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Research on the Influence of Cross Passage on High-speed Maglev Train Pressure Waves in Tunnels

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Abstract

This study aims to investigate the influence of cross passage on pressure waves in tunnels during the operation of high-speed maglev trains. Utilizing computational fluid dynamics numerical simulation techniques, a three-dimensional, unsteady, compressible Navier-Stokes equation coupled with the k-ω turbulence model was established to model the flow field inside the tunnel with cross passage. The results showed that increasing the diameter of the cross passage can significantly reduce the peak-to-peak pressure on the train body surface, while placing the cross passage in the middle of the tunnel minimizes the peak-to-peak pressure variation. Additionally, an increase in the length of the cross passage leads to an increase in the peak-to-peak pressure variation on the train body surface. Therefore, the design and arrangement of cross passage are crucial for mitigating the impact of pressure waves. The results of this study provide important references for ensuring the safe operation of high-speed maglev trains.

Keywords: high-speed maglev train, train, tunnel, pressure wave, cross passage, numerical simulation.

1 Introduction

High-speed maglev trains, as a potential solution for future urban transportation, have garnered widespread attention for their operation within tunnels. When the train speed reaches 600 km/h, the pressure wave in the tunnel increases significantly, with the pressure reaching up to 10 kPa for individual high-speed maglev train passing through and up to 20 kPa when two trains meet in a tunnel [1]. The high-intensity pressure waves pose significant challenges to the aerodynamic design of high-speed maglev train bodies, and effective control of these pressure waves is crucial for ensuring train safety and improving passenger comfort.

Previous studies have extensively discussed the generation mechanism, propagation laws, and measures to reduce pressure waves inside tunnels [2]. However, most of the research has focused on high-speed trains with speeds less than 350 kilometers per hour, and there are relatively few publicly available reports on the aerodynamic problems of 600 km/h maglev trains in tunnels. Mei [3], Jia [4], and others have used the characteristic line method of a one-dimensional compressible unsteady non-isentropic flow model to study the characteristics of compression wave propagation when high-speed maglev trains pass through tunnels, the excitation and attenuation characteristics of compression waves, the influence of tunnel length and cross-sectional area of tunnels on pressure waves, and predicted the variation of micro-pressure waves at the tunnel exit. Han [5], using a three-dimensional unsteady compressible fluid model and slip mesh technology, studied the influence of maglev train speed on tunnel pressure waves and found that the maximum pressure on the train surface is related to train running speed to the power of 2.35.

Research on the impact of tunnel components, such as portal buffer devices, vertical shafts, and cross passages, on pressure waves, currently mainly focuses on the field of high-speed trains. Honda et al. [6-7] studied a high-speed train passing through a tunnel with a buffer structure at a speed of 500km/h, and found that the buffer structure can effectively reduce the gradient of the initial compression wave at the tunnel entrance and the micro-pressure wave at the tunnel exit. Zhang et al. [8] studied the energy-saving effect of vertical shafts on natural ventilation in ultra-long tunnels through theoretical analysis and optimized the diameter and position of vertical shafts. Zhao et al. [9], through numerical simulation, analyzed in detail the influence of vertical shaft shape, cross-sectional area, and connection form with the tunnel on the propagation law of compression waves inside the tunnel, demonstrating that vertical shafts can effectively alleviate the peak value of initial compression waves and micro-pressure waves, with a significant pressure reduction effect. Hu et al. [10], based on a three-dimensional unsteady compressible fluid model, studied the influence of cross passage on the force and thermal effects of vehicles in vacuum tunnels, showing that after setting cross passage, the aerodynamic resistance and thermal effects experienced by vehicles passing through are reduced. Luo et al. [11], using a combination of dynamic model experiments and numerical simulations, studied the influence of cross passage on the generation and propagation of compression waves and micro-pressure waves in tunnels, finding that the cross passage can reduce the peak pressure of initial compression waves, regulate pressure pulsations in tunnels, and reduce micro-pressure waves. Su et al. [12], through one-dimensional theoretical analysis and full-scale cold smoke experiments, studied the relationship between subway tunnel fan airflow parameters and cross passage ventilation speed, quantifying the effects of train position, fire heat release rate, and main tunnel ventilation speed on the critical speed of cross passage.

