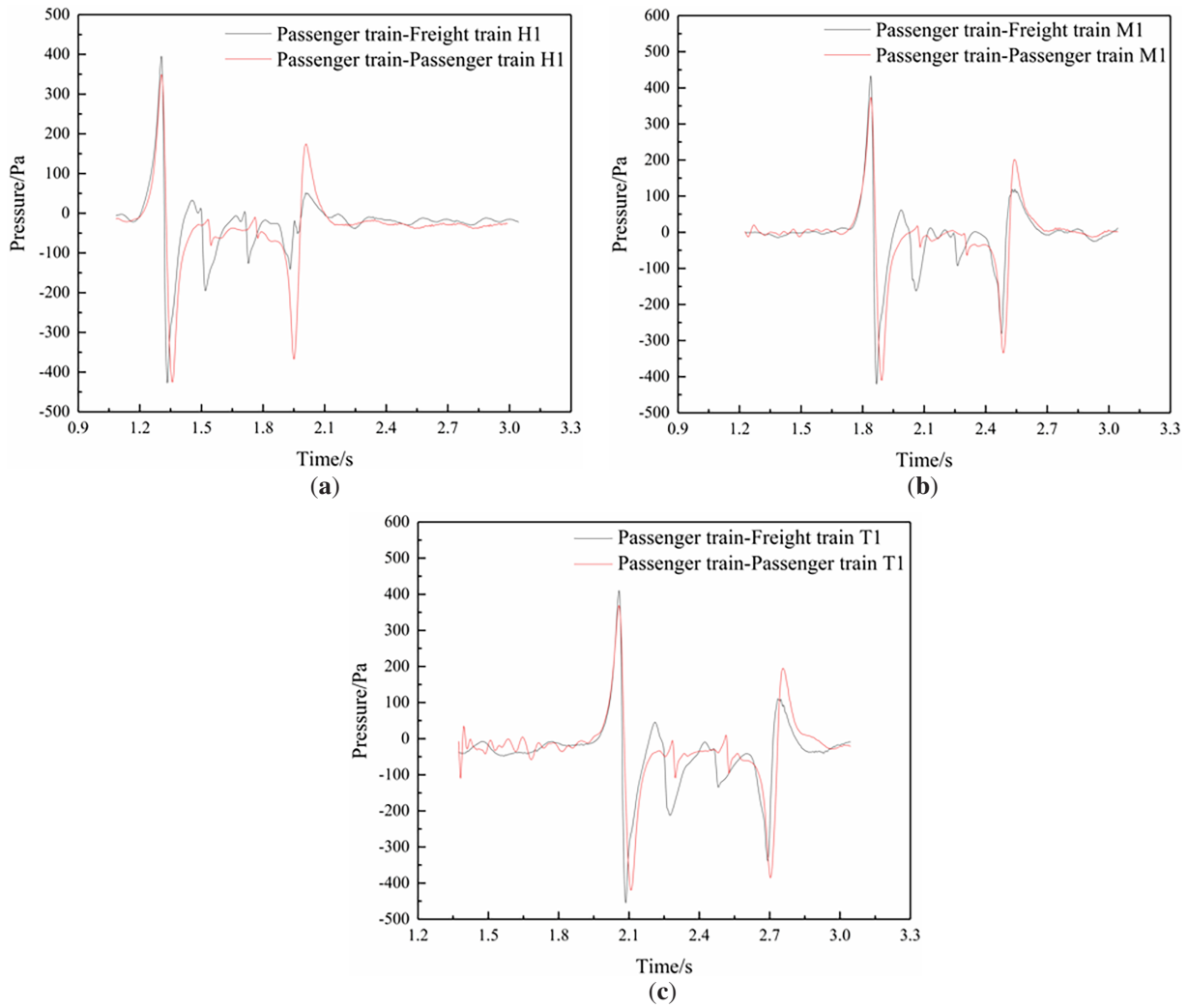


Figure 18: Pressure variations at surface measurement points on high-speed trains during a 200 km/h passing maneuver between a freight train and a mixed passenger-freight train. (a) Pressure Variation at Measurement Point H1. (b) Pressure Variation at Measurement Point M1. (c) Pressure Variation at Measurement Point T1.

