



## Research Article

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# Effect of geometry simplification and boundary condition specification on flow field and aerodynamic noise in the train head and bogie region of high-speed trains

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**Abstract:** The purpose of this study is to determine a suitable modeling method to make CFD simulation more efficient for aeroacoustics optimization of the bogie region of high-speed trains. To this end, four modeling methods are considered, which involve different geometry simplifications and boundary-condition specifications. The corresponding models are named the three-car marshalling model, computational domain shortening model, carbody shortening model and sub-domain model. Combining the detached eddy simulation (DES) model and Ffowcs Williams-Hawkings (FW-H) equation, the unsteady flow field and far field noise of the four models are predicted. To evaluate the effect of the different modeling methods, the time-averaged flow field, fluctuating flow field and far field noise results of the four models are compared and analyzed in detail with the results of the three-car marshalling model used as basis for comparison. The results show that the flow field results of the bogie region predicted by the four models have relatively high consistency. However, the usage of the non-time varying outlet boundary conditions in the computational domain shortening model and sub-domain model could affect the pressure fluctuation on the upstream carbody surface. When only the bogie region is used as the source surface, the differences between the far-field noise results of the three simplified models and the three-car marshalling model are all within 1 dB; when the train head is used as the source surface, the results of the carbody shortening model and the three-car marshalling model are more consistent.

**Key words:** Bogie region; Train head; Flow field; Aerodynamic noise; Geometry simplification; Boundary conditions

## 1 Introduction

With the continuous improvements in train operation speed, the problems related to train aerodynamics are increasingly prominent, one of which is aerodynamic noise (Meskine et al., 2013; Thompson, 2008; Thompson et al., 2015). As with other aerodynamic problems, optimization of train aeroacoustics performance mainly relies on wind tunnel test and numerical simulation. The length of a typical eight-car high-speed train is about 200 m. Such a large size makes it impossible to conduct wind tunnel tests on full-scale train models. In China, the 1:8

scaled three-car model is commonly used for wind tunnel tests (Ding et al., 2016; Li et al., 2022). Research on Reynolds number effects and observation of the flow field in the middle of the train have demonstrated the rationality of this approach (Bell et al., 2017; Chang et al., 2021; Khier et al., 2000). The biggest advantage of the wind tunnel test is its high reliability, but it is not suitable for large-scale shape parameter optimization, because it is usually difficult to implement shape modification on a physical prototype used for wind tunnel test. With the rapid development of computational technologies, numerical simulation has become another option for aerodynamic and aeroacoustics optimization. Compared with the wind tunnel test, the model configuration is more flexible in numerical simulation, and a large number of design modifications can be completed in a short period of time. However, in terms of aerodynamic noise, it is still a time-consuming work to pre-

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dict the response to design changes through numerical simulation due to the high requirements of grid size, time step size and geometry accuracy.

Different from the influence of changes in component shape must be evaluated on a whole vehicle model in aerodynamic drag optimization. The main noise sources of high-speed trains are relatively independent and there is not a strong coupling effect among the flow field and sound field of different sources. Therefore, when optimizing train aeroacoustics performance, the components as the main noise sources can be optimized one by one (Li et al., 2020a). The bogie region is one of the most important aerodynamic noise sources of high-speed trains (Meskine et al., 2013; Lauterbach et al., 2012; Li et al., 2022; Thompson, 2008; Thompson et al., 2015;). Numerous experimental and numerical results have shown that although a high-speed train has multiple bogies, the aerodynamic noise generated by the first bogie of the leading car is far greater than that of other bogies (Meskine et al., 2013; Li et al., 2022; Thompson, 2008; Thompson et al., 2015). Therefore, aerodynamic noise control of the bogie region should be focused on the first bogie of the leading car. In view of this, the three-car model does not seem to be the most suitable choice for CFD based aeroacoustics optimization of the bogie region, because the areas we are really interested in are only concentrated at the train head and the foremost bogie region, while the use of a three-car model makes a large number of grids wasted in areas that have little impact on the flow phenomenon of interest. To make CFD simulation more efficient for aeroacoustics optimization of the bogie region, a suitable modeling method is needed.

In fact, due to the high computational cost of aeroacoustics simulation, many studies on aerodynamic noise have attempted to use some model simplification methods to improve the efficiency of CFD simulation. In a study on aerodynamic noise generated by the head streamlined surface of a high-speed train (Liu et al., 2011), the streamlined surface of the head car and tail car were directly connected to build a geometry model. The authors evaluated the effect of the middle body length on pressure distribution on the carbody surface by steady Reynolds-averaged Navier-Stokes (RANS) simulation and found that when the middle length is greater than 8 m, further increase

in the middle body length has little effect on the pressure distribution on the carbody surface. However, it is not clear how the middle body length affects the aerodynamic noise of the head streamlined surface. Minelli et al. (2020) used a computational domain shortening model to study the aerodynamic noise generated by a simplified ICE train head. In their model, the train geometry was truncated by the outlet of the computational domain at the middle of the head car and the outlet boundary was set as pressure outlet with gauge pressure of 0. In a study on wind noise generated by the A-pillar and side mirror region of a heavy truck (Yao et al., 2018), the researchers tried to reduce the simulation cost by simplifying the trailer model, including removing some components from the trailer and modifying the tail shape. The simulation results show that these simplifications have little effect on flow characteristics in the A-pillar region. This also indicates that the geometrical modification of downstream components has a limited effect on the flow field around the distant upstream components. The sub-domain model is also a method to enhance the computational efficiency of aerodynamic noise simulation. The so-called sub-domain is a part of a larger computational domain. During the simulation, the time-averaged flow field of the large computational domain is first calculated by steady RANS simulation, and the obtained flow field data are mapped to the boundary of the sub-domain as boundary conditions for further analysis through unsteady simulation. Karbon et al. (2005) applied the sub-domain method to the aeroacoustics optimization of a passenger car's roof rack. The dominant frequency and ranking of the sound pressure level of different models predicted by CFD simulation are in good agreement with the wind tunnel test results. In a recent study, Schell et al. (2020) employed the sub-domain method to simulate the squealing of a car side mirror. Their simulation reproduced this complex aero-acoustic feedback phenomenon and accurately captured the frequency associated with the squealing. In recent years, the sub-domain method has also been applied to the aerodynamic noise simulation of high-speed trains. Gao et al. (2017) tried to predict the aerodynamic noise of a full-scale train head shape with the sub-domain method. Zhao et al. (2020) validated the effectiveness of the sub-domain method based on a 1:40 scaled train model, and observed that

the numerical results of the time-averaged vorticity distribution in the wake of the pantograph closely resembled those obtained by the PIV test. Furthermore, they found that the pressure-spectrum structures of the two measurement points on the carbody surface obtained by the simulation are consistent with the test results, albeit with an overall pressure level difference of about 3.8 dB.

Based on the above review, it is evident that various modeling methods have been applied for aerodynamic noise simulation of the bogie region or could serve as a reference for this. However, there is currently a lack of research that quantitatively compares the flow field and aerodynamic noise obtained from different modeling methods. In this study, four modeling methods applied to the aerodynamic noise simulation of the bogie region are considered, which involve different geometry model simplifications and boundary condition specifications. The four models are called the three-car marshalling model, the computational domain shortening model, the carbody shortening model, and the sub-domain model. In a sense, the last three models can be regarded as simplified versions of the three-car marshalling model. A comparative analysis is conducted on the simulation results of the four models, with the results of the three-car marshalling model used as basis for comparison, to evaluate the effectiveness of different modeling methods in accurately reproducing the flow field and far-field noise in the train head and bogie region. The results will provide a basis for the selection of modeling methods for subsequent research on aerodynamic noise control measures for the bogie region.