This study uses computational fluid dynamics (CFD) numerical simulation technology, combined with the special structure of the tunnel cross passage, to establish a tunnel internal flow field model to simulate the operation process of high-speed maglev trains inside the tunnel. By comparing simulation results under different working conditions, the impact of cross passage on pressure waves is analyzed to guide actual vehicle and tunnel design.

2 Methods

2.1 Train and Tunnel Models

The train model used in this study is depicted in Figure 1. The train model is a full-scale 3-car set of high-speed maglev train, featuring streamlined nose with smooth body surfaces and components such as inter-car fairing and suspension systems. The maglev train has a height of 4.2 meters, a width of 3.7 meters, and a total length of 81.2 meters.

Figure 2 shows a tunnel model with cross passage. In the numerical simulation of this article, the tunnel adopts a single-track tunnel with T-shaped track beams. The cross section of the tunnel is shown in Figure 2(a). The tunnel length is 600 meters and the clearance cross-sectional area is 92 square meters. The cross section of the cross passage consists of a square with side length D and a semicircle with diameter D, as shown in Figure 2(b). For ease of description, we define the distance between the cross passage and the tunnel entrance as L, and the length of the cross passage, that is, the distance between the two tunnels, as H, as shown in Figure 2(c).

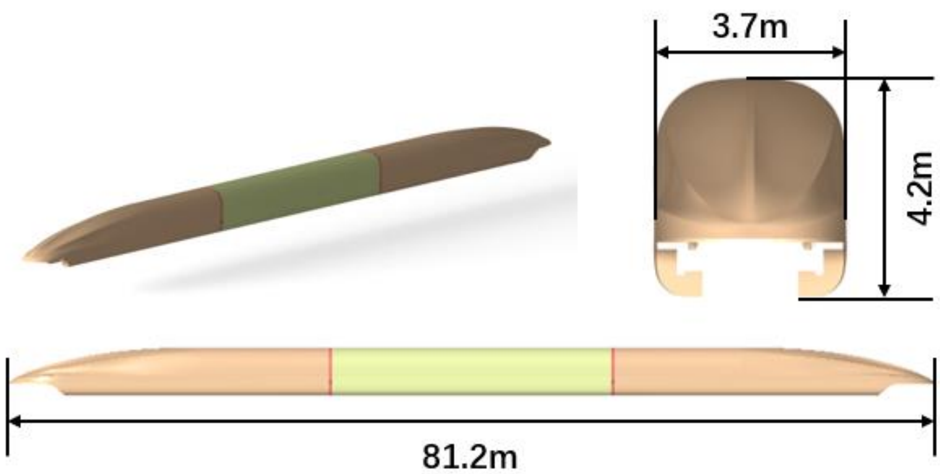
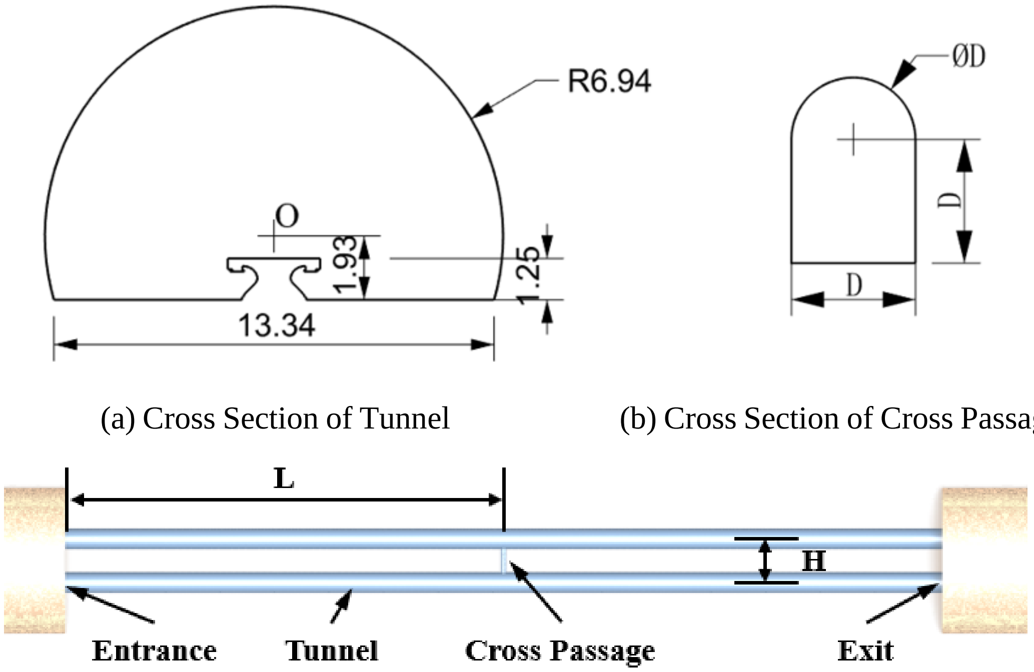