Table 11 shows that under passenger-freight passing conditions, the absolute values of the positive and negative peak amplitudes, as well as the full-wave peak amplitude, of the head wave at all measurement points on the high-speed train are higher than those under passenger-passenger passing conditions. Under passenger-freight conditions, the values at measurement points H1, M1, and T1 were 395, 433, and 411 Pa, respectively, while under passenger-passenger conditions, the corresponding values were 349, 374, and 369 Pa. The positive wave peak values under passenger-freight conditions were 13.2%, 15.8%, and 11.4% higher than those under passenger-passenger conditions, respectively; under the passenger-freight condition, the negative wave peak values at each measurement point were -428, -420, and -455 Pa, while under the passenger-passenger condition, they were -425, -410, and -419 Pa. The absolute values of the negative wave peaks under the passenger-freight condition were 0.7%, 2.4%, and 8.6% higher than those under the passenger-passenger condition, respectively; the overall increase was far smaller than that of the positive wave, with only the T1 measurement point showing a significant increase; the full-wave peak values under passenger-freight conditions were 823, 853, and 866 Pa, while under passenger-passenger conditions they

were 774, 784, and 788 Pa. The full-wave peak values under passenger-freight conditions were 6.3%, 8.8%, and 9.9% higher than those under passenger-passenger conditions, with the overall increase remaining stable within the 6%–10% range, and the increases at the M1 and T1 measurement points being more pronounced. Regardless of whether it is a passenger-passenger or passenger-freight encounter, the positive peak values at the M1 measurement point are the highest (374 Pa for passenger-passenger, 433 Pa for passenger-Freight), while those at the H1 measurement point are the lowest (349 Pa for passenger-passenger, 395 Pa for passenger-freight), indicating that the measurement points in the middle of the train body are most strongly affected by the positive pressure impact; under passenger-passenger conditions, the full-wave peak at the T1 measurement point was the highest (788 Pa), and under passenger-to-freight conditions, the full-wave peak at the T1 measurement point was similarly the highest (866 Pa). This indicates that the T1 measurement point is the most unfavorable location for high-speed trains to withstand overall aerodynamic impact, and this characteristic is not affected by the type of passing train.

Table 11: Pressure wave amplitude at measurement points during passing of passenger-freight and passenger-passenger trains at 200 km/h.

Types of Passing Trains and Measurement Points	Head Wave/Pa		
	Positive Value	Negative Value	Full-Wave Peak
Passenger Train-Passenger Train H1	349	−425	774
Passenger Train-Freight Train H1	395	−428	823
Passenger Train-Passenger Train M1	374	−410	784
Passenger Train-Freight Train M1	433	−420	853
Passenger Train-Passenger Train T1	369	−419	788
Passenger Train-Freight Train T1	411	−455	866

5 Conclusion

This paper takes the CRH380A train as its subject of study, employing the CFD (Computational Fluid Dynamics) RANS $k-\epsilon$ turbulence model and moving mesh technology. The accuracy of this method was verified through mesh sensitivity tests and comparison with wind tunnel test results. Building upon this methodological framework, the study investigated the patterns of change in surface pressure characteristics when the CRH380B train and an express freight train pass each other on a bridge deck. The following main conclusions were drawn:

- (1) When a high-speed train and a freight train pass each other, both trains exhibit two positive pressure peaks and two negative pressure peaks. During this process, fluctuations occur due to factors such as bogie and train clearances. Analysis of measurement points along the cross-sections of the high-speed train's head car and the freight locomotive reveals that the pressure waves on the passing side are significantly greater than those on the non-passing side, and the pressure wave values gradually decrease toward the measurement points near the roof.
- (2) High-speed trains are calculated based on a speed of 200 km/h, while freight trains are calculated based on speeds ranging from 120 to 200 km/h, with increments of 20 km/h. For freight trains, both the full-wave peak and the square of the speed exhibit a linear relationship at the midpoint of the passing side of each car; for high-speed trains, once the freight train's speed exceeds 160 km/h, the full-wave peak of the pressure head wave at the midpoint of the passing side of each car exhibits an approximately exponential nonlinear increase. This is caused by the train's passing Mach number exceeding 0.3, at which point the effects of air compressibility become significant.

- (3) When freight trains pass each other, the full-wave peak value of the measuring point on the passing side of the freight train is 49.9%–52.9% higher than that of a freight train passing a passenger-freight train. This indicates that, due to their blunt exterior, the pressure waves generated by freight trains are approximately 1.5 times greater than those of a freight train passing a passenger-freight train; When passenger trains pass each other, passenger-freight full-wave peaks are 6.3%–9.9% higher than passenger-passenger peaks, indicating that the aerodynamic characteristics of high-speed train passing are superior to those of passenger-freight train passing. However, this paper does not examine different passing speeds of passenger-freight trains on embankments, which could serve as a topic for future research.

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Conflicts of Interest: The authors declare no conflicts of interest.

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