## 2 Numerical methods

### 2.1 DES model

Detached eddy simulation (DES) is a hybrid method. Its basic idea is to use the large eddy simulation (LES) model in the separated zone and the RANS model in the near wall region. Control of the solving region of the two models is achieved by modifying the length scale in the original turbulence model. The DES method combines the advantages of RANS and LES, and offers a good compromise between accuracy and cost. Based on the original DES method, two variants have been proposed successively, namely the delayed detached eddy simulation

(DDES) and the improved delayed detached eddy simulation (IDDES), to solve the problem of grid-induced separation and log-layer mismatch (Spalart et al., 2006; Shur et al., 2008). In recent years, both DDES and IDDES methods have been widely used to simulate the unsteady flow field around high-speed trains (Guo et al., 2020; Li et al., 2020b; Minelli et al., 2020; Wang et al., 2020; Zhu et al., 2017). Based on our test of the turbulence models, the DDES model based on the shear stress transport (SST)  $k-\omega$  model is selected to numerically solve the unsteady flow field around the train in this study.

### 2.2 FW-H equation

The FW-H equation is a theoretical description of the sound generated by the interaction between moving objects and fluids, as shown in equation (1) (Williams and Hawkings, 1969),

$$\begin{aligned} & \frac{1}{c_0^2} \frac{\partial^2}{\partial t^2} [p'H(f)] - \nabla^2 [p'H(f)] \\ &= \frac{\partial}{\partial t} [\rho_0 v_n \delta(f)] - \frac{\partial}{\partial x_i} [p_{ij} \hat{n}_j \delta(f)] + \frac{\partial^2}{\partial x_i \partial x_j} [T_{ij} H(f)] \end{aligned} \quad (1)$$

where  $c_0$  is the speed of sound,  $t$  indicates time,  $p'$  is sound pressure,  $x_i, i=1,2,3$  is the Cartesian coordinate component,  $f=0$  is the equation of the source surface,  $H(\cdot)$  is the Heaviside function,  $\rho_0$  is the density of the undisturbed fluid,  $v_n$  is the component of the sound source surface velocity in the outward normal direction,  $\hat{n}_j$  is the unit vector of the outward normal direction at a point on the source surface,  $p_{ij} = p\delta_{ij} - \sigma_{ij}$  is the fluid compressive stress tensor,  $\sigma_{ij}$  represents the viscous stress,  $\nabla$  is Nabla operator, and  $T_{ij}$  is the Lighthill stress tensor.

According to Lighthill's acoustic analogy, the three terms at the right end of equation (1) correspond to the monopole source, dipole source and quadrupole source. By using the Green's function from classical acoustics, the far-field sound pressure can be expressed as the superposition of the contributions of the three source terms. In this study, the quadrupole source term is neglected due to its low radiation efficiency in low Mach number flow and minimal contribution to far-field noise. In addition, the numerical simulation is based on wind-tunnel mode. The train surface remains static and rigid, so the monopole

source term is also equal to 0. Consequently, the far-field noise only includes the contribution of dipole sources, which can be expressed by equation (2) (Farassat, 2007):

$$\begin{aligned}
 p'(x,t) = & \frac{1}{4\pi c_0} \int_{f=0} \left[ \frac{\dot{l}_r}{r(1-M_r)^2} \right]_{ret} dS \\
 & + \frac{1}{4\pi} \int_{f=0} \left[ \frac{l_r - l_M}{r^2(1-M_r)^2} \right]_{ret} dS \\
 & + \frac{1}{4\pi c_0} \int_{f=0} \left[ \frac{l_r(r\dot{M}_r + c_0 M_r - c_0 M^2)}{r^2(1-M_r)^3} \right]_{ret} dS
 \end{aligned} \quad (2)$$

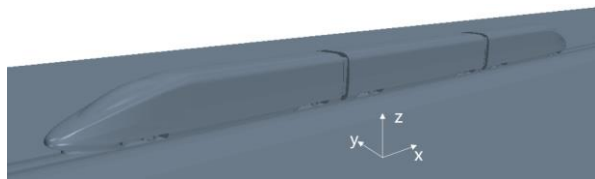
$$l_r = l_i \hat{r}_i \quad \dot{l}_r = \dot{l}_i \hat{r}_i \quad l_M = l_i M_i \quad M_r = M_i \hat{r}_i$$

where  $l_i = p_{ij} \hat{n}_j$ ,  $M_i$  is the component of the Mach number of the sound source in the  $x_i$  direction, and  $r$  is the distance between a point  $y$  on the source surface and receiver point  $x$ . The meaning of the other variables is the same as in equation (1). The subscript *ret* of the integral term indicates that the relevant variables are evaluated at the restarted time  $\tau = t - r/c_0$ .

### 3 CFD model

#### 3.1 Geometry model, computational domain and boundary conditions

A 1:8 scaled electric multiple unit (EMU) model is taken as the research object. Fig. 1(a) shows a three-car model consisting of a head car, mid car, and tail car. The coordinate system defined for current simulation is also depicted in Fig. 1(a), with the negative direction of the x-axis aligned with the train operation direction. Fig. 1(b) and (c) further shows the geometry of the train head and bogie region, which will be used as source surfaces for far-field noise calculation. Although simplified to some extent, the bogie model is still sufficient to reflect the structural characteristics of its real counterpart (Dong et al., 2019).



(a) Three-car marshalling model

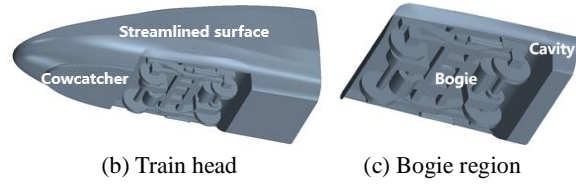


Fig. 1 Geometry model

In addition to the three-car marshalling model (abbreviated as TCMM below), three simplified models are established, namely the computational domain shortening model (CDSM), carbody shortening model (CSM) and sub-domain model (SM), as shown in Fig. 2. The carbody height  $H=474.5$  mm is taken as the characteristic length and the relevant geometry sizes are also marked in Fig. 2. The total length of the TCMM is  $20.86H$ . In the case of CSM, a straight smooth surface connects the streamlined surface of the head car and tail car over a length of  $2.94H$ . The foremost bogie configuration is preserved while the rear one is removed. For the CDSM and SM, the head car is truncated by the outlet boundary, and the reserved middle body length is about  $1.47H$ .

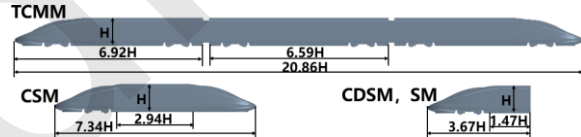


Fig. 2 Schematic diagram of train geometry and size

The computational domains established for the four models are shown in Fig. 3. For the TCMM, the distance from the inlet of the domain to the nose tip of the head car is  $20H$ . The width and height of the domain are  $18.2H$  and  $10.54H$  respectively, making the blocking ratio less than 0.5%, which is sufficient to simulate the operation condition of a train running in open air. The distance from the nose tip of the train tail to the outlet of the domain is  $45H$ , which is sufficient to ensure full development of the wake flow of the train. For the CSM, SM and CDSM, the width and height of the domain and the distance from the nose tip of the head car to the inlet of the domain are same as those of the TCMM, while for the CDSM and SM, the outlet boundary truncates the carbody in the middle of the head car. For the CSM, meanwhile, the distance from the nose tip of the train tail to the outlet of the domain is slightly shorter than that of the TCMM.

For all four models, the inlet boundary of the computational domain is set as velocity inlet with an inflow velocity of 69.44 m/s. The top and both sides

of the computational domain are set as symmetry boundary. The ground and track surfaces are set as moving wall with no-slip, with the same velocity as the inflow velocity, to simulate the relative motion between the train and the ground during actual operation. The outlet of the computational domain is set as pressure outlet. For the TCMM, CDSM and CSM, the gauge pressure is set as 0. For the SM, the pressure and turbulence parameters at the outlet boundary are obtained by a steady RANS simulation based on the TCMM.