Figure 1: Geometric Model of High-Speed Maglev Train.



(a) Cross Section of Tunnel (b) Cross Section of Cross Passage

(c) Tunnel and Cross Passage

Figure 2: Tunnel Model with Cross Passage.

2.2 Numerical Simulation Model

The high-speed maglev train studied in this paper operates at a speed of 600 km/h and involves issues such as the generation, propagation, and interference of tunnel compression waves and expansion waves. Therefore, this study considers the compressibility of air and selects the three-dimensional, unsteady, compressible Navier-Stokes equations as the governing equations, with turbulence simulated using the k-ω two-equation model.

The relative motion and data exchange between the train and the ground/tunnel are realized using overset grid technology, dividing the computational domain into a background region and an overset region (containing the moving train). The background region encompasses the entire computational domain, while the overset region contains the moving train. To accurately capture the pressure wave characteristics generated when the train enters the tunnel and ensure sufficient development of the flow field before the train enters the tunnel, the lengths of the atmospheric regions at the tunnel entrance and exit are set to 250 m, with the distance between the train's front and the tunnel entrance approximately 100 m, as shown in Figure 3. The boundaries of the computational domain outside the atmospheric regions are set to non-reflective boundary conditions, while the train body is set to a no-slip wall boundary condition.

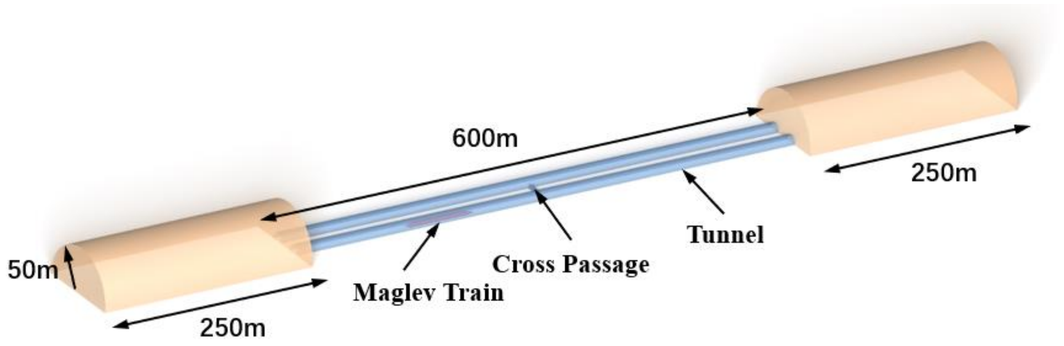
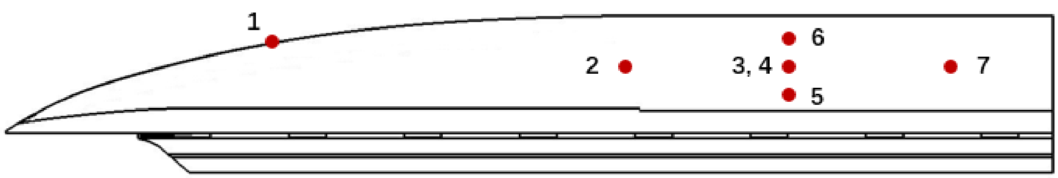


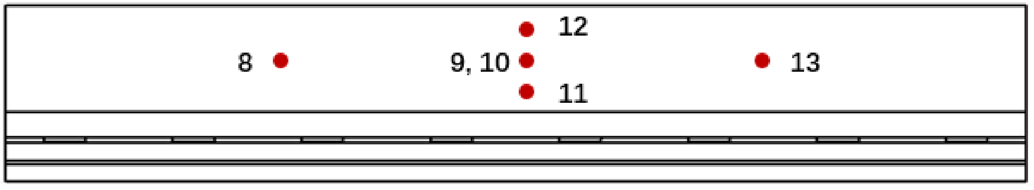
Figure 3: Computational Domain.

