Aerodynamics of Metro Passing the Tunnel with Speed over 90km/h

Dong-jin Zhu¹, Zheng Wang², Jia-qiao Hu, Yao-zheng Zeng³ and Tian Li²

ABSTRACT

With reference to some relevant domestic and abroad standards on EMU and high-speed railway vehicles, this paper makes a study on the aerodynamic evaluation standard and evaluation indexes of the metro with speed over 90km/h when it passes the tunnel. It also elaborates the principle of the generation of pressure wave undulation in the vehicle and makes suggestions on ride index improving including measures to enhance vehicle air tightness, increase tunnel cross section, control operation speed limit and improve line status.

Key words: metro; aerodynamics; pressure; ride index

1. INTRODUCTION

When a vehicle is running through a tunnel, it may lead to a series of problems on aerodynamics, such as abrupt fluctuation of air pressure, the increase of

¹ CRRC Puzhen Bombardier Transportation Systems Limited, Nanjing 210031, China;
2. Southwest Jiao Tong University, Chengdu 610031, China;
3. Technical Center, CRRC Nanjing Puzhen Co., Ltd., Nanjing 210031, China;
Zhu Dong-jin, Technical experts of CRRC, Vehicle Manager, CRRC Puzhen Bombardier Transportation Systems Limited, 11 Floor, Unit 2, Building 11, Mingfa Group JiangSU Business Park, Pukou North Road #5, Pukou District, Nanjing, China.
aerodynamic resistance, generation of complex air flow and micro-pressure wave at the portal, etc. Those problems are not obviously shown for the metro with the speed level under 90km/h. However, with the operation or the construction of many metro lines with vehicle speed level higher than 90km/h in China, those problems come about gradually. For example, the driver and passengers feel uncomfortable because of the air pressure wave generated when a metro passes a tunnel. In this case, more attention is paid to aerodynamics study for a metro vehicle passing a tunnel.

2. EVALUATION ITEMS OF AERODYNAMICS FOR A METRO PASSING A TUNNEL

There are no defined criteria and indexes for the evaluation of aerodynamics for an urban railway transit vehicle including metro vehicle passing a tunnel. With reference to some relevant domestic and abroad regulations for multiple units and high speed railway vehicles, the items to evaluate the aerodynamics of a metro vehicle passing a tunnel shall mainly include: maximum pressure fluctuation amplitude, ride comfort, portal micro-pressure wave, aerodynamic load borne by vehicle and pressure intensity of attachments in tunnel.

2.1 Maximum Pressure Fluctuation Amplitude

Maximum pressure fluctuation amplitude refers to the maximum value of “peak to peak”, which is normally generated when two trains from different directions are meeting at the “worst position” in the tunnel. The minimum pressure difference causing middle ear barotrauma is 8.0kPa. Working Team C218 of European Railway Research Institution (ERRI) suggests [1]: from the medical point of view, to ensure the health of passengers and trainmen, the allowed maximum pressure fluctuation amplitude in the car is 10kPa and the worst condition that the tightness of the train is completely lost (index of tightness is equal to zero) shall be considered.

According to European standard EN14067-3 [2] and with reference to the other relevant European standards, the relational expression of carbody surface pressure fluctuation amplitude of a single train passing a one-line tunnel:

$$\Delta P = \rho v^2 \beta / (1 - 2\beta)$$  \hspace{1cm} (1)

In the expression,

\(\Delta P\) refers to the carbody surface pressure fluctuation amplitude;

\(v\) refers to the running speed of the train;
\( \beta \) refers to the blockage ration;

\( \rho \) refers to the air density.

When the train passes a one-line tunnel with the speed of 120km/h and the blockage ratio is 0.3250, the car-body surface pressure fluctuation amplitude is about 1264Pa. Therefore, the maximum pressure fluctuation amplitude generated when a metro passing a tunnel will not reach the above mentioned limit in the medical point of view.

2.2. Evaluation Index of Ride Comfort

According to Supplement Regulation of Relevant Standard on Railway Tunnel Design and Construction (Railway Construction 【2007】No.88)[3], the following criteria is used to evaluate the ride comfort:

- Tunnel with single line: pressure in car <0.80kPa/3s
- Tunnel with double line: pressure in car <1.25kPa/3s

CFD software is used to simulate the pressure change inside and outside the train when the train is passing a tunnel with the speed of 90km/h and 100km/h. See details in Figure 1.