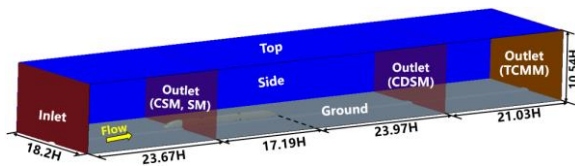


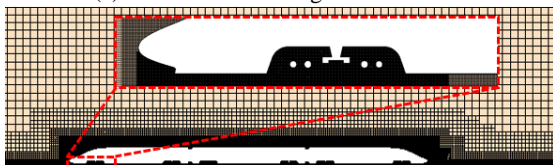
Fig. 3 Computational domain

### 3.2 Mesh strategy

A hybrid mesh strategy combining trimmed and prism layer meshes is used to discretize the computational domain. The maximum grid size of the head streamlined surface is set as 3 mm. The grid size of the bogie and cavity surface is controlled within 0.375-1.5 mm. Several blocks are established for local refinement of the volume grids around the train in the TCMM, as shown in Fig. 4(a). As for the three simplified models, the same refinement strategy is used, but the size and position of the refinement blocks are adjusted according to the length of the train model. 15 layers of fine prism grids with an initial height of 0.01 mm and stretching ratio of 1.2 are generated on the train surface. This ensures that the wall  $y^+$  values in most areas of the train surface are less than 1, meeting the requirements of the DES model. Fig. 4(b) shows the meshing results of the TCMM. Table 1 lists the volume cell counts of the four models.



(a) Blocks for volume grids refinement



(b) Meshing result

Fig. 4 Refinement blocks and meshing result (TCMM)

Table 1 Volume cell counts of the four models

Model	TCMM	CDSM	CSM	SM
Number of cells	120 million	25 million	33 million	25 million

### 3.3 Solver setup

The Mach number of current simulation is below 0.3, so the air is considered as a gas with constant density. The segregated flow solver based on the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm is used to solve the discretized flow governing equations. The convection term is discretized by a hybrid scheme of second-order upwind and central differencing, and the diffusion term is discretized by the second-order scheme. The second-order hybrid Gauss-LSQ method is used for gradient calculation. The second-order implicit method is adopted for time marching with a time step size of  $5 \times 10^{-5}$  s. Following the principle of containing 10 sampling points per time period, the noise components up to 2000 Hz is expected to be accurately analyzed. Meanwhile, the convective Courant-Friedrichs-Lewy (CFL) number of most cells in the domain are below 2.5 (check after calculation), which is enough to achieve a stable solving (Siemens PLM software, 2017). To accelerate convergence, the simulation of the unsteady flow field is initialized with a convergent steady field obtained through RANS simulation. After the running of the first 0.4 s of the simulation that ensure the full development of the transient flow field, the flow field data is collected for another 0.25 s for far-field noise calculation. For the SM, an additional steady RANS simulation based on the TCMM is needed to obtain the boundary conditions of the sub-domain outlet. This RANS simulation lasts for 4500 steps to ensure convergence. The averaged values of pressure and turbulence parameters of the last 1000 iterations are recorded and mapped to the sub-domain outlet as boundary conditions.

## 4 Validation of the mesh strategy and numerical methods

### 4.1 Clean cavity case

The existence of the bogie cavity makes the flow field in the bogie region exhibits certain cavity flow characteristics. Therefore, the "clean cavity" (no object in the cavity) model is selected as a case to validate the mesh strategy and numerical methods. This

case is based on the experiments in Ref. (Plentovich et al., 1993). The cavity has a length-depth ratio of 6:1 and width-depth ratio of 4:1, which are close to the geometrical characteristics of the bogie cavity in current study. The depth and length of the cavity are  $d_1=61$  mm and  $D_1=366$  mm respectively, and the Mach number of incoming flow is equal to 0.2. The corresponding computational domain and boundary conditions are shown in Fig. 5, which are established by referring to the settings used by Kim et al. (Kim et al., 2020).

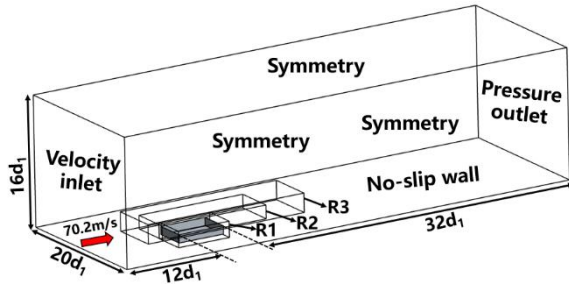


Fig. 5 Computational domain of the clean cavity case

To test the influence of grid size, three sets of meshes are established by modifying the surface grid size of the cavity and the volume grid size in blocks R1-R3 (marked in Fig. 5), named mesh1-mesh3. The number of volume cells of them are 2.8million, 6million, and 8million, respectively. Detailed mesh parameters are listed in Table 2, the mesh parameters of mesh2 corresponds to the grid size of the bogie cavity surface in current study.

Table 2 Mesh parameters of the clean cavity case

	mesh1	mesh2	mesh3
Cavity	1.8 mm	1.5 mm	1.2 mm
Rregion1(R1)	1.8 mm	1.5 mm	1.2 mm
Rregion2(R2)	3.6 mm	3 mm	2.4 mm
Rregion3(R3)	7.2 mm	6 mm	4.8 mm

Fig. 6 presents a comparison between the pressure coefficient  $C_p$  ( $C_p = (p - p_\infty) / (0.5 \rho u_\infty^2)$ ) on the bottom surface of the cavity calculated based on three sets of meshes and the test results (Plentovich et al., 1993). The pressure data is measured on a line probe with a lateral distance of 60.96 mm from the central line of the cavity. At the front and mid part of the cavity, the simulation results are in good agreement with the test results, and the pressure coefficient exhibits a trend of uniform distribution close to 0. At the rear part of the cavity bottom surface, the pressure value increases rapidly with the increase of  $d/D_1$  ( $d$  is the distance from the point probe to the cavity front

wall). The simulation results indicate an overestimation of the pressure values but still align with the observed trend of the test results. With the further refinement of the mesh, this situation did not significantly improve. Therefore, the difference in the pressure results at the rear part of the cavity is likely to be caused by the difference between the simulation and the actual test environment, including differences in inflow quality and failure to fully reproduce the geometry of facilities in the wind tunnel test (the cavity was installed on a suspended flat plate in the wind tunnel test). Considering that the pressure distribution at the bottom of the cavity obtained by current simulation has the same trend as the test results, and the difference between them is also within an acceptable range, it is appropriate to adopt the mesh parameters of mesh2 to generate the surface mesh of the bogie cavity.

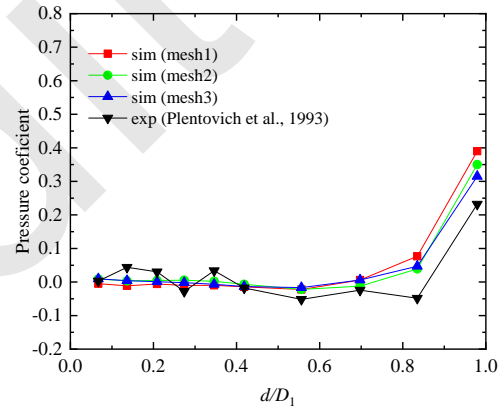


Fig. 6 Comparison of simulation and test results of the pressure distribution

## 4.2 Simple bogie case

The simple bogie model proposed by Zhu (2015) is selected as another case to validate the mesh strategy and numerical methods. The model is composed of two wheelsets and a simple side frame, and is 1:10 scaled, with the wheel diameter  $D_2$  equal to 92 mm and axle diameter  $d_2$  equal to 17.5 mm. Since the model is symmetric about the midspan section of the axle, the wind tunnel test in Ref. (Zhu, 2015) was conducted on a half-bogie model, as shown in Fig. 7 (a). The computational domain and boundary conditions of this case are shown in Fig. 7(b), and are also consistent with the settings in Ref. (Zhu, 2015).

To test the influence of grid size, three sets of meshes are established by modifying the grid size of the bogie surface and the volume grid size around the

bogie, named as mesh1-mesh3, and the volume cell counts of them are 2.8million, 3.9million and 9million, respectively. The corresponding mesh parameters are listed in Table 3, and the mesh parameters of mesh2 are close to the surface grid size of the bogie in section 3.2.