2.3 Distribution of Pressure Probes

To study the pressure waves acting on the surface of the high-speed maglev train as it passes through tunnels, a series of pressure probes are arranged on the surfaces of the three cars. The locations of these pressure probes are illustrated in Figure 4. Seven probes are arranged on the front car, as shown in Figure 4(a). Probe 1 is located in the streamlined nose region, while probes 2 to 7 are situated along the straight section of the head car, with probes 3 and 4 symmetrically positioned about the centerline of the car body. Six pressure probes are positioned on the middle car, labeled 8 to 13, as depicted in Figure 4(b). Probes 9 and 10 are symmetrically located about the centerline of the car body. The arrangement of pressure probes on the rear car is identical to that on the front car, resulting in a total of 20 probes distributed across the whole train.



(a) Head Car



(b) Middle Car

Figure 4: Distribution of Pressure Probes.

3 Results

3.1 Influence of Cross Passage Diameter on Pressure Waves

This section investigates the effect of different cross passage diameters on the surface pressure of the train body when a maglev train passes through a single-track tunnel with cross passage connecting to another tunnel of the same cross-section at a speed of 600 km/h. The length of the cross passage H used in the simulation is 30 meters, the distance between the cross passage and the tunnel entrance L is 300 meters, and the cross passage diameters D are 2.9 meters, 3.2 meters, 3.5 meters and 3.8 meters respectively. Figure 5 shows the peak-to-peak pressure distribution on all pressure probes of the train body surface. It can be seen that as the diameter of the cross passage increases, the peak-to-peak pressure of the vehicle body surface decreases significantly.

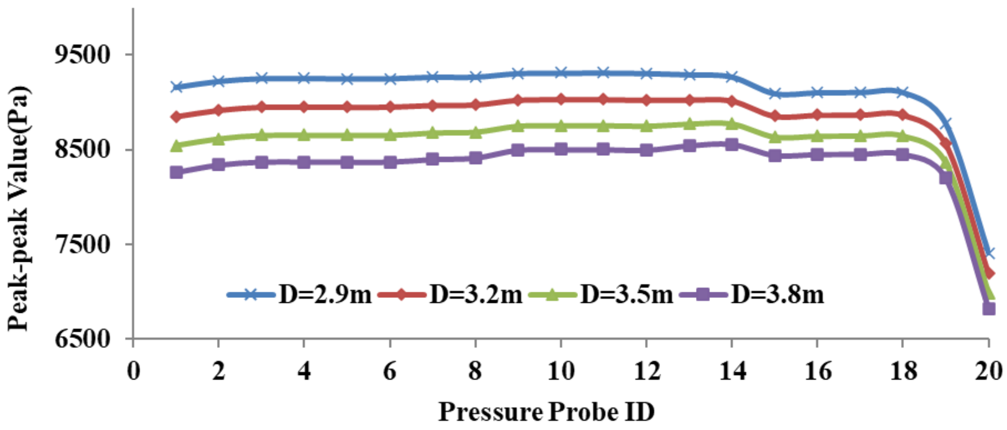


Figure 5: Peak-to-peak Pressure Distribution (H=30m, L=300m).

Table 1 presents the statistics of maximum peak-to-peak pressures on the body surface corresponding to different cross passage diameters, while Figure 6 illustrates the fitting curve between cross passage diameter and maximum peak-to-peak pressure value. It is evident that there exists a quadratic polynomial relationship between the cross passage diameter and the maximum peak-to-peak pressure value on the train surface. Therefore, for a fixed tunnel, there exists an optimal cross passage diameter that maximizes the mitigation effect of cross passages on pressure waves.

Cross passage diameter D (m)	2.9	3.2	3.5	3.8
Max. peak-to-peak pressure on train surface (Pa)	9311	9030	8776	8559

Table 1: Maximum Peak-to-peak Pressure Statistics (H=30m, L=300m).