With the decrease of speed, the maximum internal pressure fluctuation amplitude decreases. When the train is running at the speed of 100km/h, the maximum internal pressure fluctuation amplitude is 734kPa and the maximum internal pressure fluctuation amplitude within 3s is about 1170kPa. When the train is running at the speed of 90km/h, the maximum internal pressure fluctuation amplitude is 560kPa and the maximum internal pressure fluctuation amplitude within 3s is about 900kPa.
According to the value simulation in figure 1 and the following test results, the ride comfort index for the train passing a tunnel with the speed higher than 90km/h will approach or even exceed the above-mentioned criteria. On the other hand, for the metro train with the speed of or lower 80km/h, there are few papers studied the aerodynamics for the metro train passing a tunnel with the critical speed higher than 90km/h.

When the metro train passes a tunnel with the speed higher than 90km/h, the ride comfort index will easily exceed the allowed range.

2.3 Evaluation Index of Micro-pressure Wave

The criteria of micro-pressure wave is shown as follows: if there is no building within 50m to the portal of tunnel, the peak of micro-pressure wave at 20m to the portal of tunnel is less than 50Pa; if there is building within 50m to the portal of tunnel, the peak of micro-pressure wave at the area of building is less than 20Pa. The micro-pressure wave is mainly studied for the high-speed train with the speed higher than and equal to 350km/h. When the train passes a tunnel of 700m with the speed of 120km/h, at the area of 20m to the tunnel portal, the pulse pressure is shown in figure
2. According to the figure, the micro-pressure generated when the metro train passes the tunnel satisfies the above-mentioned criteria with a high safety margin.

![Figure 2. Pressure Change at the Area with 20m to Tunnel Portal.](image)

**2.4 Aerodynamic Load Borne by Vehicle**

According to Provisional Regulation on Vehicle Strength Design and Test for the Railway Vehicles with Speed of and higher than 200km/h (Kejiaozhuang 【2001】 No.21)\(^d\) issued by Technology Office of Railway Ministry, regarding vehicle static strength evaluation, 4000Pa shall be taken for aerodynamic load. According to the regulation of Article 4.2.2 in UIC (International Union of Railway) Leaflet 566, the changing amplitude which shall be borne by the train itself and its window shall be alternating load of ±2500Pa with frequency of 3Hz. When the carbody strength calculation and fatigue simulation is performed, the above-mentioned index can be added to the fatigue loads to verify whether the vehicle structure can satisfy the above-mentioned index requirements.
2.5 Aerodynamic Load of Attachments in Tunnel

According to High-speed Railway Design Regulation Article Explanation[5], 3300Pa is recommended to be taken as the additional pressure for the hollow attached facilities in the tunnel with a double portal and single line in the level of 250km/h, such as tunnel door. Therefore, during the design and construction verification of the attachments in the tunnel for metro operation, the above-mentioned index or similar index shall be referred to.

3. GENERATION AND TRANSMISSION PRINCIPLE OF INSIDE AND OUTSIDE PRESSURE WAVE

When the metro vehicle enters a tunnel, the flowing space for the air around vehicle will be limited and squeezed suddenly by the wall of the tunnel. When the head car enters the tunnel, there will be compression wave resulting in pressure rising. On the other hand, when the tail car enters the tunnel, there will be expansion wave resulting in pressure lowering. The above-mentioned two kinds of waves will be transferred in the tunnel round and round in sound velocity. Some energy will be radiated to the outside of tunnel at the tunnel portal (i.e., micro-pressure wave) and some energy will be reflected back towards the tunnel portal.

Figure 3(a) shows the pressure wave change on the external surface of head car with the time for the whole process from a vehicle entering a tunnel till it leaving the tunnel.

In Figure 3(b), the black line refers to the displacement of the test points of the head car and tail car in the tunnel. Viewing from the left side, the first red full line refers to the positive pressure wave generated when the head of vehicle enters the tunnel and the first blue dotted line refers to the negative pressure wave generated when the tail of vehicle enters the tunnel. When the positive pressure wave reaches the tunnel portal, it will reflect a negative pressure wave towards the tunnel, which is shown in blue dotted line. On the other hand, when the negative pressure wave reaches the tunnel portal, it will reflect a positive pressure wave towards the tunnel, which is shown in red full line.
In Figure 3(b), \(1\)\(2\)\(3\)\(4\)\(5\)\(6\) refer to the special times of the test points of head of vehicle during the operation in tunnel and the corresponding pressure wave of the test points of head of car (see figure (a)). The six special times are listed respectively as follows:

- After the head car enters the tunnel, the generated positive compression wave is transmitted to the test point \((1)\) in figure and the pressure at the test point starts rising;
- After the tail car enters the tunnel, the generated expansion wave is transmitted to the test point \((2)\) in figure and the pressure at the test point starts decreasing;
- When the compression wave is transmitted to the tunnel portal and reflected back to the test point in the way of expansion wave \((3)\) in figure, the pressure at the test point continue to decrease;
- When the expansion wave is transmitted to the tunnel portal and reflected...
back to the test point in the way of compression wave (④ in figure), the pressure at the test point continue to rise;
✧ When the secondary expansion wave is transmitted to the tunnel portal and reflected back to the test point in the way of compression wave (⑤ in figure), the pressure starts decreasing;
✧ When the secondary compression wave is transmitted to the tunnel portal and reflected back to the test point in the way of expansion wave (⑥ in figure), the positive pressure at the test point reaches the peak value and the pressure starts decreasing;

Record the pressure wave fluctuation of the test point continuously to obtain the fluctuation curve as Figure 3(a). In this case, the pressure wave fluctuation can be known for certain point outside the head of vehicle when it passes a tunnel. With the influence of vehicle tightness and carbody strength, the outside pressure wave fluctuation will be transmitted to the inside of vehicle with certain attenuation. The change rules of inside pressure are similar to those of outside pressure. Because of the act of vehicle tightness, the inside pressure wave fluctuation will be a little bit later than the outside pressure wave fluctuation.

The pressure wave generated when a vehicle passes a tunnel in high-speed railway line is a complex issue on aerodynamics. Regarding the urban railway transit vehicle with the speed under 90km/h, because the speed of the vehicle passing the tunnel is not high and the generated pressure wave fluctuation has less influence, less attention is paid and it is not necessary to have a specific study. With the increase of speed and no obvious improvement on air tightness for the metro train with speed high than 90km/h, the following problems caused by inside pressure wave fluctuation due to the outside pressure wave fluctuation are clearly found, such as an earache, tinnitus and etc. for drivers and passengers.

4. SUGGESTIONS ON RIDE COMFORT IMPROVING

At present, there are no obvious criteria for the influence of inside pressure wave fluctuation on the ride comfort index for driver and passengers during the urban railway vehicle operation both domestic and abroad. It’s not proper to refer to the criteria for the other kinds of vehicle or medical index because the index in medical point of view is a kind of safety index for human-beings. The range is relevantly big. It cannot be used to evaluate the ride comfort. According to the standards such as Railway Construction [2007] No.88, the distance between stations for the mainline railway is relatively big and the pressure wave fluctuation change frequency is
relatively low during the operation, which can be accepted by the drivers and passengers. Regarding metro operation, the train starts and stops frequently during the operation, the inside pressure wave fluctuation will have an impact on the ears of drivers and passengers repeatedly and even have a long-term influence on the physical and psychological health of drivers and passengers. Therefore, for the construction of urban rail transit line with the speed higher than 90km/h, full consideration shall be taken for the situation occurred when the train passes a tunnel (including suddenly different area, such as open station and etc.). The measures are suggested as follows:

4.1 Increase Vehicle Air Tightness

Now, it’s widely believed that the air tightness of metro vehicle is low. However, there are no precise definition and measurement criteria. Refer to the definition for high-speed multiple units\textsuperscript{[6]}: after the tightness under train operation status is simulated, inflate and charge the pressure, then measure the time required for the inside pressure decreasing from 4000Pa to 1000Pa, i.e., inside air tightness index. In foreign countries, the European Railway Research Institution\textsuperscript{[3]} suggests that $\tau<0.5s$ shall be taken as the air tightness index of the non-tight vehicle for calculation and analysis. Figure 4 shows the value simulation of the inside pressure wave fluctuations under three load cases (air tightness index of 0s, 0.5s and 1s) when the train enters a tunnel with the speed of 120km/h. We can find that the improving of vehicle air tightness index can reduce the inside pressure wave fluctuation obviously. Normally, the following measures can be taken to improve the air tightness of vehicle, such as design improving on vehicle ventilation outlet, door, window strip, gangway, piping hole and etc.
Figure 4. Comparison of Inside Pressure Wave Fluctuation under Different Air Tightness Indexes.