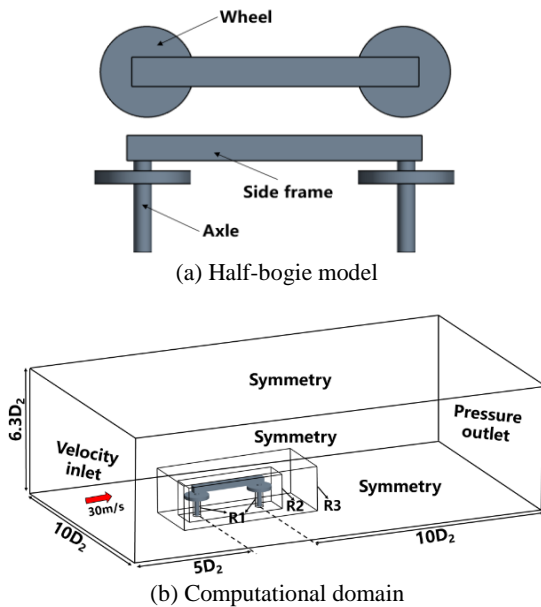


Fig. 7 The simple bogie model and corresponding computational domain

Table 3 Mesh parameters of the simple bogie case

	mesh1	mesh2	mesh3
Axle	0.75 mm	0.375 mm	0.1875 mm
Wheel and side frame	1.5 mm	1.5 mm	0.75 mm
Region1(R1)	0.75 mm	0.75 mm	0.375 mm
Region2(R2)	1.5 mm	1.5 mm	1.5 mm
Region3(R3)	3 mm	3 mm	3 mm

The far-field noise results of the receiver named "top microphone" in Ref. (Zhu, 2015) is used to validate the numerical results. The specific coordinates of the receiver can also be found in Ref. (Zhu, 2015). Fig. 8 illustrates a comparison between the spectrum results obtained by current simulation and from the wind tunnel test. The simulation results based on three sets of meshes and test results are in good agreement with regard to spectrum shape. The main frequency of the wheelset lift fluctuation is also well predicted by the three sets of meshes, with relative error of 7%, 2.2% and 2.3% respectively. However, the sound pressure level at this frequency in the simulation results is slightly higher than the test results and the same phenomenon was found in the numerical results in Ref. (Zhu, 2015). This is mainly because the symmetry boundary used in the simulation has

stronger spanwise uniformity than the solid wall used in the experiment, which strengthens the coherent vortex shedding on the axle and makes noise level corresponding to the vortex shedding frequency higher (Zhu, 2015). Considering that the difference between the simulation results of mesh2 and mesh3 is small and the results of them are closer to the test results, it is appropriate to apply the mesh parameters of mesh2 to the aerodynamic noise simulation of the bogie region.

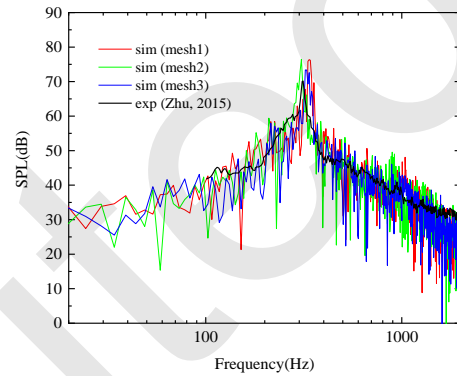


Fig. 8 Far-field noise comparison for the simple bogie model

## 5 Results and discussion

### 5.1 Flow field results

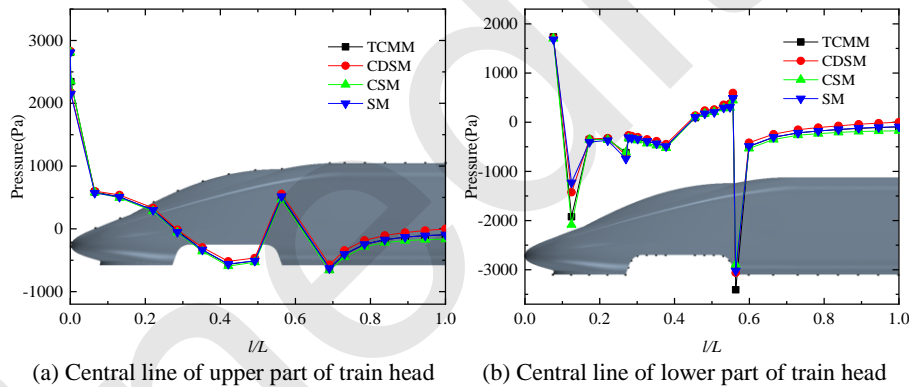
Accurate simulation of the flow field is the premise of accurate prediction of the far field noise. In this section, the time-averaged flow field and fluctuating flow field results obtained by the four models are compared and analyzed to evaluate the effect of different modeling methods on flow field in the train head and bogie region.

#### 5.1.1 Time-averaged pressure

The pressure distribution on the section where the carbody is truncated in the CDSM and SM is checked first (For the CSM and TCMM, the time-averaged pressure data is extracted on the section that at the same position relative to the carbody), as shown in Fig 9. It is evident that due to the implementation of a 0-gauge pressure-outlet boundary condition in the CDSM, it fails to reproduce the pressure distribution with gradient on this section as the TCMM, CSM and SM do. Compared with the TCMM, the CSM overestimates the negative pressure around the train, while the SM underestimates the negative pressure on both sides of the lower part of the carbody, but the relative difference between the results of the SM and TCMM is not as obvious as that

between the CSM and TCMM. Overall, on this section, the pressure distribution of the SM is the closest to that of the TCMM.

Fig. 10 further presents the time-averaged pressure distribution on the central line of the train head to provide a quantitative comparison. A local coordinate system is defined to describe the position of the pressure probe, where  $l$  is the longitudinal distance between the point probe and the nose tip of the train head,  $L=3.67H$  is the total length of the geometry model of the CDSM and SM, and the value of  $l/L$  is taken as the abscissa in Fig. 10. It can be observed that there is an excellent agreement among pressure results of all four models on the streamlined surface. Downstream from the streamlined surface, the pressure on the straight section of the carbody gradually recovers to zero. Comparatively, the CDSM exhibits a faster pressure recovery than the TCMM, while the CSM shows a slightly slower recovery. The pressure results of the SM and TCMM exhibits the closest



(a) Central line of upper part of train head

(b) Central line of lower part of train head

Fig. 10 Time-averaged pressure distribution on the central line of the train head

### 5.1.2 Time-averaged velocity

Fig. 11 illustrates the time-averaged velocity distribution on longitudinal section S1 and horizontal section S2. The results show that the time-averaged velocity field results of the four models are also in good agreement; even the vortex patterns in the bogie cavity are not significantly different. When the airflow passes the front side edge of the bogie cavity, a shear layer forms and extends downstream. The airflow diverted downward from the nose tip forms a small separation zone at the front edge of the cowcatcher, which corresponds to the first negative pressure peak observed in Fig. 10 (b). Then, the airflow reattaches to the bottom surface of the cowcatcher and forms a jet shear layer when passing the rear edge of the cowcatcher, showing a clear boundary with the low-speed zone in the cavity.

agreement. At the lower part of the carbody, two negative pressure peaks can be observed near the front edge of the cowcatcher and the rear edge of the bogie cavity, which indicate the strong flow separation there. For the negative pressure peak at the bottom of the cowcatcher, the TCMM and CSM yield relatively consistent results, which are higher than those obtained from the CDSM and SM. At the rear edge of the bogie cavity, all three simplified models slightly underestimate the negative pressure compared to the TCMM. Downstream from the cavity, similar trends of pressure recovery to that of the upper part can be observed.