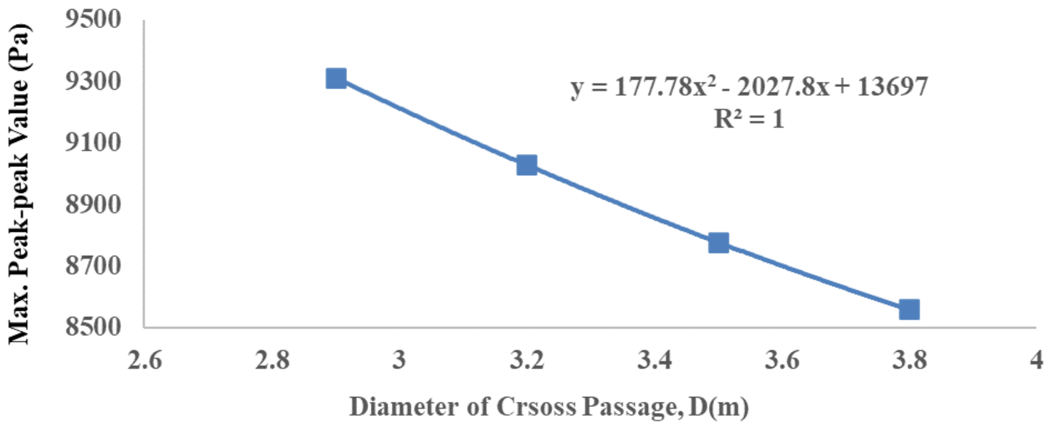


Figure 6: Fitting Curve of Cross Passage Diameter and Peak Pressure.

3.2 Influence of Cross Passage Distance from Tunnel Entrance on Pressure Waves

This section explores the effect of the distance of the cross passage from the tunnel entrance on the surface pressure of the train body when a maglev train passes through a single-track tunnel with cross passage connecting to another tunnel of the same cross-section at a speed of 600 km/h. The cross passage length H selected for simulation is 30 meters, the cross passage diameter D is 3.8 meters, and the distances between the cross passage and the tunnel entrance L are 200 meters, 300 meters and 400 meters respectively. Figure 7 shows the peak-to-peak pressure distribution on all pressure probes of the train surface. Table 2 shows the statistics of the peak-to-peak pressure of the vehicle body surface corresponding to different distances between cross passage and the tunnel entrance. It can be found that when the cross passage is at 300m, that is, in the middle of the tunnel, the peak-to-peak value of the surface pressure is the smallest. Arranging cross passages away from the middle of the tunnel will increase the peak-to-peak pressure changes on the train surface.

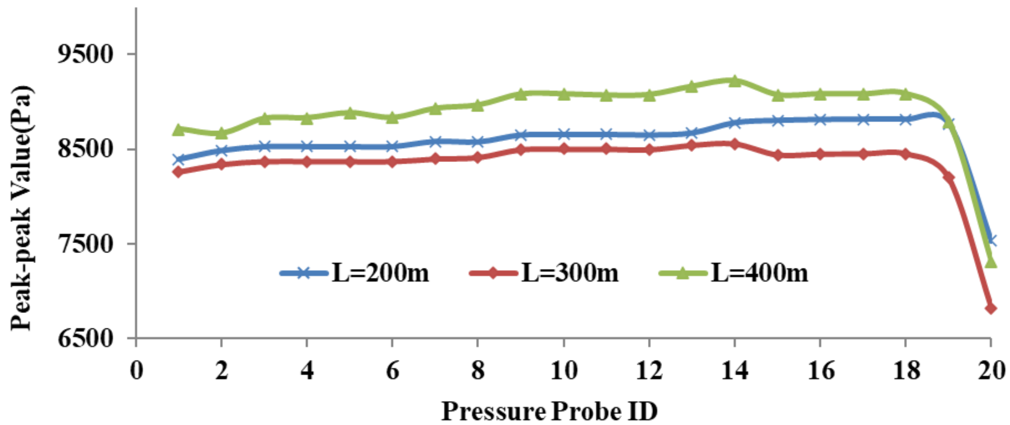


Figure 7: Peak-to-peak Pressure Distribution (H=30m, D=3.8m).