4.2 Increase Area of Tunnel Cross-section

Increasing the area of the tunnel cross-section means decreasing of blockage ratio. According to Express (1), we can find that increasing the tunnel section (decreasing the blockage ratio) can effectively reduce the pressure wave fluctuation amplitude in tunnel and decrease the inside pressure wave fluctuation range in further. However, increasing the area of the tunnel cross-section requires a high cost.

4.3 Perform Speed-limited Operation

Based on the value simulation results of figure 1 and figure 4, the following test results and actual riding feelings, the inside pressure wave will approach the criteria limit when the vehicle enters and leaves the tunnel with the speed of and above 90km/h. Even on the vehicle with actually measured result lower than the criteria limit, some test personnel still feel uncomfortable due to tinnitus and earache during the measurement. Because the carbody surface pressure change amplitude is in direct proportion to the train operation speed, with consideration of the operation experience that the most domestic metro operation with speed of and lower than 90km/h will not cause any uncomfortable feelings on human, we can consider to reduce the speed when the metro train with speed of and above 90km/h enters and leaves a tunnel, which can effectively improve the ride comfort of drivers and passengers under the impact of internal pressure wave.
Meanwhile, if the vehicle accelerates when it enters a tunnel or there are many trains are entering or leaving the tunnel, accelerating or decelerating in one tunnel, the “piston-type” pressure wave fluctuation will be formed which may have an influence on the inside pressure wave fluctuation of other trains. Figure 5 shows the pressure wave fluctuation of an accelerating train in tunnel followed with the other train enters the tunnel with the speed of 80km/h. We can find that there are two rising processes of the pressure values for the test points of the front train. The first rising occurs at 27.5s. It is the fluctuation caused by the iterative computations of flow field generated from vehicle speed rising. The second rising occurred at 28.75s. It is relatively high instantaneous change of pressure when the compression wave generated when the second train enters the tunnel transmitting to the test point of the first train (front train). In the figure, 80-100 refers to the switch of speed from 80km/h to 100km/h. With the increase of speed, the surface pressure amplitude increases sharply. Therefore, proper measures can be taken to control the speed for the train entering a tunnel. In this case, the surface pressure fluctuation amplitude can be reduced so as to reduce the inside pressure fluctuation amplitude.

Figure 5. “Piston-type” Pressure Wave of Two Trains with Different Speeds.
Therefore, when the vehicle speed limitation solution is defined, the corresponding locations of the operating trains shall be considered.

### 4.4 Improvement Measures on Line

The conditions of the line, especially the damping device type adopted at the portal of tunnel, also has great impact on ride comfort.

Figure 7 shows the inside pressure fluctuation of the metro train in three different lines entering the tunnel with the speed of about 115km/h. In figure 7(a), (b) and (c), the pressure fluctuation amplitudes within 3s are respectively 827Pa, 706Pa and 701Pa. Compared with the first line in 7(a), the other two lines are new lines with horn-type transition area in the portal of tunnel. The transition area with bevel uptilting. In addition, improvements are taken for the ventilation shaft in the tunnel. From figure 7, we can find that the improvements on line design can reduce the inside pressure fluctuation when a train enters and leaves a tunnel so as to improve the ride comfort.

![Graph showing pressure fluctuation over time](image-url)
Figure 6. Actually-measured Change inside Metro Train (Vehicle Speed about 115km/h).

5. CLOSING

The rapid development of urbanization in China promotes the development of subway-based urban rail transit to be remote and high-speed. In this paper, through the simulation analysis and test of the tunnel aerodynamics for metro train with speed
of and more than 90km/h, introduce the problems such as the pressure wave fluctuation and the ride comfort when the high-speed metro train passing a tunnel. It makes suggestions on inside ride comfort improving by increasing vehicle air tightness, increasing the area of the tunnel cross-section, improving the tunnel entrance or performing speed limited operation for the high-speed metro construction.

1) With reference to some relevant domestic and foreign regulations on multiple unit and high-speed railway vehicles, the paper discusses the evaluation criteria and evaluation indexes on aerodynamics for metro train with speed of and more than 90km/h passing a tunnel.

2) This paper explains the principle on generation of inside pressure wave fluctuation and the demands on ride comfort improving.

3) This paper makes suggestions on ride comfort improving as follows, increasing vehicle air tightness, increasing the area of the tunnel cross-section, performing speed-limited operation and improving tunnel line conditions.

REFERENCES

4. Provisional Regulation on Vehicle Strength Design and Test for the Railway Vehicles with Speed of and higher than 200km/h (Kejiaozhuang 【2001】No.21).