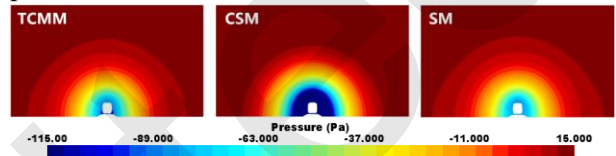


Fig. 9 Time-averaged pressure distribution on the outlet section in the CDSM and SM

Fig. 12 provides a quantitative comparison of the time-averaged velocity distribution in the shear layers below and on the side of the bogie cavity. Two line probes are located on sections S1 and S2, as marked in the background of Fig. 12. Below the bogie cavity, the streamwise velocity  $V_x$  experiences a rapid decrease after entering the bogie cavity area. At the rear edge of the cavity, a peak of  $V_x$  can be observed due to the local flow acceleration caused by the diversion effect of the cavity rear wall. After the airflow leaves the cavity area,  $V_x$  gradually increases. The time-averaged lateral velocity  $V_y$  is not equal to 0, which is attributed to the asymmetry of the bogie structures. The vertical velocity component  $V_z$  initially increases to the maximum positive value after the airflow enters the bogie cavity area, which corresponds to the process of the shear layer rolling up to



enter the cavity. The consistency of the maximum value and change tendency of  $V_z$  in the four models indicates that they predict identical positions where the shear layer rolls up. After that,  $V_z$  quickly changes to the maximum negative value, which corresponds to part of the airflow flowing out of the bogie cavity due to the obstruction of the cavity rear wall. On the side of the cavity, the distribution of streamwise velocity  $V_x$  resembles to that observed at the line probe beneath the cavity, because only in terms of flow in x-direction, the flow at these two positions can be perceived as airflow passing through a backward step and a forward step in tandem. In the middle part of the line probe, a significant difference can be observed between the  $V_x$  results of the CDSM, SM and TCMM, while the difference between the results of the CSM and TCMM is minor. The lateral velocity  $V_y$  shows a

small negative value first, indicating that the airflow tends to roll inward to enter the cavity from both sides. At the rear edge of the cavity,  $V_y$  becomes negative again, which is due to the cavity rear wall forcing the airflow to turn to both sides. The distribution of the vertical velocity  $V_z$  is similar to that observed at the line probe beneath the cavity, indicating that the velocity field here is also affected by the shear layer rolling up below the cavity.

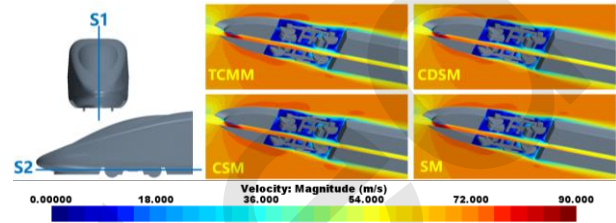


Fig. 11 Time-averaged velocity distribution

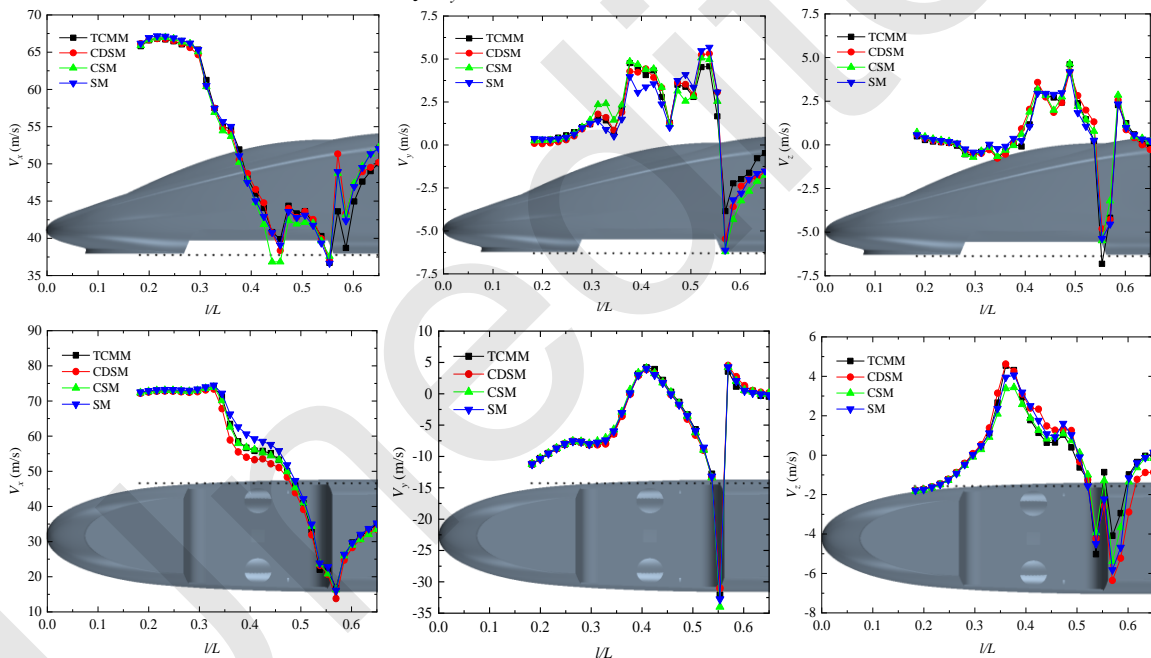


Fig. 12 Time-averaged velocity distribution (Up: Line probe beneath the bogie cavity Down: Line probe at the side of the bogie cavity)

### 5.1.3 Fluctuating pressure

Fig. 13 shows the fluctuating pressure distribution of the train head and bogie region of the four models. Obviously, the amplitude of the fluctuating pressure in the lower part of the train is much higher than in the upper part. The most violent pressure fluctuation occurs at the bottom of the cowcatcher, the lower surface of the bogie (the lower part of the wheel, traction motor and gearbox, and the lower surface of the bogie frame), the rear wall of the bogie cavity, and the carbody surface that connected with the cavity

rear wall. These locations are also the areas with the highest dipole source intensity.

Fig. 14 further compares the fluctuating pressure results on the central line of the train head. On the head streamlined surface, significant relative differences can be observed between the simulation results of the four models. Among them, the results of the CDSM and SM are relatively consistent, while the results of the CSM and TCMM are closer. Compared with the TCMM and CSM, the CDSM and SM underestimate the intensity of the pressure fluctuation

on the head streamlined surface, and with the increase of  $l/L$ , this kind of underestimation becomes more obvious. Considering the differences between the four models, this underestimation is likely due to the use of non-time-varying outlet boundary conditions in the CDSM and SM. At the lower part of the carbody, the simulation results of the four models have the same trend, and the relative difference is small. Two fluctuating pressure peaks appear at the front of the bottom surface of the cowcatcher and the lower part of the cavity rear wall, which are consistent with the two negative pressure peaks observed in Fig. 10(b). The largest relative difference between the four models also occurs in these two positions. At the bottom surface of the cowcatcher, the simulation results of the CSM and TCMM are relatively consistent, while the CDSM and SM underestimate the amplitude of

the fluctuating pressure here. At the rear edge of the bogie cavity, the results of the SM and TCMM are relatively consistent, while the CDSM and CSM underestimate the amplitude of the fluctuating pressure here.