Distance between cross passage and tunnel entrance L (m)	200	300	400
Max. peak-to-peak pressure on train surface (Pa)	8815	8559	9219

Table 2: Maximum Peak-to-peak Pressure Statistics (H=30m, D=3.8m).

3.3 Influence of Cross Passage Length on Pressure Waves

This section investigates the influence of the line spacing, i.e., the length of the cross passage, on the surface pressure of the train body when a maglev train passes through a single-track tunnel with cross passage connecting to another tunnel of the same cross-section at a speed of 600 km/h. The diameter of cross passage D used in the simulation is 3.8 meters, the distance between the cross passage and the tunnel entrance L is 300 meters, and the lengths of the cross passage H are 30 meters, 40 meters and 50 meters respectively. Figure 8 shows the peak-to-peak pressure distribution on all pressure probes of the train surface. Table 3 shows the statistics of the maximum peak-to-peak pressure values on the car body surface corresponding to different cross passage lengths. It can be found that as the length of the cross passage increases from 30 meters upwards, the peak-to-peak pressure change on the vehicle body surface increases. This is because the cross passage is equivalent to a tunnel entrance or exit, and the increase in cross passage length is not conducive to the separation and propagation of pressure waves.

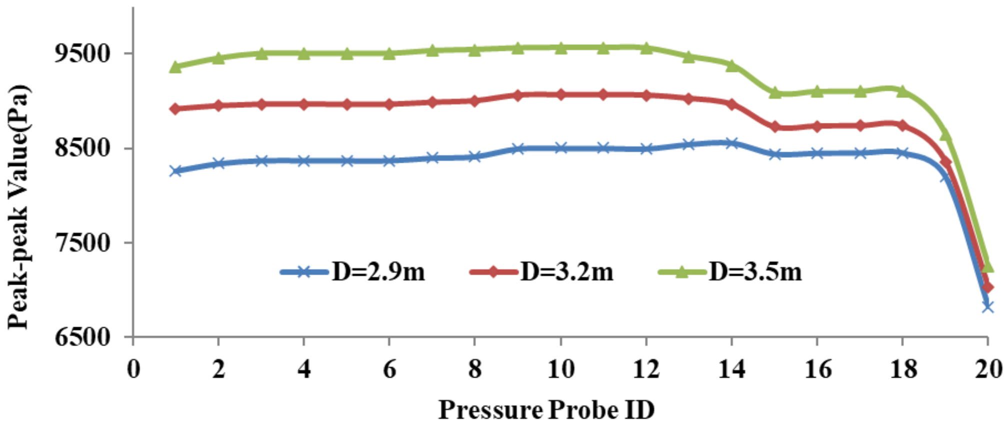


Figure 8: Peak-to-peak Pressure Distribution (L=300m, D=3.8m).

Cross passage length H (m)	30	40	50
Max. peak-to-peak pressure on train surface (Pa)	8559	9067	9565

Table 3: Maximum Peak-to-peak Pressure Statistics (L=300m, D=3.8m).

4 Conclusions

This paper selects a tunnel length of 600 meters, a cross passage diameter of 3.8 meters, a distance between cross passage and the tunnel entrance of 300 meters, and a cross passage length of 30 meters as the baseline tunnel configuration. Using numerical simulation methods, the influence of different cross passage diameters, distances between cross passages and tunnel entrance, and cross passage lengths on the pressure waves of the train surface when a high-speed maglev train passes through the tunnel at 600 km/h is studied. The following conclusions are drawn:

(1) Increasing the cross passage diameter significantly reduces the peak-to-peak pressure on the train body surface. For a fixed tunnel, there exists an optimal cross passage diameter that maximizes the mitigation effect of cross passages on pressure waves.

(2) When the cross passage is located at a distance of 300 meters from the tunnel entrance, i.e., at the middle position of the tunnel, the peak-to-peak pressure on the train surface is minimized. Arranging cross passages away from the middle of the tunnel will increase the peak-to-peak pressure.

(3) Increasing the cross passage length from 30 meters upwards increases the peak-to-peak pressure on the train surface. That is, increasing the cross passage length is disadvantageous for the separation and propagation of tunnel pressure waves, resulting in an increase in peak-to-peak pressure.

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