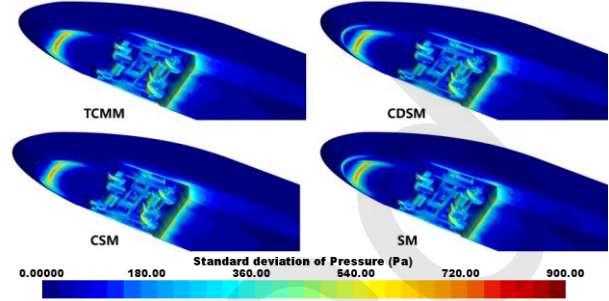
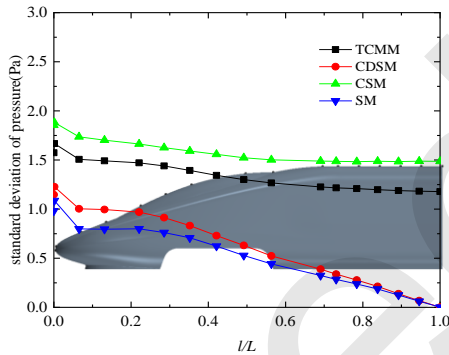
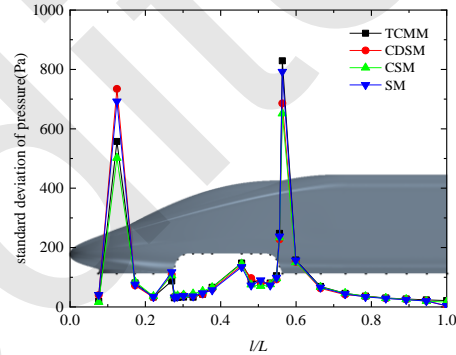


Fig. 13 Fluctuating pressure distribution in the train head and bogie region



(a) Central line of upper part of train head



(b) Central line of lower part of train head

Fig. 14 Fluctuating pressure distribution on the central line of the train head

### 5.1.4 Fluctuating velocity

Fig. 15 shows the time-averaged turbulent kinetic energy  $TKE$  distribution on sections S1 and S2 ( $TKE = 1/2(u'_i u'_i)$ ;  $u'_i$  is the fluctuating velocity in the  $x_i$  direction). Obviously, the most intense velocity fluctuation also occurs in the bogie region, especially in the shear layers formed at the rear edge of the cowcatcher and the front side edge of the bogie cavity.

Fig. 16 presents a quantitative comparison of the fluctuating velocity in the shear layers beneath and on the side of the bogie cavity. The results show that the fluctuating velocity profile in the shear layers beneath and on the side of the bogie cavity simulated by the four models has good consistency and the relative difference between the results of the four models presents a random distribution. As the strength of the velocity fluctuation can reflect the stability of the shear layer, the above results also indicate that the dynamic process of formation, development and de-

stabilization of the shear layers in the four models are also quite consistent.

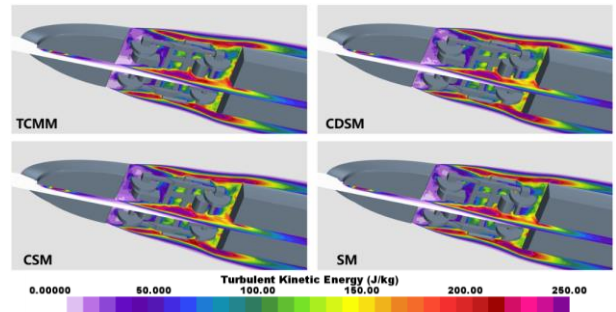


Fig. 15 Time-averaged turbulent kinetic energy distribution

### 5.1.5 Vortex structures

Fig. 17 shows the instantaneous vortex structures defined by the  $Q$ -criterion.  $Q$  is the second invariant of the velocity gradient tensor, defined as  $Q = \frac{1}{2}(\Omega_{ij}\Omega_{ij} - S_{ij}S_{ij})$ , where  $\Omega_{ij}$  is the vorticity tensor and  $S_{ij}$  is the rate-of-strain tensor. As is evident

from the observations, there is a remarkable consistency in the instantaneous vortex structures across the four models. At the front part of the cowcatcher, the vortex structures formed by the flow separation interact with the bottom surface of the cowcatcher, causing severe pressure fluctuations there. The shear

vortex structures with high vorticity form at the leading edge of the bogie cavity and develop downstream, then roll up and invade into the cavity, resulting a strong impingement on the lower part of the bogie and the rear wall of the bogie cavity, as well as violent pressure fluctuation there.

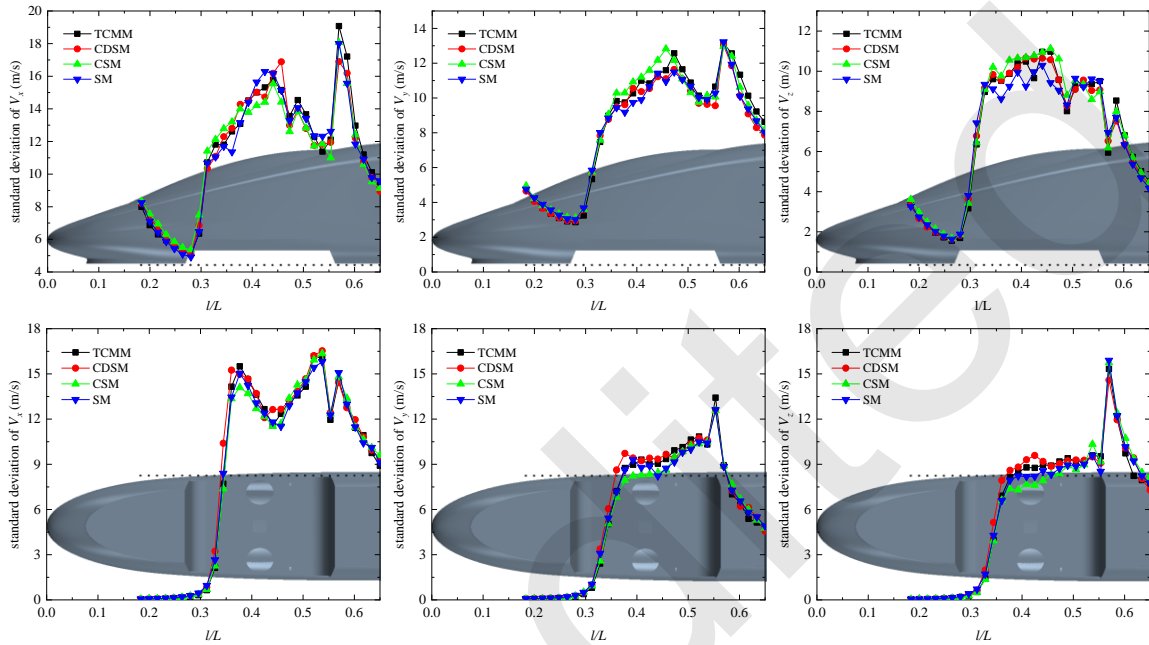


Fig. 16 Fluctuating velocity distribution (Up: Line probe beneath the bogie cavity Down: Line probe at the side of the bogie cavity)

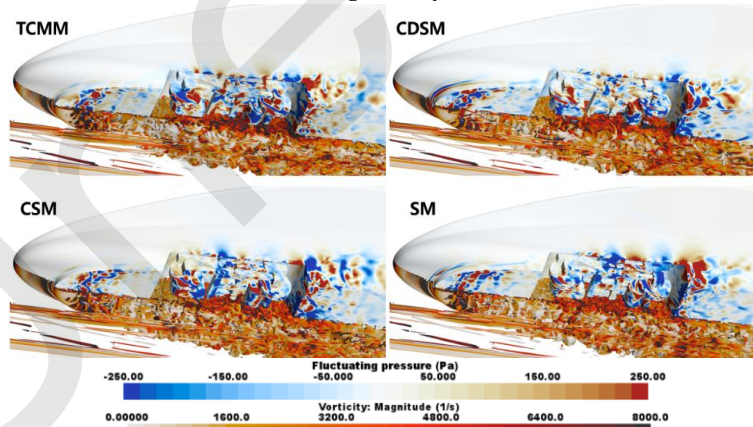


Fig. 17 Instantaneous vortex structures defined by Q-criterion ( $Q = 5000$ )

## 5.2 Far-field noise results

As shown in Fig. 18, the receivers for far-field noise assessment are arranged along two circles (a horizontal circle in the XOY plane and a vertical one in the YOZ plane); the centers of the circles coincide with the geometry center of the bogie model and the radius is 2.5 m.

As mentioned earlier, the train head (Fig. 1(b))

and bogie region (Fig. 1(c)) are used as source surfaces to calculate the far-field noise. Fig. 19 presents the comparison of the overall sound pressure level (OASPL) results of the four models. In most radiation directions, there is no obvious difference between the OASPL results of the two source configurations, indicating that the noise radiation of the train head in most directions is dominated by the bogie region. The most significant difference between the results of the

two source configurations occurs within a small radiation-angle range on both sides of the bogie, with a maximum difference of about 3 dB. In addition, at the receiver above the bogie in the YOZ plane, the OASPL results with the train head used as the source are slightly higher than when the bogie region is used as the source, with a difference of about 1.5 dB. Based on the definition of the source surfaces, the aforementioned differences can be attributed to the con-

tribution of dipole sources distributed on the head streamlined surface and cowcatcher. Considering that these dipole sources can make significant contribution to the far-field noise in some specific directions, it is more rational to use the entire train head (encompassing the head streamlined surface, cowcatcher, and bogie region) as the noise source when conducting aeroacoustics optimization for the bogie region.

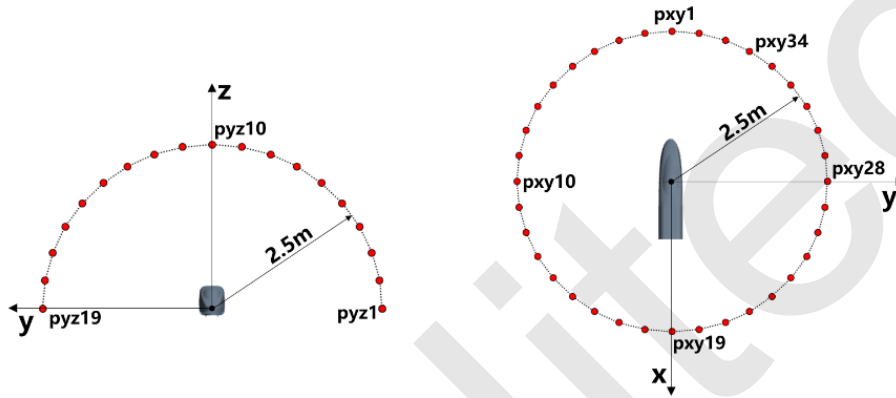


Fig. 18 Arrangement of the far-field noise receivers

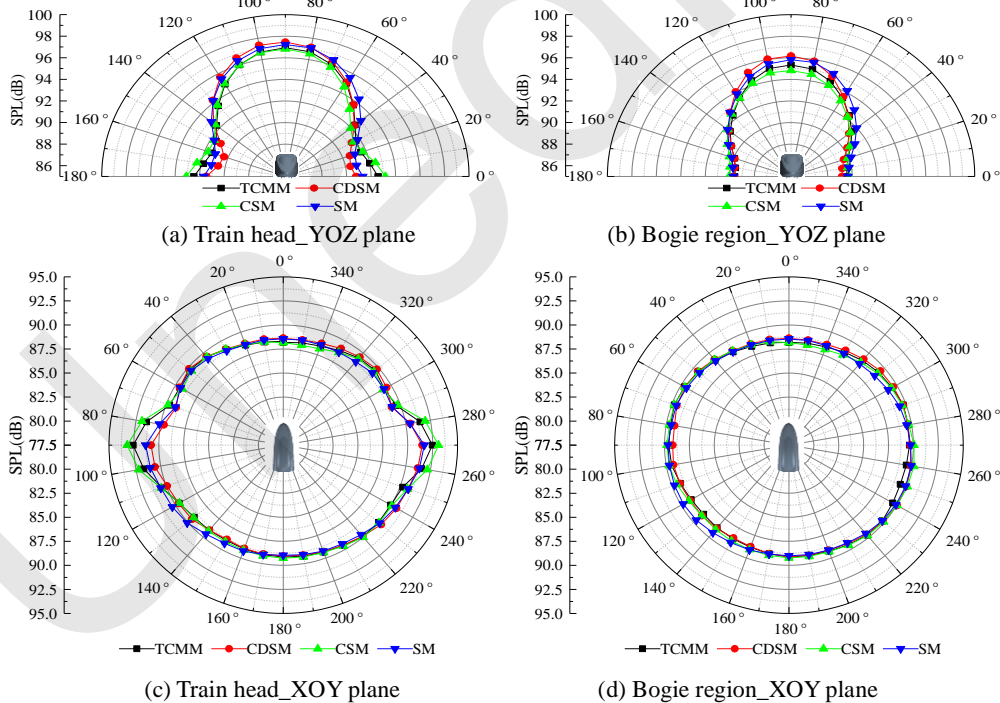


Fig. 19 OASPL results in the XOY and YOZ planes

To give a quantitative description of the difference in the far-field noise results between the three simplified models and the TCMM, define  $\Delta\text{SPL}$  as the absolute value of the difference between the OASPL results of the simplified model and TCMM. Based on the OASPL results in Fig. 19, the average and max-

imum  $\Delta\text{SPL}$  of the three simplified models are summarized in Fig. 20. The results show that when the bogie region is set as the source surface, the differences between the far-field noise results of the three simplified models and that of the TCMM are all within 1 dB. This is consistent with the comparison of

the fluctuating pressure results at the lower part of the carbody shown in Fig. 14(b). When the train head is set as the source surface, the maximum difference between the OASPL results of the CDSM and TCMM is around 1.8 dB, and the maximum difference between the OASPL results of the SM and TCMM is around 1.3 dB, both occurring at pxy28 (marked in Fig. 18); while the difference between the OASPL results of the CSM and TCMM here is still less than 1 dB. According to the previous analysis, the dipole sources on the head streamlined surface and cow-catcher make a significant contribution to the total noise at this receiver. Combined with the fluctuating pressure results in the upper part of the train shown in Fig. 14(a), the difference between the OASPL results of the CDSM, SM and TCMM at this receiver can be attributed to underestimation of the pressure fluctuation on head streamlined surface in the CDSM and SM. In addition, in terms of the average difference, the results of the CSM and TCMM also have minimal discrepancy, regardless of whether the bogie region or the train head is used as the source surface.

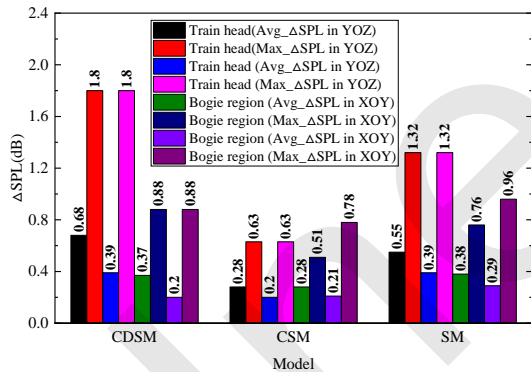
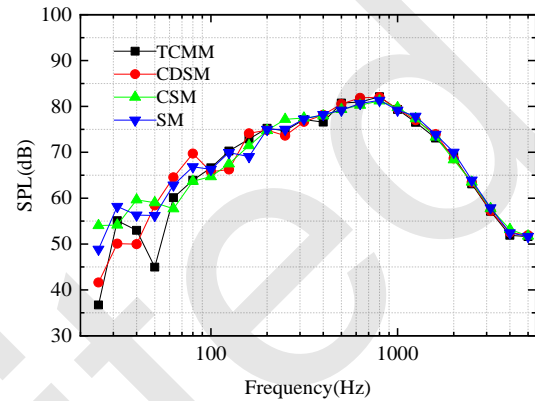


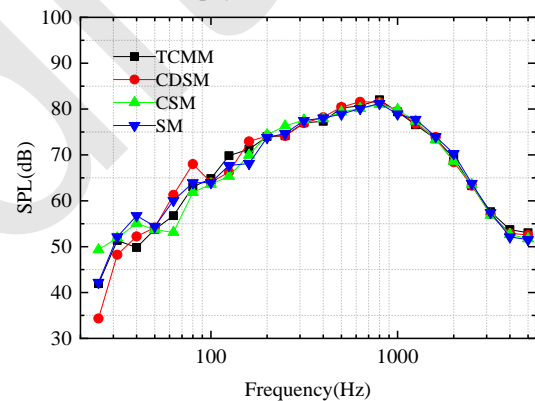
Fig. 20 Statistics of the difference between the OASPL results of the three simplified models and TCMM

Fig. 21 further shows the noise spectrum results at pxy34 and pxy28. At pxy34, whether the train head or bogie region is used as the source surface, the spectrum results of the four models show little difference in the frequency band above 100 Hz. This is because the dipole sources on the streamlined surface and cowcatcher make no obvious contribution to the total noise there. In the frequency band below 100 Hz, the difference in sound pressure level is mainly due to the fact that the current sampling time is not long enough to analyze the low-frequency noise components (below 100 Hz). At pxy28, when the bogie region is set as the source surface, the spectrum re-

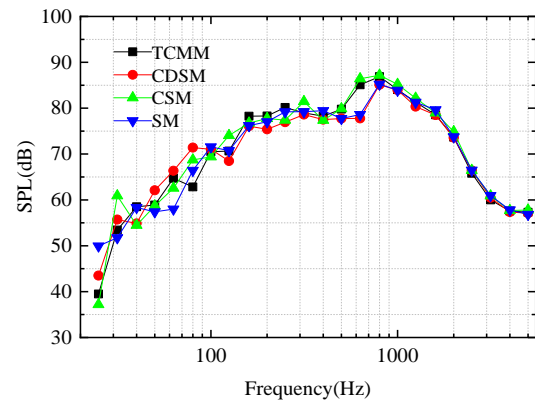
sults of the four models are also in good agreement above 100 Hz. But, when the train head is considered as the source surface, the sound pressure level of the TCMM and CSM in the frequency band with a central frequency of 630 Hz is about 10 dB higher than that of the CDSM and SM, which accounts for the difference in OASPL results at pxy28 observed in Fig. 19.



(a) pxy34 (Train head)



(b) pxy34 (Bogie region)



(c) pxy28 (Train head)

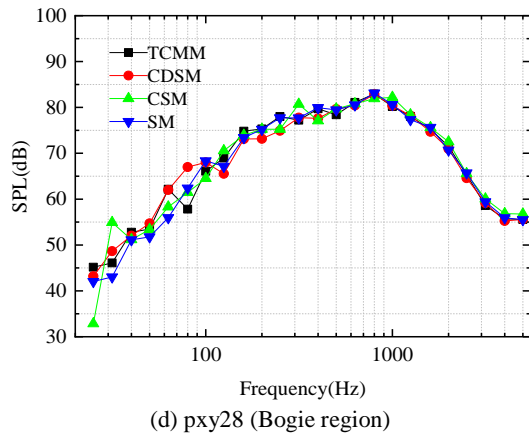


Fig. 21 Noise spectrum results of pxz34 and pxz28

## 6 Conclusions

In order to determine a suitable modeling method to make CFD based aeroacoustics optimization more efficient for the bogie region of high-speed trains. A numerical study is conducted to evaluate the effect of different modeling methods on flow field and aerodynamic noise in the foremost bogie region of a high-speed train in this paper. The reliability of the numerical methods is indirectly validated through a clean cavity case and simple bogie case. By comparing and analyzing the simulation results, the following conclusions are drawn.

(1) The time-averaged pressure distributions on the train surface predicted by the three simplified models are in good agreement with the results of the TCMM. The slight difference in pressure distribution caused by model simplification is only observed in the straight section of the carbody downstream from the head streamlined surface. The time-averaged velocity fields in the bogie region predicted by the three simplified models are also consistent with the results of the TCMM.

(2) The pressure fluctuation at the lower part of the train is much more intense than that at the upper part of the train. Compared with the TCMM, pressure fluctuation results in the bogie region of all three simplified models are in consistent with those of the TCMM. As for the upper part of the train, both the CDSM and SM show an underestimation of the pressure fluctuation here, while the result of the CSM is in good agreement with that of the TCMM. The usage of the non-time-varying outlet boundary conditions in the CDSM and SM is likely to weaken the pressure fluctuation on the head streamlined surface and the carbody surface upstream the outlet boundary.

(3) The most severe velocity fluctuation also occurs in the bogie region, especially in the shear layers formed at the front side edge of the bogie cavity and the rear edge of the cowcatcher. The fluctuating velocity results of all four models are also in good agreement. Since the strength of the velocity fluctuation can reflect the stability of the shear layer, it can be considered that the dynamic process of the formation, development and destabilization of the shear layers in the four models also appears to be consistent.

(4) When only the bogie region is used as the noise source, the far-field noise results of the three simplified models are very consistent with those of the TCMM, with difference of OASPL within 1dB. When the whole train head is used as the source surface, due to the underestimation of dipole source intensity on head streamlined surface in the CDSM and SM, the OASPL results of them and of the TCMM can differ by up to 1.3 dB and 1.8 dB in certain specific directions, while the difference between the OASPL results of the CSM and TCMM is still less than 1 dB. Therefore, the CSM seems to be a good choice for aeroacoustics optimization of the bogie region. It can significantly improve the efficiency of CFD simulation while ensuring consistency with the results of the TCMM.

## Acknowledgments

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## Author contributions

Jiawei SHI and Yuan HE designed the research. Jiawei SHI processed the corresponding data. Jiawei SHI wrote the first draft of the manuscript. Jiye ZHANG and Tian LI revised and edited the final version.

## Conflict of interest

Jiawei SHI, Yuan HE, Jiye ZHANG, and Tian LI declare that they have no conflict of interest.

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## 中文概要

**题目:** 几何简化和边界条件指定对高速列车车头和转向架区域流场和气动噪声的影响

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**目的:** 本文的目的是确定一种合适的简化建模方法以使 CFD 模拟在高速列车转向架区域气动声学优化中更高效。

**创新点:** 1. 确定了一种合适的简化建模方法, 在保证与三车编组模型中头车第一个转向架区域流场和声学结果一致性的同时显著提高 CFD 模拟在高速列车转向架区域气动声学优化中的效率; 2. 通过对三种简化模型和三车编组模型流场和声学结果的对比和分析, 确定了三种简化模型中涉及的不同几何简化和边界条件指定对车头和转向架区域流场和气动噪声的影响机理。

**方法:** 1. 在三车编组模型的基础上, 建立用于高速列车转向架区域气动噪声计算的三种简化模型; 2. 结合 IDDES 模型和 FW-H 声类比理论建立转向架区域非定常流场和气动噪声预测的数值模型, 通过低马赫数空腔模型和简单转向架模型对数值方法和网格策略进行验证; 3. 以三车编组模型的计算结果为基准, 对三种简化模型和三车编组模型的流场和声学结果进行对比和分析, 确定与三车编组模型计算结果一致性最好的建模方式并揭示三种简化模型中涉及的不同几何简化和边界条件指定对车头和转向架区域流场和气动噪声的影响机理。

**结论:** 1. 基于三种简化模型计算得到的列车表面时均压力分布和转向架区域时均速度分布与三车模型的计算结果非常一致; 2. 列车下部的压力波动较列车上部剧烈得多。三种简化模型的转向架区域脉动压力结果与三车模型的计算结果有很好的

一致性。在列车上部, 计算域缩短模型和子域模型低估了车头流线型表面上的压力波动, 而车体缩短模型的结果与三车编组模型的结果吻合较好。这是计算域缩短模型和子域模型中使用的非时变出口边界条件造成的; 3. 当仅以转向架区域作为声源时, 三种简化模型的远场噪声结果与三车编组模型的结果间的差异都很小, 总声压级差异均在 1 dB 以内。当以整个车头作为噪声源时, 由于计算域缩短模型和子域模型对车头流线型表面偶极子源强度的低估, 它们与三车编组模型的总声压级结果最大差异分别为 1.3 dB 和 1.8 dB, 而车体缩短模型与三车编组模型的总声压级结果差异仍在 1 dB 以内。因此, 车体缩短模型是转向架区域气动声学优化的一个很好的选择, 它可以在保证与三车编组模型计算结果一致性的同时显著提高 CFD 模拟的效率。

**关键词:** 转向架区域; 车头; 流场; 气动噪声; 几何简化; 边界条件